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City University of New York, 1991

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LOUDNESS OF QUASI CONTINUOUS IMPULSE NOISE

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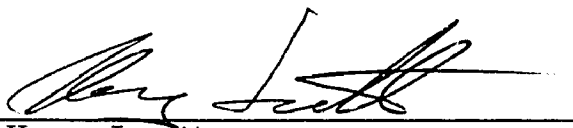
Anne C. Balant

A dissertation submitted to the Graduate Faculty in
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of the requirements for the degree of Doctor of
Philosophy, The City University of New York.

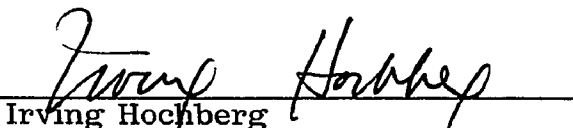
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Abstract

LOUDNESS of QUASI CONTINUOUS IMPULSE NOISE

by

Anne C. Balant

Adviser: Professor Harry Levitt

The loudness of quasi continuous impulse noise has been studied as a function of impulse duration and repetition rate, and the spectral shape and relative level of steady background noise. The measurements were performed on 1-second trains of white-noise bursts with exponentially decaying envelopes. The repetition rates were 5 to 100 Hz. The impulse durations were adjusted so that the duty factor of the impulse train (product of the repetition rate and the effective duration of the impulses) varied from 0.025 to 0.1. Steady white background noise was added at peak-to-background ratios of 10, 20 and 30 dB. The loudness levels of the stimuli relative to a steady white noise reference stimulus at a presentation level of 60.5 dB L_{eq} were measured in ten normal-hearing subjects using an adaptive testing procedure.

Under most conditions, the loudness levels of the quasi continuous impulse noise stimuli were best predicted by the equivalent sound pressure level, L_{eq} , indicating that the "equal energy" relation was followed. At the 50 and 100-Hz repetition rates, the loudness level of the impulse noise test stimuli at the 20 and 30-dB peak-to-background ratios exceeded that of the reference stimulus due to the "roughness effect". The loudness levels of the stimuli at the lower repetition rates, on the

other hand, was significantly less than the equal energy prediction at the shortest durations, which suggests that auditory temporal integration depends on the duty factor of the impulse train. The data of experiment 1 were fit by a simple model involving the duty factor of the impulse train and the difference between the L_{eq} of the impulsive component and the L_{eq} of the steady background noise component of the test stimuli.

In the second experiment, the spectral shape of the background noise did not significantly affect the point of subjective equality, However, there was a significant interaction between background noise spectrum and peak-to-background noise ratio which was suggestive of a masking process.

- To Dad -

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CHAPTER 1

INTRODUCTION

1.1 Overview

One of the primary goals of studying the effects of noise on humans is to assess the psychoacoustical and physiological consequences of noise exposure in order to establish exposure criteria. Psychoacoustically based criteria are intended to limit effects such as annoyance or interference with communication due to exposure to noise at levels that are too low to cause damage to the auditory system. Exposure limits for noise that is potentially damaging are based on "damage risk criteria" (Hodge and Price 1978). These criteria limit the amount of noise-induced permanent or temporary auditory threshold shift (Kryter 1970) that is acceptable in a given percentage of the exposed population.

The other primary goal of research on the effects of noise is to obtain information about the physiological and perceptual aspects of the processing of sound by the auditory system. Studies of this nature reach beyond the simple question of how much noise is acceptable in a particular context. Instead, the dependence of a psychoacoustical quantity (such as loudness) or a physiological process (such as the development of a permanent threshold shift) on the parameters of the noise is studied. The results of such experiments are compared with the predictions of existing auditory models and are used to develop new

models.

Considerable progress towards both the establishment of exposure limits and the development of auditory models has been achieved in the area of continuous noise. The same goals apply, but have been less completely achieved, in the case of impulse noise, i.e. sounds of short duration that are characterized by rapid excursions of sound pressure level. It is well known that transient or impulsive sounds act differently upon the auditory system than do continuous sounds (Brueel 1976). These differences are both physiological and psychoacoustical, and they depend upon the characteristics of the impulse noise. For example, impulse noise may be divided into two categories; isolated impulses, such as those produced by weapons fire; and quasi continuous impulse noise which consists of trains of repeated impulses. Quasi continuous impulse noise that includes a high level of either steady or fluctuating continuous background noise has been shown to be more damaging physiologically than comparable levels of either of its components (Cohen, Kylin, and Labenz 1966; Walker 1972; Hamernik et al. 1974; Thiery and Meyer-Bisch 1988).

The auditory hazards of impulse noise have been known for over two centuries (Ramazini 1713, Fosbroke 1831), and physiological research in the area has focused primarily on defining damage risk criteria for human exposure (Hodge and Price 1978). Through the use of threshold shift studies in humans and animals, as well as more invasive experiments in animals (Henderson and Hamernik 1986), several different countries have developed damage risk criteria for noise. Many of these criteria are based on the equal energy hypothesis (Martin 1976), which states that damage is correlated with time-integrated exposure rather than peak level. As

will be seen below, many aspects of these criteria remain controversial. For example, most damage risk criteria are based on impulses that are isolated or repeated at low repetition rates. They do not address the additional hazard that has been observed when quasi continuous impulse noise includes a high level of steady or fluctuating background noise.

The psychoacoustical effects of impulse noise have been studied during the past five or six decades (Moore 1982, 50), and many of the key problems remain unsolved. For example, extensive research on the perception of isolated impulses and repetitive impulse trains has led to the standardization of the impulse sound level meter (International Electrotechnical Commission 1973, 1979; Kundert 1974); but neither the output of this meter nor the loudness estimation methods that have been developed for continuous noise completely predict the subjective response to impulse noise (Pedersen, Lyregaard, and Poulsen 1977). Moreover, the combination of quasi continuous impulse noise and continuous background noise has received comparatively little attention, despite its prevalence in the environment and the fact that, in analogy with the physiological findings, it may be more aversive psychoacoustically than either of its components.

Recent research on the psychoacoustical effects of impulse noise has continued to focus on the determination of an appropriate model, meter, or statistical measure to classify quasi continuous impulse noise and to predict its psychoacoustical impact (Pedersen, Lyregaard, and Poulsen 1977; Rice 1989). Progress has been hindered, however, by several unresolved problems. There has been disagreement as to the definition of the term "impulse noise" itself, and on the distinction between quasi continuous noise impulse noise and isolated bursts (American National

Standards Institute 1971). As will be seen in the next chapter, additional problems arise in the measurement and characterization of impulse noise.

Comparison of the results of different experiments has been problematical as well because several different psychoacoustical quantities are measured; the experiments are subject to variability in interpretation of the test instructions; and the results depend to a degree on the experimental methods that are used. Moreover, impulse noise parameters such as duration and repetition rate span a wide range of values, but there are psychoacoustical effects that only occur over a subset of this range, making it difficult to develop a cohesive model that applies to all possible conditions. For example, some early research has suggested that a "roughness effect" (Miller and Taylor 1948; Pollack 1969; Terhardt 1974) may affect the psychoacoustical response to impulse noise. Roughness is a harsh, tonal quality that arises when noise is subject to periodic amplitude modulation at rates high enough that the individual amplitude fluctuations are no longer distinguishable to the listener (Terhardt 1974). Thus the psychoacoustical effects of impulse noise at high repetition rates (above approximately 20 Hz) may be very different from those observed at lower repetition rates.

The experiments described here were designed to determine the loudness of quasi continuous impulse noise as a function of impulse duration and repetition rate, and the spectral shape and relative level of steady background noise. The primary purpose of the study was to explore two psychoacoustical "transition zones". One zone is the boundary between impulses that are effectively isolated and quasi continuous impulse noise. The only current definition of this boundary is based on the properties of an unspecified measuring device rather than

on psychoacoustical criteria (American National Standards Institute 1971). The other transition zone is the boundary between pure impulse noise and impulse noise that has a psychoacoustically significant amount of continuous, steady background noise. Another goal of the study was to determine if the loudness of impulse noise depends on the spectral shape of the background noise, because of masking effects, for example. If such a masking effect were found, it might indicate which regions of the spectrum are most significant in determining the loudness of impulse noise.

Two experiments were performed using impulses that were synthesized by gating white noise with an exponential envelope function. The first experiment explored the loudness of impulse noise as a function of repetition rate, impulse duration, and the peak-to-background ratio of steady white background noise. The values of these parameters were chosen to explore both of the transition zones described above. In the second experiment, the spectral shape and peak-to-background ratio of the background noise were varied. In both experiments, an adaptive two-alternative-forced-choice procedure was used to measure the loudness of the impulse noise test stimuli compared to a steady white noise reference stimulus.

1.2 Outline of Dissertation

Chapter 2 covers the "Generation and Measurement of Impulse Noise". The first half of the chapter introduces impulse noise production, characteristics, and terminology. Various definitions of impulse noise are reviewed and a working definition for the purposes of this dissertation is proposed. The second half of the chapter gives an overview of impulse

noise measurement, including sound level measurement, and temporal and spectral analysis techniques.

In Chapter 3, "Physiological Effects of Impulse Noise", a brief review of research on the acoustic trauma due to impulse noise is presented. Section 3.2 covers damage risk criteria and raises some of the issues that are also a concern in the psychoacoustics of impulse noise.

In Chapter 4, the past five decades of research on the "Psychoacoustical Effects of Impulse Noise" are reviewed. The chapter begins with a discussion of the various psychoacoustical quantities that can be measured in assessing human response to impulse noise and the different techniques that are used to measure them. This is followed by a discussion of research on the psychoacoustical effects of impulse noise, including isolated impulses, repetitive impulse trains, and repetitive impulse trains with added continuous background noise. Finally, the application of loudness models to impulse noise is addressed.

Chapter 5, "Hypotheses and Experimental Design" describes the experimental hypotheses and the reasoning behind each decision that was made in developing the design of the experiments.

Chapter 6, "Synthesis and Characterization of Impulse Noise Stimuli" is the first of two chapters detailing the way in which the design that was discussed in Chapter 5 was implemented. This chapter includes an overview of the synthesis method, the hardware and software used to generate the impulse noise test stimuli, and the methods by which they were characterized.

In Chapter 7, "Experimental Methods", the subjects and the psychoacoustical testing procedures are described. The operation of the testing software is explained. The chapter concludes with an account of

the procedures used in the calibrating the system and conducting the experiments.

Chapter 8, "Results" describes the data obtained in the experiments and the way in which they were analyzed.

In Chapter 9, "Discussion", the results of the experiments are reviewed. A simple model for the results is developed and discussed.

"Conclusions and Recommendations for Future Study" are found in Chapter 10.

CHAPTER 2

GENERATION AND MEASUREMENT OF IMPULSE NOISE

2.1 Introduction

The measurement of impulse noise is a complex problem because impulse noise may be generated by a number of different mechanisms which result in a broad range of physical parameters. In order to measure impulse noise, one must be able both to detect it and to characterize it. The detection requires that there be an accepted definition of impulse noise in terms of specific detection criteria. However, several different definitions of impulse noise, each based on its own set of detection criteria, may be found in the literature and in various national and international standards. The characterization requires that there be agreement on what variables are to be measured and the means by which this should be done. Although numerous descriptors of impulse noise have been proposed for its characterization, there has not been a consensus on which ones are most appropriate, nor on exactly how they should be determined.

2.2 Generation of Impulse Noise

2.2.1 Types of Impulse Noise Waveforms

There are two basic impulse noise waveforms, often referred to as type A and type B, that are generally produced by different mechanisms

(Guignard 1973). Figure 1a illustrates the type A impulse (also known as the Friedlander or N-wave), which is characterized by a simple N-shaped waveform with sharp leading and trailing edges. This waveform is typical of sonic booms and explosions. The type B impulse shown in figure 1b is characteristic of impacts. This waveform consists of a sharp onset and an exponentially decaying envelope with multiple oscillations, or ringing.

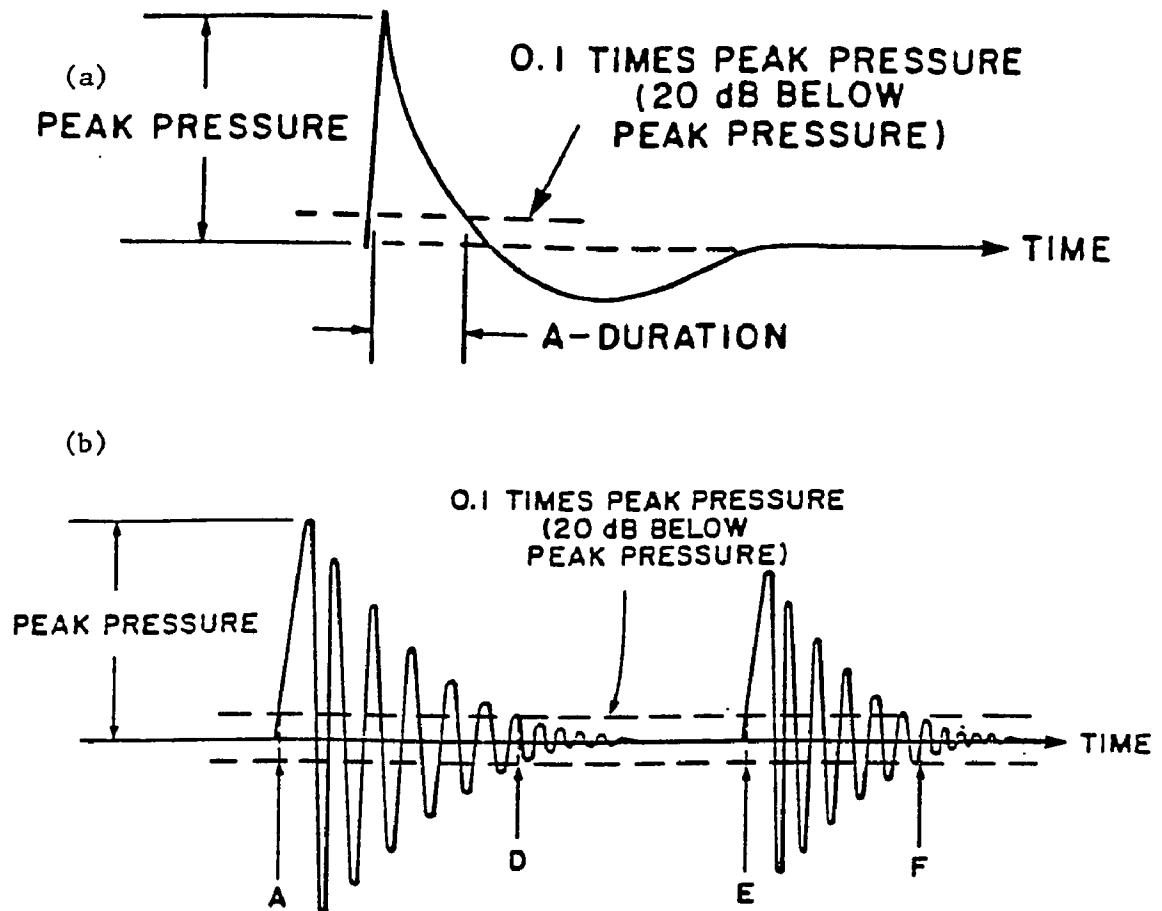


Figure 1. The two types of impulse waveform: a, the Type A (N-wave or Friedlander) impulse waveform, characterized by the A duration; b, the type B or "impact" waveform. The B duration is the time during which the envelope of the impulse (and of its reflection, if any) is within 20 dB of the peak level. (American National Standards Institute 1986).

2.2.2 Generation of Type A Impulse Noise

The predominant sources of Type A impulse noise are sonic booms and weapons fire. Sonic booms (Hassel 1978) occur when an object travels faster than the local speed of sound, causing wave fronts of the pressure disturbances to coincide and form a shock wave (an abrupt increase in the pressure). The crest of this wave forms the "Mach cone" (Hassel 1978) which propagates at the same speed as the source, and a sonic boom is heard in the regions of intersection between the cone and the ground. The shock wave has a Type A waveform because the moving object initially causes a dramatic local pressure increase, followed by a decline to a value below the ambient pressure at the edge of the source (for example, a jet airfoil), and then a rapid return to the ambient. The shape is also affected by the geometry of the surface and by propagation through the atmosphere, which tends to attenuate the high frequency components and reduce the steepness of the rising edge (Niedzwicki and Ribner 1978). Typically, sonic booms have peak pressures on the order of 130 dB and durations of about 300 msec (Hassel 1978).

The impulses produced by explosions (e.g., weapons fire) are also acoustical shock waves with a type A waveform, but with much shorter durations than the sonic boom. Small handguns produce impulses with significant high frequency energy (2-8 kHz) and durations of order 0.5 msec (Bruehl 1976, 1977, Price 1986). Larger weapons such as howitzers and canons generate lower frequency impulses with durations ranging from approximately 10-100 msec and spectra that peak around 1 kHz (Berglund, Berglund, and Lindberg 1986, Jussil, Jukkal, and Jukka 1987, Price 1986). The initial steep rising edge of a weapons fire impulse

waveform is well-described by the Friedlander curve, but the remainder usually shows secondary peaks due to significant reflections from the ground Price (1986). The peak levels of weapons impulses may easily exceed 160 dB.

2.2.3 Generation of Type B Impulse Noise

Type B impulses are characterized by an exponentially decaying envelope with multiple oscillations or "ringing", and are usually produced by impacts. However, impact noise may be produced by several different mechanisms and may include type A as well as type B components.

An impact is defined as "a single collision of one mass in motion with a second mass that may be either in motion or at rest" (Peterson 1980, 190). The prediction of the parameters of the resulting acoustical impulse from the impact conditions is a complex problem. In a review of impact noise, Akay (1978) discusses five different impact noise production mechanisms that may occur separately or in combination: rigid body radiation, transient and steady state response to deformation, fracture noise, and air ejection.

Rigid body radiation is the dominant mechanism if the impact is a collision of rigid bodies without deformation or penetration of one mass into the other (for example, a collision at normal incidence between two bars with flat end-surfaces). The radiation is caused by the rapid deceleration of the colliding objects under conditions such that the duration of the impact is less than the time it takes the resulting sound waves to traverse the objects (Otherwise, the dominant mechanism is deformation, which will be described below). In the case of colliding

spheres, there is an empirical inverse relation between the diameter of the sphere and frequency at which the spectrum of the resulting impulse noise peaks. The sound pressure level produced by rigid body radiation increases with impact velocity.

If deformation of one or both bodies occurs, the resulting impact noise will have two components: an immediate, transient response due to the rapid surface deformation, and a pseudo-steady-state response due to "ringing". For example, the pressure-time history of a metal ball dropped on a plate appears to have a type A waveform with a duration of about 100 μ sec. The ringing begins about 500 μ sec later and has the type B waveform. The peak pressure varies approximately linearly with the momentum of the bodies. The amount of high-frequency spectral energy in the ringing component and the steepness of its onset increase with increasing stiffness and hardness of the colliding bodies. If severe deformation occurs, fracture noise becomes significant (e.g., in punch presses). A more rapid fracture leads to a higher frequency spectrum.

Another, less common impulse noise generation mechanism is the ejection of air by the colliding bodies, which dominates in cases where the radiation due to the rigid body and ringing mechanisms is negligible, i.e. in collisions of parallel, viscoelastic surfaces without deformation. A refractive wave is formed in the gap between the bodies as they approach. The resulting impulse noise is typically of low frequency.

This variety in the production mechanisms of impact noise is partially accountable for the wide range of impulse noise parameters that may result. The other main factor is the tremendous variety of industrial and office machines that produce impact noise. Dym (1977)

has identified over 400 different categories of industrial impact sources. Some examples from the literature illustrating the range of typical repetition rates, durations, peak levels, and spectral content are given below.

The repetition rate of impact noise is governed by the operation of the source. Some sources have a constant repetition rate, e.g., wire and bar cutters, newspaper cutters, and punch presses, which typically produce 1-30 impacts per second. Others have variable repetition rates, for example, the clanking of bottles in an assembly line, or hammer blows in hand forging. Some impacts, for example those produced by bolt setters, are so infrequent that they are effectively isolated bursts. At the other extreme are high-repetition-rate impact sources such as typewriters and dot matrix printers.

The duration of impact noise is also quite variable. Hammer blows may be less than 1 msec in duration (Bruel 1977); typewriter impacts are usually 2-3 msec but may be up to 300 msec long depending on conditions (Sapega 1959); typical metal forming and shearing machine impacts range from 35 to 160 msec (Oldrich 1990); while impulses from exhausted air having durations of about 400 msec have been recorded (Pashier-Vermeer, Van den Berg, and Leeuw 1980).

The peak sound pressure levels of impact noises reported in the literature range from 55 dB at the operator position for an impact printer (Erbes 1986) up through 150 dB in the case of the metal forming machines (Oldrich 1990).

The spectral features of impact noise are also quite variable, and they are not simply related to the impulse duration. For example, a paper by Bruel (1977) shows A-weighted one-third octave-band spectra

for three different impacts: a hammer blow on a brass block, which has a rising spectrum up through 10 kHz; a punch press, which has a broad peak in the 1-2 kHz range; and a bottle impact which has sharp spectral structure peaking near 4 kHz. Similar variability may be seen in the examples reported by Pashier-Vermeer, Van den Berg, and Leeuw (1980). Exhausted air, for example, has a spectrum that rises at 2.5 dB per octave up through 40 kHz, the spectrum of nail impacts is flat from 250 Hz to 40 kHz, while the spectrum of noise due to automatic pressing peaks near 500 Hz.

2.3 Measurement Quantities and Terminology

The measurement of impulse noise is complicated by its characteristic rapid excursions in sound pressure level. In order to fully define and characterize impulse noise, a variety of descriptors have been proposed. Definitions of these descriptors, and of some of the more fundamental quantities on which they depend, will be provided here.

When the pressure-time history of individual impulses is measured, the following definitions are commonly used (American National Standards Institute 1986):

Rise time: The rise time is usually defined as the time in seconds required for the signal to increase from 10 percent to 90 percent of its peak value.

Duration: As was mentioned in the last section, there are two basic impulse waveforms. Figure 1 shows how the duration is specified for each type. In the case of shock wave impulses, the A-duration is the time during which the first, positive pressure excursion is within 20 dB

of its maximum value. However, some authors use the time at which the onset rises above the ambient level to the time at which ambient is reached again (Guignard 1973). The analogous quantity for impact waveforms is the B duration, which is obtained by determining the time during which the envelope of the pressure fluctuations is within 20 dB of the maximum. If a dominant reflection from a nearby surface occurs, the B-durations of the original impulse and its reflection are added. If the impulses overlap, the time between impulses may be used as an effective duration (Pashier-Vermeer, Van den Berg, and Leeuw 1980).

The overall sound pressure level of any time-varying noise (fluctuating or impulsive) is characterized by reporting either the "equivalent continuous sound pressure level" or the "sound exposure level". The equivalent continuous sound pressure level, L_{eq} , of a given time-varying sound is defined as the level of an equivalent steady sound that would have the same mean squared sound pressure as the given sound within a specified period of time. (The term "equivalent continuous sound pressure level" is used by the International Standards Organization Standard ISO 1996 (1982), while the corresponding American National Standards Institute standard, ANSI S12.9 (1988) has adopted the term "time-averaged sound level"). The conventional sound pressure level is defined as:

$$(2.1) \quad L_p = 10 \log \left(\frac{p}{p_0} \right)^2$$

(where p is the RMS sound pressure and p_0 is a reference sound pressure of 20 μ Pa). The equivalent continuous sound level is:

$$(2.2) \quad L_{eq} = 10 \log \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} \frac{p(t)^2}{p_o^2} dt$$

where $p(t)$ is the instantaneous sound pressure, and the integration limits, t_1 and t_2 , correspond to the start and stop times of the measurement. The total integration time $(t_2 - t_1)$ must be specified. For example, if a digitally sampled time-pressure waveform is linearly averaged over 5 seconds, the result is written L_{eq} (5 sec). Averaging times ranging from 1 second to several hours are commonly found on integrating sound level meters (see section 2.6.2.3). The A-weighted equivalent sound pressure level, L_{Aeq} , is defined in the same manner as L_{eq} except that the squared instantaneous sound pressure is filtered by a conventional A-weighting network.

The sound exposure level, L_E , (International Standards Organization 1988) is obtained by integrating the squared instantaneous sound pressure over a measurement time, $T = (t_2 - t_1)$ and then comparing the results to a reference sound exposure $p_o^2 T_o$:

$$(2.3) \quad L_E = 10 \log \frac{1}{T_o} \int_{t_1}^{t_2} \frac{p(t)^2}{p_o^2} dt$$

where p is the instantaneous sound pressure, the reference sound pressure, p_o , is 20 μ Pa, T_o is 1 second, and the integration time $T = (t_2 - t_1)$. Thus, the equivalent continuous sound level and the sound exposure level are simply related:

$$(2.4) \quad L_E = L_{eq} + 10 \log \left(\frac{T}{T_o} \right)$$

The A-weighted sound exposure L_{AE} is defined in the same manner as L_E except that the A-weighted instantaneous sound pressure, p_A is substituted for the instantaneous sound pressure, p .

Both the equivalent sound pressure level and the sound exposure level may be measured directly with an integrating sound level meter. There are also several derived quantities that specifically pertain to impulse noise. These descriptors are calculated from measured sound pressure levels and/or from a digitized time-pressure waveform of the impulse noise.

The "crest factor" is defined as the ratio of the maximum instantaneous value of a waveform observed in a given measurement interval to its RMS value in the same interval (Peterson 1980). A noise with large amplitude excursions has a higher crest factor than a steady noise.

The "kurtosis" is a statistical measure which was originally applied to the impulse noise produced by helicopter blades (Erdreich 1986). Kurtosis is calculated from the amplitude distribution of the digitized waveform, i.e. from the distribution of the frequency of occurrence of an amplitude value as a function of amplitude. The second and fourth moments of this distribution, m_2 and m_4 , are calculated;

$$(2.5) \quad m_4 = \frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^4$$

$$(2.6) \quad m_2 = \frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2$$

where N is the number of samples in the distribution, which has a mean value $\bar{x}$. The kurtosis, B_2 , is the obtained from these two moments

$$(2.7) \quad B_2 = \left(m_4 / m_2 \right)^2$$

Conventionally, the difference between the calculated kurtosis and the kurtosis of Gaussian noise, which is 3.0, is reported. A digitally sampled pressure-time waveform of Gaussian noise and its amplitude distribution are shown in figure 2.

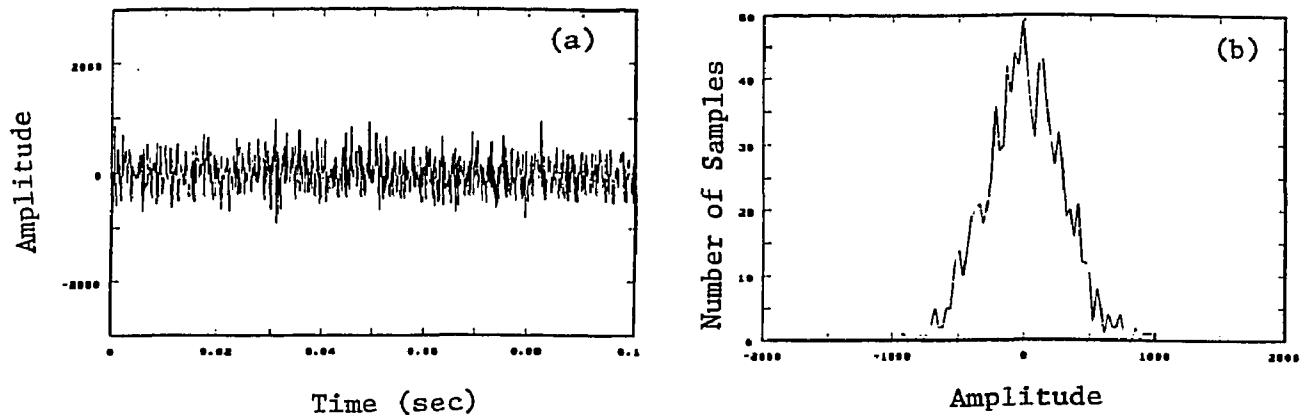


Figure 2. a, time-waveform of Gaussian noise; b, computed amplitude distribution for Gaussian noise in a, with a kurtosis of 3.0.

Figure 3, which was adapted from a paper by Erdreich (1986), shows the relationship between the characteristics of several waveforms and their kurtosis.

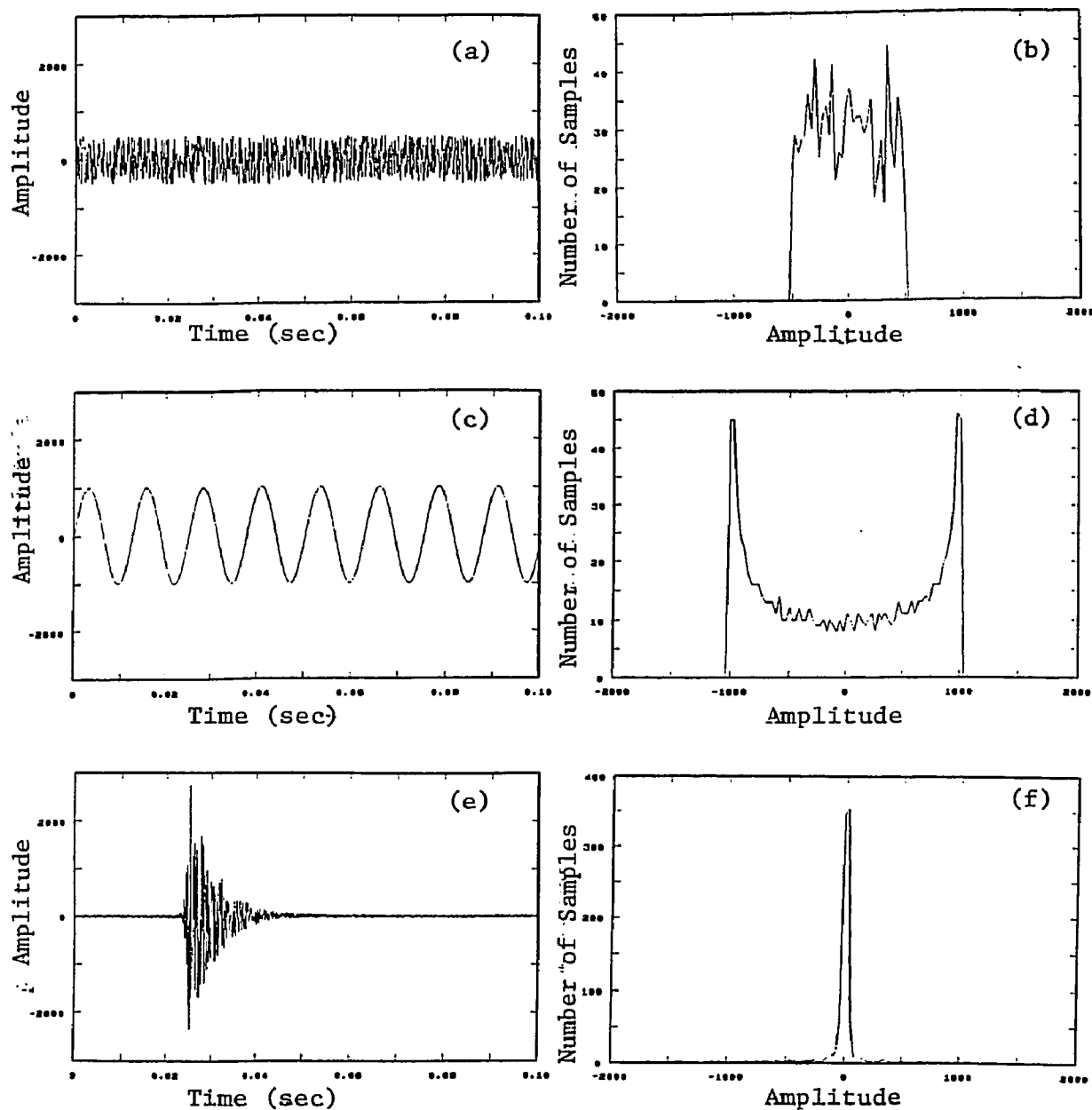


Figure 3. Time waveforms, amplitude distributions and kurtosis: a, time-waveform of uniformly distributed noise; b, computed amplitude distribution for uniform noise in a, with a kurtosis of 1.8 (-1.2 relative to Gaussian noise); c, time-waveform of a sine wave; d, computed amplitude distribution for sine wave in c, with a kurtosis of 1.5 (-1.5 relative to Gaussian noise); e, time-waveform of an impulse; f, computed amplitude distribution for impulse in e, with a kurtosis of 28.8 (25.8 relative to Gaussian noise).

The uniform noise in figure 3 has a distribution in which all values are equally likely and is therefore less sharply peaked than that of the Gaussian noise shown in figure 2. Its kurtosis is 1.8, or -1.2 relative to Gaussian noise. The sine wave clearly has even less tendency to assume values near zero than the uniform noise and its relative kurtosis of -1.5 is therefore even lower than that of the uniform noise. On the other hand, the amplitude distribution of the impulse noise is more sharply peaked than that of the Gaussian noise, and has a kurtosis of 25.8 relative to Gaussian noise.

In addition to the kurtosis, there are several other impulse noise descriptors that are currently in use. Some of these impulse noise descriptors are based on the "short-term L_{eq} " (or L_{Aeq}) time series (Sirieys and Commins 1980; Commins and Sierys 1981; Sidhammed and Commins 1983; Commins et al. 1985). The short-term L_{eq} series is obtained by performing a sequence of L_{eq} measurements with a short measurement interval (usually 10 msec). This reduces the amount of data that must be processed in calculating various impulse noise descriptors while retaining most of the sharp temporal structure of the waveform (Laville, Fournol, and Commins 1986; Wallis and Berry 1989).

One of the impulse noise descriptors that is calculated from the short-term L_{eq} time series is the "saliency" (Berry 1985, 1987, 1989; Berry, Wallis, and Rozwadowski 1989). Saliency is calculated by taking the difference between the highest short-term L_{Aeq} value in the measurement interval and the RMS level over the same interval. Another indicator that has been proposed is the "increment" which is the largest increase observed between two successive short-term L_{Aeq} values in the measurement interval (Berry 1985, 1987, 1989; Berry, Wallis, and

Rozwadowski 1989). The same authors have also explored the standard deviation of the short-term L_{Aeq} series as an impulse noise descriptor.

Berry et al (1979) have used the "ISO descriptor" which was originally developed for helicopter noise and is not based on the short-term L_{Aeq} time series:

$$(2.8) \quad \bar{I} = \frac{1}{N} \sum_{i=1}^N \frac{(v_i - S)^2}{S}$$

where S is the mean of the squared values of the impulse waveform:

$$(2.9) \quad S = \frac{1}{N} \sum_{i=1}^N v_i^2$$

Since the standard deviation of a variable is given by:

$$(2.10) \quad \bar{I} = \frac{1}{N} \sum_{i=1}^N \frac{(x_i - \bar{x})^2}{N}$$

the ISO indicator can be shown to be the standard deviation of the squared waveform, normalized by the mean, S , of the squared waveform.

2.4 Definitions of Impulse Noise

Several different definitions of impulse noise may be found in various national and international standards. American National Standards Institute (ANSI) standard S12.7 (1986), Methods for

measurement of impulse noise defines impulse noise as a "short burst or series of bursts of sound pressure" having a pressure-time history "that includes a rise to peak pressure, followed by a decay of the pressure envelope" (American National Standards Institute 1986, 2). In ANSI S1.13 (1971), an impulse is defined as a brief excursion of sound pressure that significantly exceeds the ambient level and has a duration of less than 1 second.

Both International Standards Organization (ISO) standard 2204 (1979) and ANSI S1.13 include a classification scheme in which noise is first categorized as steady or non-steady. The term "non-steady" noise encompasses fluctuating, intermittent, and impulse noise. According to ANSI S1.13, the term "impulse noise" includes two subcategories, isolated bursts and quasi continuous impulse noise. The standard further states that isolated bursts are "individually distinguishable with a sound level meter" (American National Standards Institute 1971, 13), while quasi continuous impulse noise is defined as impulses that are not resolvable with a sound level meter and may vary in amplitude and burst spacing. In Appendix B of this same standard, isolated burst impulse noise is defined as consisting of bursts with a duration of less than 250 msec at half maximum, at repetition rates of less than 5 Hz. Furthermore, the A-weighted peak sound pressure level averaged over 10 bursts must be 15 dB higher than the A-weighted sound pressure level. (i.e. using the terminology of section 2.3, the A-weighted crest factor must exceed 15 dB).

Although the crest factor is an integral part of the ANSI definition of impulse noise, and has also been widely adopted for impulse noise detection (Passchier-Vermeer, van den Berg, and Leeuw 1980;

Thiery 1987), its use is problematic. Erdreich (1986) has demonstrated that crest factor is an unreliable measure of impulsiveness because it depends on the amplitude of the largest peak in the measurement time window and is therefore dependent on the length of the window relative to the repetition rate of the impulses. For example, including more than one impulse of a repetitive train in the measurement window decreases the crest factor because only the largest amplitude impulse is considered; the others are treated as background and contribute only to the RMS level.

This problem with the use of crest factor has led Erdreich (1986) to recommend using the kurtosis of the amplitude distribution to define and detect impulse noise. He has shown that, depending on the measurement interval, kurtosis and crest factor are monotonically related, but that kurtosis takes all of the peaks in the measurement interval into account rather than just the maximum. However, in cases where there are long intervals of background noise between low- repetition-rate impulses, the choice of measurement time interval has a significant effect on the value obtained. Furthermore, the maximum kurtosis that may be measured is bound by the sample size, so that the kurtosis may increase if the measurement interval is expanded.

A definition of impulse noise based on the difference between the A-weighted levels measured with the impulse (I) and slow (S) time constants of a sound level meter is given in Appendix D. of ISO 7779-1988(E) (International Standards Organization 1988). The noise is considered impulsive if the difference $\Delta L = L_{AI} - L_{AS}$ exceeds 3 dB.

A scheme which classifies impulse noise into three types, A, B, and C, has been proposed by Coles and Rice (1971). The type A and

type B impulse noise waveforms were discussed in section 2.2.1 and illustrated in Figure 1. Type C impulse noise is characteristic of industrial sites in which impact noise is produced in a reverberant environment that may also contain continuous or fluctuating background noise sources. Type C impulse noise is basically equivalent to quasi-continuous impulse noise as defined in ANSI Standard S1.13 (American National Standards Institute 1971), but the definition explicitly includes the combination of impulses and continuous background noise, as well as the case of overlapping impulses.

These two cases are illustrated schematically in figure 4. Figure 4a shows the envelope of a train of exponentially decaying type B impulses with added steady background noise. The minima between impulses remains above the zero (ambient) level because of the background noise. In figure 4b, the impulse decay time is long compared to the repetition period, such that the envelopes of the individual impulses overlap. Thus the minima between impulses remains above the ambient level because of the overlap, even though no background noise has been added.

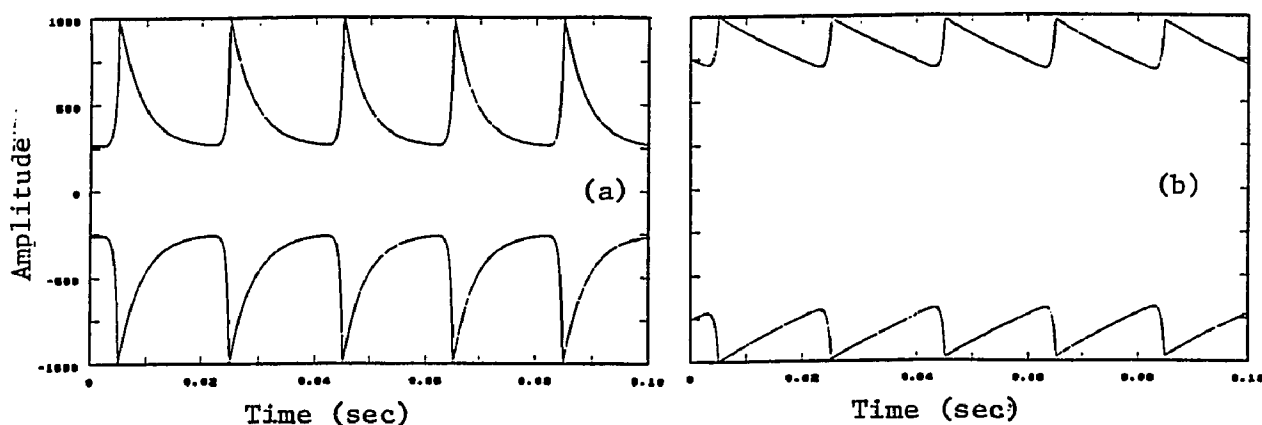


Figure 4. Type C impulse noise. **a** Envelope of type C impulse noise with non-overlapping repetitive impulses with steady continuous background noise. **b** Envelope of type C impulse noise without background noise, but with repetitive impulses overlapping.

2.5 Proposed Definition of Impulse Noise

The following definitions are proposed for the purposes of this dissertation:

An impulse is defined as a transient excursion in sound pressure such that (a) the instantaneous peak level exceeds the "effective ambient level" by 10 dB or more, (b) the duration of the excursion is less than 1.0 seconds, and (c) the rise and/or fall time from the peak level to the effective ambient level is less than 250 msec.

The effective ambient level is defined as the level exceeded by the noise for 90 percent of the time. In the absence of background noise, the effective ambient level is equivalent to what is generally defined as the ambient level, i.e. the level that would be measured with the noise source removed. However, in cases where the background level is high, of the impulses overlap, the effective ambient is a measure of the L_{eq} of the steady, continuous portion of the noise.

The duration of the excursion is the difference in time between points on the rising and the trailing edges of the impulse that are 20 dB down from the peak (i.e. the conventional A-duration).

Impulse noise is any noise that contains one or more of these transient excursions during the observation period. Impulse noise may be divided into two sub-categories: steady or quasi continuous impulse noise and intermittent impulse noise. Steady or quasi continuous impulse noise consists of a train of successive impulses separated in time by less than 1 second. Intermittent impulse noise includes "isolated" impulses (those that are separated in time from any other impulses by 1 or more seconds) and any train of repetitive impulses in which an interval of one or more seconds occurs between some of the impulses.

2.6 Measurement of Impulse Noise

2.6.1 Overview

The measurement of noise can be divided into three general categories: measurement of sound pressure or sound exposure levels; measurement of the pressure-time waveforms; and measurement of spectra, including narrow-band Fast Fourier Transform (FFT) analysis and measurement of octave-band or one-third octave-band spectra. The choice of measurement procedures depends on the information that is needed and on the type of noise being measured.

Steady noise may be fully quantified by measurements in the first and last of these categories. In the case of impulse noise, it is often necessary to measure the pressure-time waveform as well. Isolated impulses or low-repetition-rate trains of impulses may be adequately described by reporting basic parameters such as impulse duration and peak level. More sophisticated techniques must be used when measuring quasi continuous impulse noise, particularly when the peak levels and durations of the bursts in the impulse train vary in time. Moreover, measurement of the overall sound pressure and sound exposure levels of impulse noise is not as straightforward as it is in the case of steady noise (Kundert 1974). Appropriate time constants must be chosen; the measuring system must possess both an adequate slew rate (the ability to respond to an abrupt increase in voltage) and sufficient dynamic range to record the signal accurately (American National Standards Institute 1986); and care must be used in the selection of microphones. As will be seen below, the performance of sound level meters and dosimeters is less than ideal for most impulse noise measurements (Kundert 1982), and

precautions must also be taken when performing impulse noise measurements in the frequency domain (Hewlett Packard Corporation 1985).

2.6.2 Sound Level Measurements

2.6.2.1 Introduction to Sound Level Meters. The sound level meter is probably the most widely used device for acoustical measurements. The sound pressure due to an acoustic wave is measured and reported as the sound pressure level, L_p , in decibels (dB) relative to a reference sound pressure (p_0) of 20 μ Pa:

$$(2.13) \quad L_p = 10 \log \left(\frac{p}{p_0} \right)^2$$

where p is the RMS sound pressure in pascals.

The first sound level meters (SLMs), referred to as "Noise Meters", were developed in the 1920s, as an outgrowth of work at Bell Laboratories (Kundert 1977). Early milestones in the development of the sound level meter included dramatic technical improvements in the microphones and the detection electronics. More recent advances include the impulse and the integrating sound level meters.

A block diagram of a conventional sound level meter (Kundert 1977; Nabelek 1982) is shown in figure 5. The input stage is a high quality microphone (usually an air or electret condenser microphone of either 25 mm or 12.5 mm diameter) which provides a nearly omnidirectional response. In the next stage, the desired frequency weighting is applied to the signal. Most meters include the standard A, B, and C frequency weightings, which approximate the Fletcher-Munson equal-loudness

contours at 40, 70, and 100 dB SPL respectively. Other options include a flat response, filters (octave-band or narrower), and sometimes specialized weightings such as the D-weighting curve which was designed to simulate the perceived noisiness of aircraft sounds (Hassel and Zaveri 1978). After passing through the frequency weighting network, the signal is squared and exponentially averaged in the RMS detection stage. The averaging time constants are 1 second ("slow") and 125 msec ("fast"). The slow time constant is intended to allow visual averaging of fluctuating signals. The output of the RMS detection stage is displayed on a digital or panel meter.

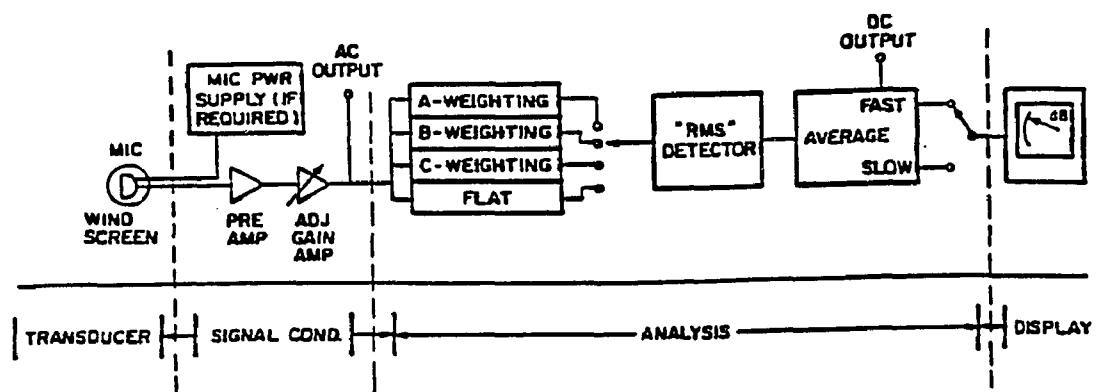


Figure 5. Block diagram of a sound level meter (Nabelek 1982).

2.6.2.2 Development of the Impulse Sound Level Meter. Sound level meters were originally designed and standardized for the measurement of steady, continuous sounds. Meters that met these standards (American National Standards Institute 1983; International Electrotechnical Commission 1965, 1973a) were applied to the measurement of impulse

noise with inconsistent and unsatisfactory results (Niese 1956, 1958).

During the 1950s, a series of psychoacoustical studies was carried out in order to develop a meter circuit that would simulate the perception of impulse noise by the human auditory system.

One group of experiments was performed by Niese (1956, 1958, 1959, 1960, 1961) in Dresden, and led to the proposal of a nomogram procedure for assessing impulse noise (Niese 1958); and another group was performed by Port (1959) in Stuttgart. In 1961, Germany submitted a proposal to the International Electrotechnical Commission (IEC) based on the results of these early experiments. The proposal specified tolerances for the response of an impulse sound level meter circuit to several standard impulses (Reichardt 1965). However, as Zwicker (1961) observed, this proposal was based on studies that were inconclusive and did not fully characterize the human response to impulse noise.

Further research was conducted during the 1960s in order to improve the IEC proposal. By this time, there was general agreement that the impulse sound level meter should consist of an exponential averaging (RC) circuit with rise and fall times chosen to simulate the integration time constants of the human auditory system. After performing extensive loudness measurements on amplitude-modulated isolated and repeated noise bursts, Port (1963a, 1963b) concluded that the ear functions as an equal energy detector below 70 msec, and that the meter time constants should be a rise time of 70 msec and a fall time of 350 msec. (The separate fall time implies that, if the input level stops increasing, the output decays according to the 350-msec time constant rather than the 70 msec rise time constant). The results of Niese (1965), however, were consistent with rise and fall times of 25 msec.

In 1965, Reichardt reviewed the literature and concluded that almost all the research supported a value for the integration rise time of 23-70 msec, but that there was tremendous variability between subjects (Reichardt and Muller 1965). His own experimental results agreed best with the Niese proposal at repetition rates below 3 Hz. Between 3 and 10 Hz, either set of time constants yielded good agreement with the data. However, between 10 and 100 Hz, both proposals underestimated the loudness of the impulses. The discrepancy was greatest when the repetition rate was constant due to the roughness effect (Miller and Taylor 1948; Terhardt 1974). Close to the auditory threshold, however, the roughness component vanished and the measured auditory integration time constant decreased.

Zwicker (1966) found that the loudness of tone bursts was unaffected by repetition rate below 10 Hz, with a two-fold increase in loudness for a tenfold increase in repetition rate above 10 Hz. He obtained auditory integration time constants of 15 msec for amplitude modulated sine waves, and 25 msec for amplitude modulated broad-band noise.

The revised proposal to the IEC for an impulse sound level meter circuit was ultimately based on the work of Niese (1965). This proposal was incorporated into a supplement to IEC Publication 179 (1973a) which was approved as IEC 179A (1973b). This standard was then consolidated with IEC 123 (1965), (the "ordinary" sound level meter standard) and IEC 179 (1973a), (the "precision" sound level meter standard) to form IEC 651 (1979). The latter standard specifies four grades of sound level meters: survey (Type 3), ordinary (Type 2), precision (Type 1), Reference standard (Type 0). The corresponding

ANSI standard, S1.4 (1983), has similar classifications.

In these impulse sound level meter standards, the impulse circuit is specified in terms of its response to a particular set of input conditions. This response is usually achieved by exponential averaging with a rise time of 35 msec averaging in place of the usual fast or slow averaging circuit and by placing a peak detector with an integration period of 200 μ sec or less and a fall time constant of 1.5 seconds between the averager and the output indicator (Kundert 1974) as shown in figure 6. The tolerances of the time constants that are given in IEC 651 (1979) are consistent with the response of modern digital indicators and wide range panel meters (Kundert 1974).

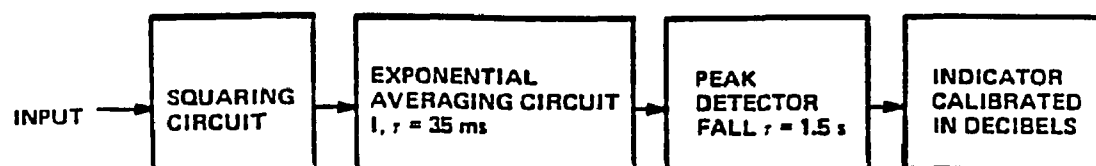


Figure 6. Schematic block diagram of the impulse sound level meter (Nabelek 1982).

Although the impulse sound level meter has been standardized for almost three decades, survey of the literature suggests that it has not been widely accepted (Lahti and Starck 1980; Martin 1976; Rosenheck and Hoffman 1977). For example, ISO 1999 (1975) recommends the assessing the level of occupational quasi continuous noise by adding 10 dB to the level measured by a sound level meter set to the Slow (1 second) time constant. The impulse time-weighting is not included in the

Japanese standard for precision sound level meters (Japanese Industrial Standards Organization 1988). The impulse time-weighting is used when determining the quantity $L_{AI}-L_{Aeq}$ as specified in ISO 7779 (1988), but the ordinary crest factor $L_{peak}-L_S$ is at least as widely used. An analysis of different types of repetitive impulse noises by Bruel (1876, 1977) suggests that the values of L_{AF} and L_{AI} are often the same within a few decibels if the repetition rate is high enough. This lack of acceptance has been recognized by Standards organizations as well. The most recent sound level meter standard, IEC 651 (1979) states that:

In the past, frequency weighting and time weighting have been associated with certain characteristics of the ear. However, recent work has not substantiated these historical associations so that frequency and time weighting characteristics of sound level meters may be considered to be conventional....

... standardization of the I (impulse) time-weighting characteristic does not imply that the relationship between loudness or hearing damage risk of impulsive sounds and the physical characteristics of sounds is thereby precisely represented. (International Electrotechnical Commission 1979, 9).

However, although the ability of the impulse sound level meter circuit to predict the psychoacoustical or physiological effects of impulse noise has been called into question, there are advantages to the use of the impulse sound level meter. Kundert (1974) has shown that the impulse precision sound level meters that are commercially available are superior to non-impulse (Type 1) precision SLMs for measuring the RMS levels of time varying signals. The Type 1 meter is accurate only for crest factors below 10 dB, and will read low by up to 10 dB low at higher crest factors. The impulse-precision meter is essentially a type 1

sound level meter, but, when it is used in the fast or slow rather than the impulse mode, it is as accurate as the laboratory reference standard meters (type 0) for crest factors up to 20 dB. Thus, independent of the utility of the impulse circuit, the current impulse-precision SLM offers a superior dynamic range and a high degree of accuracy for RMS measurement of time-varying signals that otherwise would only be available in Type 0 Standards meters.

According to Kundert (1974) the levels obtained in the impulse mode are comparable to those observed with the fast time constant for impulse durations over 35 msec. When shorter impulses are measured, the impulse reading typically exceeds the fast value by 5-10 dB (Kundert 1974). It has been shown that, as the impulse duration is reduced below 35 msec, the value of $L_T - L_F$ approaches an asymptotic value of 5.5 dB (Martin 1976; Rosenheck and Hoffman 1977). In other words, because of its long fall time, the impulse SLM circuit functions almost as a peak detector for isolated impulses or short-duration bursts at low repetition rates, as an RMS detector for long impulses, and as something in between for most cases of practical interest. Consequently, many researchers have begun to take advantage of the newer integrating sound level meters, as well as digital methods of temporal analysis, for measuring impulse noise.

2.6.2.3 Measurement of Integrated and Averaged Quantities. Two types of instruments are used to measure integrated noise exposure; the dosimeter (Kundert 1982) and the integrating sound level meter. The dosimeter is a special purpose instrument for assessing occupational noise exposure according to various damage risk criteria (Hodge and

Price 1978). A damage risk criterion specifies a trading relation, i.e. a correspondence between the duration of a noise exposure and its permissible level. Dosimeters integrate the total noise dose above a threshold level according these time-level trading relations. As will be seen below, the use of conventional dosimeters for the assessment of occupational hazard due to impulse noise is highly problematic. The integrating sound level meter, on the other hand, is a general purpose laboratory instrument that combines the features of a conventional sound level meter with an integrating/averaging capability for measuring time averaged sound levels, L_{eq} , and sound exposure levels, L_E , which were defined in section 2.3.

Dosimeters are subject to the same problems as the sound level meter in the measurement of impulse noise, and the situation is more severe because the current dosimeter standard (American National Standards Institute 1978) does not specify the crest factor capabilities of these instruments. In addition it has been unclear from the OSHA regulations (1971) whether impulses are to be included in the total noise dose (Kamperman 1980; Kundert 1982), and there are differences of opinion about the correct trading relations between impulse duration and level.

Recent studies have shown that dosimeters can underestimate impulse noise exposure because the squaring circuit can not follow short transients accurately, and that it actually has a response that is close to linear instead (Kamperman 1980; Wilkerson 1975). Earshen (1980) has demonstrated that, in cases where the trading relation used in the dosimeter exceeds three dB, the exposure levels may be overestimated due to the characteristics of the exponential averager circuit. Also, the

dosimeter is designed to calculate integrated hazardous exposure over a period of minutes or hours, so that its main utility is for occupational assessment. For characterization of impulse noise and for psychoacoustical research, therefore, the integrating SLM, rather than the dosimeter, has become the instrument of choice for measuring time averaged and integrated sound levels.

The requirements for integrating sound level meters are specified in IEC standard 804 (1985), which parallels the meter types and tolerances of the impulse sound level meter standard, IEC 651 (1979). In addition to the capabilities of the conventional meters, the integrating SLMs can be used to measure equivalent continuous sound pressure levels, L_{eq} , and the integrated sound exposure level, L_E .

Measurement of sound exposure levels and equivalent continuous sound pressure levels has become an accepted practice for the characterization of impulse noise (Vos and Guertson 1987; Wallis and Berry 1989). Bruel (1980, 1985, 1987a, 1987b) has used an integrating sound level meter in conjunction with a peak detector for the measurement of high-repetition-rate impulse noise. The time-averaged SPL over a 60 second interval and the peak value detected every 330 msec were recorded simultaneously. From these measurements, a crest factor was calculated for each 330 msec interval. Lahti and Starck (1980) have suggested obtaining the effective duration of an impulse by measuring its peak level and sound exposure level. The effective duration is defined as the duration of a rectangular impulse having the same peak level and the same sound exposure level as the impulse.

2.6.3 Time Domain Measurements of Impulse Noise

Time domain measurements of impulse noise are generally performed using digital instrumentation. Analog measurements are sometimes performed with an oscilloscope if the noise consists of isolated bursts or of consistent bursts that are well separated in time. Typical instrumentation consisting of a microphone, storage oscilloscope and camera, and a peak reading circuit is outlined in Appendix B of ANSI S1.13 (1971). Definitions of the quantities to be measured and specifications for the slew rate, dynamic range, and droop of the instrumentation are given in ANSI S12.7 (1986).

When measuring steep shock waves such as those produced by sonic booms or weapons blasts (type A), the choice of transducer is critical. Parmentier and Buck (1980) have enumerated the necessary characteristics including reduced size, constant sensitivity over a wide enough dynamic range, a flat frequency response, high temporal fidelity, insensitivity to accelerative forces, and minimal drift or hysteresis. The impulse wave front must be perpendicular to the transducer surface. The authors used a 1/8" capacitive microphone and several small piezoresistive and piezoelectric transducers mounted on needle probes to record acoustical shocks.

There are two primary advantages to using digital rather than analog methods to analyze impulse noise in the time domain. First, so long as the usual concerns in digital to analog conversion (e.g sampling frequency and quantization error) are taken into account, digitizing the pressure-time waveform provides superior resolution for the determination of impulse noise parameters and offers all the averaging

and data storage capabilities of currently available digital signal analyzers. Second, further processing of the data is readily accomplished. Because of these advantages, the use of digital techniques for temporal analysis of impulse noise is practically universal.

Digitally sampled pressure-time waveforms are used to calculate impulse noise descriptors such as those that were introduced in section 2.3. For example, The digitally sampled impulse waveforms can be averaged with a short integration time in order to obtain the short-term L_{eq} or L_{Aeq} time series (Berry 1985, 1987, 1989; Berry, Wallis, and Rozwadowski 1989). Usually this is done with computer, but special purpose instruments based on this concept have also been designed (Commins and Sirieys 1981; Wallis and Holding 1984). The short-term L_{Aeq} series has been used to analyze industrial impulse noise (Amadasi 1990), and is the basis of an automated impulse detection scheme using the autoregressive moving average (ARMA) model (Commins et al. 1985).

One can also calculate the cumulative pressure-time distribution of the impulse waveform, which is a histogram the number of samples that are equal to or below a given level as a function of level. Erlandson et al. (1980) have designed an analog device that records the cumulative pressure-time distribution directly. The cumulative histogram may also be obtained by measuring the amplitude distribution with a digital signal analyzer and then integrating (Svensson 1980). The amplitude distribution yields much more information than a single peak level measurement and is the basis for calculation of impulse noise descriptors such as the standard deviation and kurtosis indicators (Berry 1987, 1989; Erdreich 1986).

2.6.4 Spectral Analysis of Impulse Noise

By far the most commonly used method for spectral analysis of impulse noise is Fast Fourier transform (FFT) analysis with a digital signal analyzer. Even short, isolated transients may be measured as long as the appropriate window function and sampling times are selected. Recently, a number of non-FFT based methods have been developed (Kay and Marple 1981). Several of these techniques have been applied to impulse noise (Arai and Miura 1987; Bisping 1989).

There are several approaches to the spectral analysis of impulse noise. Narrow-band or one-third octave-band analysis can be performed on isolated bursts, but the trade-off between temporal and frequency resolution may be problematic if the burst is shorter than the minimum time window of the analyzer, which is typically 20-50 msec (Nabelek 1982). Short transients must be sampled using a uniform (rectangular) window because a tapered window such as the Hanning function will distort the rapidly rising initial peak or peaks of the impulse waveform. Isolated impulses that are longer than the maximum time window also pose an analysis problem. Unless rapid storage or overlap processing are available, some of the data will be lost (Hewlett Packard Corp 1985).

Repetitive impulses that are uniform in peak level and of constant repetition rate may be analyzed in the same manner as isolated impulses, but with the advantages of signal averaging. The choice of sampling window is dependent on the level of noise between the impulses. A uniform window is preferable unless the background is high enough to require a tapered window. Another approach is to use a Hanning window to sample an interval that includes a number of impulses to obtain a long-term average spectrum. The latter is the only workable method for

quasi continuous impulse noise with either a high background level or a time-varying repetition rate (Lahti and Starck 1980).

The problems of time resolution versus frequency resolution and of spectral splatter that are inherent in the FFT method are most severe when analyzing transient signals. Thus some of the recently developed non-FFT spectral analysis methods may be especially useful for impulse noise. Kay and Marple (1981) discuss the advantages and disadvantages of a number of these techniques compared to FFT analysis. One of these techniques, the Prony spectrum analysis method, has recently been applied to impulse noise by Bisping (1989). The method involves modeling the time waveform as a series of complex exponentials. The computation of the Prony spectrum requires more processing time than an FFT, but it yields a high resolution zoom spectrum which shows promise for impulse noise characterization (Brambilla and Caretti 1989).

Another technique that incorporates information from both the time and the frequency domain is Wigner distribution analysis. Arai and Miura (1987) have analyzed a variety of impulse noises with a Gaussian window to obtain "pseudo-Wigner distributions" which gives a spectral density as a function of both frequency and time. However, the method is problematic because of cross terms and spectral smearing.

CHAPTER 3

PHYSIOLOGICAL EFFECTS OF IMPULSE NOISE

3.1 Overview

Exposure to high-level impulse noise causes complex physical changes in the inner ear, and in some cases, the middle ear ossicles or the tympanic membrane. These changes may lead to temporary and/or permanent shifts of the auditory threshold. Through threshold shift experiments in animals and humans, histological studies, and epidemiological research, progress has been achieved in relating impulse noise parameters to the nature and degree of the resulting threshold shifts and damage to the auditory system. However, many problems remain unsolved, and the damage risk criteria that are in use do not reflect even our current state of knowledge.

The physiological effects of impulse noise on the auditory system are discussed in a recent review by Saunders, Dear, and Schneider (1985). Most of these changes involve the cochlea and primary auditory neurons. In extreme cases, breakage of the middle ear ossicles or rupture of the tympanic membrane can also occur. The inner ear changes that have been observed include injuries or loss of the stereocilia on inner and/or outer hair cells, pathological changes in the hair cell organelles, destruction of entire hair cells, destruction or dislodging of entire sections of the organ of Corti, and ruptures of the

basilar or Reissner's membranes leading to exchange of the endolymphatic and perilymphatic fluids. The metabolic consequences of cochlear trauma may include damage to the receptors through a lack of oxygenation and possibly also degeneration of cochlear nerve fibers (Theopold 1975). Metabolic processes are also thought to be responsible for the variability in the amount of trauma produced by a given noise exposure in different individuals (Saunders, Dear, and Schneider 1985).

Typically, exposure to hazardous levels of noise initially causes a temporary threshold shift (TTS), i.e. an elevation of the auditory threshold that is reversible with time. Any portion of the initial TTS that does not resolve is a noise-induced permanent threshold shift (PTS or NIPTS). The degree of TTS and/or PTS produced by an impulse noise exposure depends on the characteristics of the noise; in particular its level, repetition rate, burst duration, and spectral content (Laroche and Hetu 1990; Melnick 1978). The following research paradigms have been developed in order to establish relation between impulse noise parameters and the resulting physiological effects (Henderson and Hamernik 1986):

Threshold shift studies are performed in humans and animals. In humans, exposures are limited to levels that will produce a temporary threshold shift that recovers in minutes or hours but are not high enough to cause permanent damage. TTS recovery curves are usually diphasic, with components that have been attributed to separate mechanical and metabolic processes (Luz and Hodge 1971). The subject's auditory thresholds are usually measured at the standard audiometric frequencies two minutes after the exposure. The resulting "TTS₂" values are assumed to be equivalent to the PTS that would result from a

prolonged exposure. However, this assumption has not been proven in either humans or animals (Melnick 1978).

Threshold shift studies in animals are generally done at higher, more damaging noise levels. The resulting elevated thresholds are determined by behavioral audiometry or by brainstem response measurements. In some cases, TTS₂ is reported. Another common technique is to continue the exposure until the thresholds reach a steady-state value above which further exposure yields no significant threshold change. The resulting "asymptotic threshold shift" (ATS) (Henderson and Hamernik 1982) is thought to be more accurate than TTS₂ for estimating the potential damage due to long-term exposure to impulse noise (Saunders, Dear, and Schneider 1985).

Threshold experiments in animals have the advantage that they may be corroborated by data from anatomical and histological studies. The exposed animals (usually cats or chinchillas) are killed and their cochleas are dissected and examined. With the aid of scanning electron microscopy, a "cochleogram" summarizing the condition of the hair cells and the organ of Corti as a function of position on the basilar membrane may be generated (Lim et al. 1982).

The third research method is the retrospective epidemiological study based on questionnaires or interviews and the measurement of audiograms, as well as occupational exposure data such as the type and level of impulse noise and the number of years exposure. There are obvious difficulties in establishing an individual's exact exposure history over a period of years and in differentiating effects such as aging, disease, and non-occupational noise exposure. Moreover, as noise control regulations take hold in the workplace, the source

population for studies of this nature is dwindling. Nevertheless, epidemiological research has established the scope and severity of the noise-induced hearing loss problem and has led to the establishment of fundamental relationships between noise exposure and noise-induced hearing loss for both impulse and continuous noise (Melnick 1978).

Through extensive research by all of the above methods, progress has been made in relating the parameters of impulse noise to the nature and the extent of their effects on the auditory system. In their 1986 review article, Henderson and Hamernick conclude that impulse noise does cause mechanical damage to the cochlea, and that the recovery, if any, may be nonmonotonic. In contrast to continuous noise exposure, impulse noise yields highly variable effects even when identical exposure conditions are used for all subjects. The range of impulse parameters is an additional source of variability.

Another controversial topic addressed in the Henderson and Hamernick (1986) review is the efficacy of assigning a single number exposure parameter based on an equal energy hypothesis (EEH). The assumption behind this hypothesis is that damage to the auditory system depends only on the total amount of sound energy to which it is exposed, although the relation between the two need not be linear (Martin 1976). If the hypothesis holds, there should be a 3-dB trading relation between the duration and the level of the noise, since the product of the two determines the energy of the exposure. However, the hypothesis only appears to hold over a limited range of peak levels and durations (Henderson and Hamernick 1986; Melnick 1978). This is probably due to nonlinearities in the auditory system at high levels, and to the fact that the equal energy hypothesis ignores parameters such as

the rise time, repetition rate, and spectral content of the impulses (Henderson and Hamernik 1986, Hetu et al. 1984).

Henderson and Hamernick (1986) have also summarized the evidence for a synergistic interaction between steady and impulse noise. Both animal studies (Cohen, Kylin, and LaBenz 1966; Hamernik et al. 1974; Walker 1972) and epidemiological research (Thiery and Meyer-Bisch 1988) have shown that the adverse effects of quasi continuous impulse noise combined with steady or fluctuating continuous background noise are greater than would be obtained from exposure to comparable levels of either type of noise by itself. Recent work by Laroche and Hetu (1990) supports this conclusion and also suggests that the degree of oscillation within a type B waveform may be an important factor in the interaction. As will be seen in the next section, most of these effects have not been incorporated into current damage risk criteria.

3.2 Impulse Noise Damage Risk Criteria

Efforts to set noise damage risk criteria (DRCs) began in the 1930s. These criteria were developed initially for continuous noise. Impulse noise has only been considered more recently (Hodge and Price 1978). Damage risk criteria limit the amount of permanent or temporary threshold shift that will be accepted in a given percentage of the exposed population. Exposure limits are defined so that these criteria are not exceeded and are expressed in terms of noise parameters. For impulse noise, a relation between allowable levels and durations for a given number of impulses is defined, and a trading relationship between the number of impulses and the level is specified. The trading relationships dictate the amount by which the peak level of the impulse

noise must be lowered if the number of impulses in the exposure is increased.

The damage risk criteria (DRCs) for impulse noise in use today have been developed primarily from TTS studies on weapons fire. In 1968, Working group 57 of CHABA (Committee on Hearing, Bioacoustics, and Biomechanics 1968) developed a DRC that was based on a series of studies on the hazardous effects of impulse noise (Coles et al. 1967, 1968; Coles and Rice 1967, 1970, 1971). This criterion limits the temporary threshold shift two minutes after exposure, TTS_2 , to 10 dB at 1 kHz, 15 dB at 2 kHz, and 20 dB at 3 kHz in 95 percent of the exposed population. This parallels the criterion used to establish the current steady state noise limit of 90 dB for an eight-hour exposure except that the impulse noise criterion requires that these limits are not exceeded in 95 percent of the exposed population as opposed to 50 percent for steady noise (Hodge and Price 1978).

The CHABA criterion for impulse noise applies to exposures of 100 impulses over a period of minutes or hours, and specifies a trading relation of 5 dB of the peak level per tenfold change in the number of impulses for 1-1000 impulses. The 5-dB trading relation is based on the assumption that intermittent noise is less damaging than an equal exposure of continuous noise because of interim recovery, an assumption that may be invalid at high levels (Cluff 1980). The CHABA limit falls linearly from 165 dB (A-weighted peak level) at durations of 10 μ sec to 155 dB at 1 msec. For durations that exceed 1 msec, the limit remains constant at 155 dB if the impulse noise has a type A waveform. For type B impulse noise the curve levels off at 137 dB for durations exceeding 200 msec.

A simplified version of the CHABA DRC is in use in Japan (Hiramatsu, Takagai, and Yamamoto 1990). The limits on TTS_z for 100 impulses are the same but the impulses are specified in terms of A-weighted sound pressure level measured with a fast time constant. This simplification is based on the assumption that the noise being measured is repetitive type B impulse noise and that the sound level meter has adequate crest factor capability. A sliding correction factor is used when the number of impulses exceeds 100. The factor is approximately 20 dB at 1,000 impulses, 30 dB at 10,000, and 35 dB at 100,000 impulses.

A stricter DRC which has been adopted by the Environmental Protection Agency (1974) limits the TTS_z at 4 kHz to 5 dB for 90 percent of the population by setting the exposure limits at 12 dB below those of the CHABA DRC. Rather than aiming to protect the speech frequencies as in the CHABA DRC, the EPA levels document monitors hearing sensitivity at 4 kHz, the frequency at which noise-induced hearing loss first becomes evident.

Pfander (1980) has developed a DRC for Germany based on full recovery from noise-induced TTS within 24 hours for 90 percent of the exposed population. The exposure is specified in terms of integrated duration rather than number of impulses, which implies a 3 dB "equal energy" trading relation. The impulse duration that is used is the time that the pressure-time waveform of the impulse (rather than its envelope) is within 10 dB of the peak, rather than the conventional B duration defined in section 2.2.1. This DRC is somewhat more liberal than the CHABA criterion.

The Dutch have proposed a DRC based on the work of

Smootenburg (1982) which limits the average of TTS_z at 1000, 2000, and 3000 Hz to 15 dB in 90 percent of exposed individuals. The International Standards Organization (1975) has adopted a much less strict criterion that had been originally advanced by the American Academy of Otolaryngology and Ophthalmology. The average TTS_z at 500, 1000, and 2000 Hz is limited to 25 dB. Since the lower frequencies are far less affected by impulse noise exposure, this criterion may allow significant PTS in an unacceptably large fraction of the exposed population (Smootenburg 1982).

All of the above damage risk criteria have shortcomings due to the complexities of impulse noise. In addition to the issues of measurement that were discussed in chapter 2, several other problems arise. First, it is unclear under what range of conditions (duration, repetition rate, etc.) a 3-dB, or a 5-dB, or any trading relation may be used. The 3-dB trading relation is based on the equal energy hypothesis mentioned above, which appears to hold in a narrow range of sound pressure levels (Henderson and Hamernik 1986). Below this range, no damage is incurred regardless of exposure duration. Above this range, the acoustic trauma exhibits a nonlinear dependence on peak level and duration which can not be described by the equal energy rule.

The 5-dB trading relation used in some of the damage risk criteria was based on the assumption that there is recovery between impulses, and that damage may therefore be less than would be obtained from an equivalent continuous exposure. This assumption is probably only applicable to intermittent noise or low level impulses (Cluff 1980). If a trading relation is to be used, it should vary with the impulse repetition rate, duration, and peak level in a manner that is yet to be deduced

from experiments. The acoustic reflex may also play a role at particular repetition rates and durations (Cluff 1980).

Another problem with impulse noise damage risk criteria is that, despite the evident importance of the frequency spectrum of the impulses in determining the degree of threshold shift (Henderson and Hamernik 1986, Price 1986) none of the damage risk criteria are frequency specific. Stevin (1982) has proposed using A-weighted sound exposure levels as a first approximation, since the ear canal resonances that contribute to the shape of the A-weighting equal loudness contour may also give rise to the greater susceptibility of the auditory system to damage in the range of 2-4 kHz.

A third problem is that the current damage risk criteria are based on research with high-level type A weapons impulses at low repetition rates, whereas the most commonly encountered industrial impulse sources produce type B impulses with higher repetition rates such that there may be little or no recovery occurring during exposure. In many cases, a high level of steady or fluctuating continuous background noise is also present. Hetu et al. (1984) extended the work of Coles et al. (1967, 1968) to long-duration, type B impact noise (470 msec) at a 1-Hz repetition rate and found that the 5-dB trading relation cited above holds. However, the recent finding that the combination of impulses and continuous background noise is more damaging than the sum of their separate effects has not been incorporated into current damage risk criteria.

Thus, the establishment of effective damage risk criteria for impulse noise continues to be an area of active study. Despite numerous experiments using several different research paradigms, an impulse

noise damage risk criterion that correctly accounts for all of the pertinent aspects of impulse noise exposure has yet to be developed.

Many of the above problems are also being faced in the field of impulse noise psychoacoustics. For example, there appears to be an equal energy law for the psychoacoustical effects of impulse noise as well as for its physiological effects, but the range over which this is true has not been fully established. The psychoacoustical import of the frequency spectrum of impulse noise is also not totally understood. The effect of combining repetitive impulses with continuous background noise may be as important an issue psychoacoustically as it is physiologically, but the psychoacoustical aspects of the problem have received comparatively little attention. Another problem common to both physiological and psychoacoustical studies of impulse noise is the difficulty of determining a "single number" indicator of either physiological or psychoacoustical aversiveness. In the next chapter, these and other issues of impulse noise psychoacoustics will be taken up in greater detail.

CHAPTER 4

PSYCHOACOUSTICAL EFFECTS OF IMPULSE NOISE

4.1 Introduction

Just as the developers of damage risk criteria have been faced with the task of reducing conflicting physiological data into a workable set of impulse noise exposure limits, psychoacousticians have long attempted to deduce a simple, comprehensive model that will estimate the psychoacoustical effects of impulse noise. Before discussing the progress that has been made towards achieving this goal, the problem of determining which psychoacoustical quantities to measure and how to measure them will be addressed. Next, experiments on the psychoacoustical effects of isolated impulses and of repetitive impulse noise (both with and without continuous background noise) are reviewed. The agreement between these experimental results and various psychoacoustical models is discussed at the end of the chapter.

4.2 Psychoacoustical Quantities

The choice of the psychoacoustical quantity or quantities to measure is a primary concern in the study of the psychoacoustics of impulse noise; it is also one of the main causes of variability in the results of different studies. The most commonly measured quantities are loudness, noisiness, and annoyance. These quantities pertain to both continuous and impulse noise. A quantity that is unique to impulse

noise, "impulsivity" (Berry 1989; Brambilla and Caretti 1989) has also been studied.

Kryter (1970) has defined loudness as the subjective response that is correlated with the physical intensity of a sound stimulus, independent of other acoustical factors and of contextual factors. The term "noisiness" is used to describe the unwantedness of noise that may be attributed to its acoustical characteristics (including but not restricted to its physical intensity) but not to contextual factors.

Because noisiness depends on all of the acoustical characteristics of a noise, rather than solely on its intensity, a sound may be noisy without being particularly loud. The term "annoyance" is used for a subjective response to both the acoustical aspects of noise and the non-acoustical contextual factors. Examples of these nonacoustical factors are the novelty of the noise and its significance to the subject. Kryter has also stated that the percept of loudness is fully established after a one-second exposure to a noise, whereas the percepts of noisiness and annoyance may build up over seconds or even minutes.

The definitions of loudness, noisiness, and annoyance that have been offered by Namba (1987) are similar to those of Kryter. Noisiness is defined as "unwantedness by auditory factors" which includes both steady state (loudness) factors and spectral and temporal complexity factors (tonal components, impulsiveness, etc.). Annoyance is defined as unwantedness by nonauditory factors and includes the subjective features cited by Kryter such as the meaning of the sound and the context in which it is presented. A similar scheme has been used by Sakai (1986). Namba (1987) has pointed out that crosscultural semantic studies have shown that the meaning of terms such as loudness and

noisiness depend on cultural and linguistic factors.

On the other hand, Zwicker (1987), has suggested separating annoyance into two components. One component of annoyance is highly contextual and depends on the listener's relation to the noise source (e.g., a person playing a piano as opposed to a person listening someone else playing a piano) and seems to be analogous to what Kryter terms annoyance. The other component, according to Zwicker, is "unbiased annoyance", the main component of which is loudness. His data suggest that the unbiased annoyance depends on intensity in a manner similar to loudness, but that the exponent for the power function is slightly higher. It is unclear how, if at all, these quantities are related to noisiness, and it appears that Zwicker's definition of annoyance includes aspects of both noisiness and annoyance as defined by Kryter.

This variability of the definitions of noisiness and annoyance suggests that the two quantities, if in fact there are two, may be inseparable psychoacoustically. This may be due to the fact that it is difficult for subjects to separate the auditory and non-auditory components of their response to noise stimuli in a testing situation, and also perhaps due to semantic and cultural factors in the test instructions. However, it is generally agreed that subjects are able to perform reliable, repeatable measurements of the loudness of sounds, and that perceived loudness is the primary component of noisiness and/or annoyance (Kryter 1970; Zwicker 1987).

Recently, the perception of impulsivity of noises has been studied (Berry 1989; Brambilla and Caretti 1989, Brambilla, Caretti, and Santoboni 1988). A definition of the term impulsivity has not been published. The purpose of measuring impulsivity was to correlate the

results with annoyance ratings, as will be discussed below.

4.3 Methods for the Measurement of Psychoacoustical Quantities

4.3.1 Overview of Psychoacoustical Methods

Numerous psychoacoustical methods have been applied to impulse noise. Classical psychophysical techniques have been most extensively used, but some of the experiments have been performed with the newer adaptive techniques, and a significant number of researchers in the field have used scaling methods. An overview of these different methods may be found in the recent text by Gelfand (1981) and is summarized here.

The classical methods of psychoacoustics (and of psychophysics in general) include the method of limits, the method of constant stimuli, and the method of adjustment (Engen 1971, Gelfand 1981). The method of limits is ordinarily used for threshold detection. A stimulus is presented in successive trials of either increasing or decreasing level and the subject indicates whether or not the stimulus is perceived. Bias due to habituation (on descending runs) and anticipation (on ascending runs) is controlled by averaging the results from equal numbers of the two types of runs. The accuracy of the threshold determination is at least as large as one-half of the step size by which the levels are increased and decreased. Decreasing the step size to improve accuracy increases the time required to complete the threshold determination. If the step size is too small, however, the increased duration of test may cause the subject to become fatigued or inattentive.

In contrast to the method of limits, the method of constant stimuli (Engen 1971, Gelfand 1981) involves presenting test stimuli at a range

of fixed levels in a random order. This method is useful for threshold detection, and also for differential sensitivity and other suprathreshold measurements. For example, a variable test stimulus and a constant reference stimulus can be presented in pairs, and the subject asked to indicate whether the test stimulus is louder than the reference. One can then plot the "psychometric function" which in this case would be the percentage of "louder" judgments as a function of stimulus level. The level at which the stimulus is judged to be louder 50 percent of the time is the "point of subjective equality" or PSE. The 50 percent point on the psychometric function is considered to be the threshold when the method is used for threshold detection. The method of constant stimuli yields more information than the method of limits because the entire psychometric function is measured rather than just the point of subjective equality (or threshold). However, this additional information is obtained at the expense of long testing sessions that may lead to fatigue or inattention in the subjects.

Another form of bias that can occur in suprathreshold loudness comparisons by the method of constant stimuli, as well as other methods, is that the last stimulus that is presented in each trial tends to be slightly enhanced in loudness. Because of this "sequence effect", the PSE obtained in a set of trials in which the reference stimulus is always presented before the test stimulus may differ by one to two dB from the value that is obtained if the test stimulus is always presented first. Bias due to the sequence effect can be overcome by presenting equal numbers of trials with the two sequences and averaging the results.

The method of adjustment (Engen 1971, Gelfand 1981) is the classical method most commonly applied to impulse noise. The subject adjusts the

level of the test stimulus (continuously rather than in steps) until it subjectively matches a reference stimulus (i.e. sounds equally loud, equally noisy, etc.). The average level at which the balance is reached is the PSE. The two predominant forms of bias in this technique are the tendency of the subjects to orient to a particular dial position, and the habituation and anticipation effects mentioned above. The former problem is dealt with by using an unlabeled dial and preferably by introducing an unknown offset that is varied by the experimenter on each trial. The latter problem is corrected for by including both ascending and descending trials.

Adaptive procedures (Levitt 1978, Gelfand 1981) are related to the classical methods, but they are designed to improve testing efficiency by converging upon the target value (threshold, point of subjective equality, etc.) and placing most of the observations near that point. The term adaptive is used because the subjects' responses determine the stimulus parameters of successive trials. These methods include Békésy tracking, the "staircase" or "up-down" method and its variants, and the "transformed up-down" procedure (Gelfand 1981).

The Békésy technique (Gelfand 1981) is similar to the method of adjustment except that the stimulus level is varied automatically and the subject controls only the direction of that variation, decreasing the level when he hears the stimulus and increasing it when he does not. The result is a series of excursions and the average of the midpoints of these excursions is assumed to be the threshold level. The technique is used primarily for threshold determinations in audiometry.

The up-down or staircase method (Gelfand 1981) is an adaptive procedure in which the stimulus level is increased or decreased in

uniform steps in accordance with a simple decision rule: the direction of the variation is changed whenever the subject's response changes. For example, in a threshold detection experiment, the presentation level is increased as long as the subject does not hear the stimulus. Once the subject does report hearing the stimulus, a reversal occurs, i.e. the presentation level is decreased until the subject no longer hears the stimulus, and then increased again. The result is a series of runs in which the level is either increasing or decreasing; the average of the reversal levels is a measure of the 50 percent point of the psychometric function. This procedure converges fairly efficiently and can follow drifts in the subjects' responses. It is sometimes necessary to conduct two sets of interleaved trials simultaneously so that the subjects do not deduce the test method.

The up-down procedure is readily adapted to performing suprathreshold loudness comparisons by using a two-alternative forced choice (2AFC) method. The stimulus and reference are presented in pairs and the subject must state whether or not the test stimulus sounded louder than the reference stimulus. For example, the level of the reference stimulus is held constant, the test stimulus level is increased whenever the subject reports that it is softer than the reference, and decreased whenever it is louder. In order to keep the subject from deducing the test procedure, and in order to minimize the sequence effect, two sets of trials may be performed with the two possible test-reference orders. As in the case of the classical method of limits, there is a trade-off between the accuracy of the technique and its efficiency depending upon the step size.

A more efficient variation of the up-down method is the Parameter

Estimation by Sequential Testing (PEST) technique (Gelfand 1981) in which the stimulus level is varied in non-uniform steps. The procedure starts out with a relatively large step size. If two successive trials yield identical responses, the step size is doubled. Whenever a reversal occurs, the step size is halved. Thus the procedure converges on the subjects' PSE far more rapidly than with the ordinary up-down procedure, and, once the PSE is approached, it can be measured with greater sensitivity. As in the up-down method, the PEST procedure determines the 50 percent point on the psychometric function.

There are two variations on the up-down procedure that allow measurement of other points on the psychometric function. The Block Up Down Temporal Interval Forced Choice Procedure (BUDTIF) method (Gelfand 1981) is a modified up-down procedure in which blocks of several trials at the same level are presented. The criterion for reversal is a positive response to a certain number of trials out of the total in each block. The ratio between the criterion and the total number of trials in the block determines the percentage point on the psychometric function that is measured. For example, for threshold detection, the subject might be required to perceive the stimulus in four trials out of five before a reversal occurs. In this case, the 80 percent point on the psychometric function for detection would be measured. However, the BUDTIF method can require large numbers of trials if the starting levels are far from the desired point on the psychometric function.

The transformed up-down method (Gelfand 1981, Levitt 1970) achieves the same goal as the BUDTIF procedure, but in a more efficient manner. Instead of using blocks of trials, the transformed method applies a more complex decision rule to successive trials. One such rule,

for example, is to continue increasing the stimulus level if there is a negative response (e.g., no detection in a threshold measurement), or if there is positive response (detection) followed by a negative response in two successive trials at the same level; but to decrease the level if two successive positive responses occur. It can easily be shown that such a rule converges on the 70.7 percent point on the psychometric function (Gelfand 1981, Levitt 1970). Other rules can be deduced to determine additional points on the function. As always, the use of interleaved trials can prevent bias. One common application is to conduct two sets of trials in order to measure two different points on the psychometric function simultaneously.

The third major class of psychoacoustical procedures, scaling methods (Gelfand 1981), is fundamentally quite different from the classical and adaptive procedures. The psychophysical scaling methods require subjects to make judgments of some aspect of one stimulus relative to another (estimation), or to adjust one stimulus relative to another (production). In psychoacoustical research, the scale that is used is usually a ratio scale, i.e. one in which the values are rank ordered, have fixed relationships between them, and are ordered relative to an inherent zero point. Examples include the sone scale for loudness and the mel scale for pitch, as well as annoyance or noisiness scales.

The three procedures for establishing psychophysical scales are discriminability, category, and magnitude or ratio scaling. In the discriminability paradigm, subjects are required to discriminate small differences among the stimuli. In the category paradigm, subjects group the stimuli into categories of equal size. The magnitude or ratio scaling

paradigm requires subjects to compare the relative magnitudes of one attribute of the stimuli. This latter technique is the most commonly used of the three for psychoacoustical research.

There are several different ways of performing magnitude or ratio scaling. Ratio estimation requires the subjects to assign a number to the magnitude of the test stimulus relative to that of a reference stimulus (e.g., twice as loud, one tenth as loud). The ratio can also be expressed graphically on a number line. Magnitude estimation is nearly identical except that the reference stimulus is assigned a numerical value (e.g., 100) and the comparison is then stated in terms of numbers rather than as a ratio (e.g., 200, 10). In some cases, the subjects are asked to simply assign a number to the test stimulus and a reference stimulus is not presented.

The inverse of the ratio and magnitude estimation method is the technique of ratio and magnitude production. In ratio production, the subject is asked to adjust a stimulus to sound like the given fraction of the reference stimulus. In magnitude production, the subject hears the reference stimulus, to which a particular number has been assigned, and then adjusts the test stimulus so that its magnitude corresponds to prescribed numbers.

Both the production and the estimation techniques are subject to bias, and they yield slightly different results (Gelfand 1981). Magnitude and ratio estimation are commonly applied to measurements of the loudness, annoyance, and nosiness of impulse noise. The production techniques, which have been extensively used in generating the sone and mel scales, have not been applied to the impulse noise problem.

4.3.2 Application of Psychoacoustical Methods to Impulse Noise

In applying psychoacoustical measurement techniques to impulse noise, two concerns must be addressed. The first, which would apply to any type of test stimulus, is that the procedure and instructions that are used produce reliable, repeatable results in agreement with those obtained by other test procedures on the same stimuli. The second concern is that errors or biases due to the transient nature of impulse noise test stimuli are controlled. This second concern affects the choice of test and reference stimulus parameters, and even the way in which those parameters are measured and reported, as well as the choice of test procedures and instructions.

Several research groups have systematically addressed the above concerns by performing the same experiment by one or more methods, or by varying instructions to the subjects, and comparing the results. The details of the results of these studies will be discussed in the context of related experiments in the ensuing sections, but the measurement issues that they raise will be discussed here.

A study that probed the effects of instructions and test method on the annoyance of intermittent noise was performed by Little and Mabry in 1969. First, they measured the loudness of noise bursts by the method of constant stimuli using two different sets of instructions. The test stimuli, which were bursts of pink noise with short (usec) rise and fall times and durations ranging from 1 to 16 sec, were compared to an 8-second burst of steady noise. One set of instructions asked the subjects to simply compare the annoyance, while the other set specifically focused their attention on both the level and the duration of the stimuli.

The results of this experiment are shown in figure 7. The data obtained with the annoyance instructions are relatively flat at all levels except at the reference level of 84 dB, suggesting that the subjects' primary response was based on peak level, and that the duration was only considered when the peak levels of the test and reference stimuli were equal. The data obtained with the instruction to attend to level and duration show far more dependence on duration at all levels. The test stimuli that were shorter in duration but higher in level than the reference were relatively less annoying than in the first set of instructions, and the annoyance of the bursts at 76 and 84 dB rose more

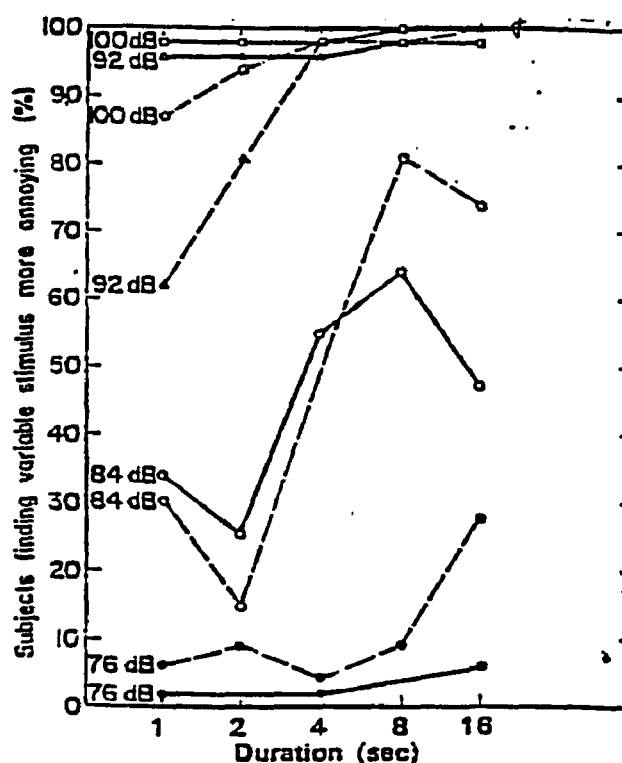


Figure 7. Results of experiment by Little and Mabry (1969) on the effect of instructions to subjects on their subjective response to intermittent noise. Solid lines, overall annoyance; dashed lines, measured annoyance when subjects were instructed to attend to both the level and the duration of the stimuli. The duration of the intermittent noise bursts is on the abscissa.

sharply with increasing duration. An analysis of variance for these data showed that the main effect for instruction set was not significant, but there were significant interactions between the instructions, the presentation level, and the burst duration.

Next, Little and Mabry (1969) performed a similar experiment in which magnitude estimation was used to measure the annoyance of the same stimuli. The results were comparable to those obtained by the method of constant stimuli. The authors concluded that the effect of varying the test method (constant stimuli versus magnitude estimation) was slight compared to the effect of changing the instructions.

An analogous experiment was performed by Stephens in 1974 using impulse noise stimuli. Subjects were asked to perform loudness scaling on equal energy tone bursts with durations ranging from 1 to 500 msec. Two sets of instructions were used: one in which the subjects were asked to attend to loudness rather than duration, and a second in which they were asked to consider only the amplitude of the tone burst. These sets of instructions are perhaps more similar to each other than those of the experiment by Little and Mabry, but nevertheless there were significant differences in the results at several of the durations. The shortest tone bursts were rated somewhat louder when the subjects were instructed to attend specifically to the amplitude of the bursts. Stephens also observed differences in the loudness of short-duration tone bursts when the measurements were repeated using the loudness balance technique.

In 1970, Reichardt and Niese published a study that specifically addressed the problem of selecting sound durations and interstimulus intervals for measurement of the loudness of impulse noise. They

defined the following constraints: First, the time interval between test stimuli must be short so that the percept due to the first stimulus presentation in each pair remains as strong as possible during the presentation of the second stimulus, but not so short that there is interference due to nonsimultaneous masking. Second, the stimulus durations should be so short that they only "weakly preactivate" the auditory system, but long enough to allow a full build-up of loudness. They also stated that subjects can not make reliable comparisons between stimuli of very different durations. Third, in order to prevent an increase in loudness due to the "roughness effect" (Miller and Taylor 1948; Terhardt 1974) due to the periodic amplitude variation of an impulse noise train, the stimuli must not be repeated rhythmically.

Based on masking data and other psychoacoustical results, Reichardt and Niese (1970) recommended limiting the interval between two stimuli to a value of 500 msec to 1 sec, the duration of steady reference stimuli to between 250 and 500 msec, and the duration of the test stimuli to between one-half and twice that of the reference stimulus. In order to compensate for the roughness effect in the measurement of the loudness of repeated impulse trains, they proposed using a series of 1-kHz tone bursts at the repetition rate and duration of the test stimulus as the reference stimulus, regardless of the type of impulse noise being studied. This latter recommendation raises a several concerns. It is unlikely that the roughness effect observed in a train of 1-kHz tone bursts would be equivalent, for example, to that observed in a train of broadband noise bursts (Terhardt 1974). Moreover, following this recommendation would make it impossible to perform a comprehensive study in which the effects of varying the repetition rate and duration of the impulses are studied

using a common reference stimulus.

As will be seen below, the recommendations of Reichardt and Niese (1970) have not generally been followed, particularly with regard to the study of repetitive impulse noise. However, it will also be shown that the relative durations of the test stimuli and the reference stimuli used to study the psychoacoustical effects of impulse noise can have at least as great an effect on the results as the use of different test instructions or different psychoacoustical methods.

4.4 Psychoacoustical Studies of Impulse Noise

4.4.1 Introduction

This literature review is divided into three main sections. The first section (4.4.2) presents some of the early studies on temporal integration of transient stimuli, most of which were performed at the threshold of audition. This general discussion is followed by a review of research on the psychoacoustical effects of the two main categories of impulse noise, type A and type B (see section 2.2.1 for definitions). Section 4.4.3 focuses on type A impulse noise, which usually consists of isolated bursts due to sonic booms or explosions. This section is divided into two parts; one on the long-duration impulses due to sonic booms, and the other on the short transients that are characteristic of explosions. Type B impulse noise, which is usually produced by impacts, is treated in section 4.4.4. The latter section is divided into three parts; isolated bursts, repetitive impulse trains, and repetitive impulse trains with continuous background noise. The application of psychoacoustical models to impulse noise is discussed in section 4.5.

4.4.2 Temporal Integration Studies

By the early part of this century, it had been discovered that the auditory threshold and the growth of loudness for transient sounds depends on their duration due to a process referred to as auditory temporal integration, or summation (Gelfand 1981; Moore 1982). The auditory system appears to respond to all of the stimulus energy that occurs within a so-called "integration time window". Increasing the duration beyond that of the integration time window has little or no influence on the threshold or loudness. For stimuli of durations shorter than the window duration, there is a trading relation between the level and the duration of the stimulus that generally follows an equal energy law (3 dB decrease in level per doubling of the duration). Models that attempt to explain the details of this summation process will be discussed in section 4.5.

Estimates of the length of the integration time window may be deduced from experiments by two basic methods. One method is to vary the stimulus duration and to measure the threshold (or loudness level) of the stimuli. The shortest duration at which the threshold (loudness) ceases to be affected by changes in the duration of stimulus is the estimate of the length of the integration time window. The other method is to measure the detectability (or loudness) of a series of stimuli of constant energy but variable duration and level. The detectability will be constant as the duration is varied for durations less than the integration time. However, when the duration exceeds the integration time, the detectability will drop because the stimulus level is being reduced but the auditory system cannot integrate over the entire duration of the stimulus in order to compensate.

The length of the integration time window and the trading relation between level and duration have been found to depend on factors such as the presentation level, rise time, and frequency content of the stimuli (Moore, 1982, 50). Both tone bursts and noise bursts have been studied. The use of tone bursts has allowed study of the frequency dependence of the integration time. However, the bandwidth of a tone burst increases as it is shortened, and its sharp onset may generate a "click" artifact which can confound the data (Gelfand 1981). The spectrum of a noise burst, on the other hand, is relatively unaffected by changes in its time-waveform (Miller 1948).

In early experiments on the temporal integration of tone bursts, Bekesy (Moore 1982, 50) deduced an integration time of 180 msec for 800-Hz tone bursts, while the data of Munson (1947) were consistent with a value of 250 msec, independent of carrier frequency, at 125, 1000 and 5650 Hz. However, in the experiments of Plomp and Bouman (1959), the integration time constant for tone bursts was found to vary from about 375 msec at 250 Hz to 150 msec at 8000 Hz. At short durations (below 5 cycles of the tone burst carrier) the threshold was higher than would be expected from the equal energy relation.

In order to maintain a constant spectrum while changing the burst duration, Miller (1948) performed analogous experiments with bursts of white noise ranging from 23 to 810 msec duration, with a reference duration of 1.55 sec. The integration time (i.e. the shortest duration at which the loudness of the test stimulus was the same as that of the reference stimulus) ranged from 60 msec at a 100 dB SPL presentation level to nearly 1 second at threshold. When the experiment was repeated using tone bursts, the measured integration time was about 250 msec at

high levels, and 500 msec near threshold.

Small, Brandt, and Cox (1964) extended the results of Miller (1948). However, they measured integration times of only 50 msec near threshold and 15 msec at 60 dB SL, which are significantly shorter than those observed by Miller. Small, Brandt and Cox found that the slope of the PSE versus duration curve was 12.5 dB per decade (5.5 dB per doubling) whereas Miller had measured 8.0 to 8.9 dB per decade.

In 1957, Green, Birdsall, and Tanner found that the detectability of equal-energy 1-kHz tone bursts in a background of white noise was constant for durations between 15 and 170 msec. The detectability decreased at durations above 170 msec, which was inferred to be the integration time. The detectability also decreased as the duration was reduced below 15 msec, so that the detectability versus duration curves were trapezoidal. This is analogous to the findings of Plomp and Bouman (1959) at short durations which were mentioned above.

Sheely and Bilger (1964) extended these results to higher and lower carrier frequencies. The duration at which the plateau commenced was found to decrease with increasing frequency but it did not correspond to a constant number of cycles of the carrier. Rather it seemed to be related to the duration at which the bandwidth of the tone burst began to exceed the critical band at the carrier frequency.

Stephens (1974) performed a similar experiment above threshold. The loudness of equal-energy 1-kHz tone bursts with durations ranging from 1 to 525 msec was measured by several different methods (see section 4.3.2). The plateau corresponding to equal detectability of the bursts extended from approximately 50 msec to approximately 250 msec.

In summary, these early studies demonstrated that the auditory

integration time generally decreases as the presentation level increases, and that, for tone bursts, it decreases with increasing carrier frequency. The detection of isolated tone or noise bursts approximately follows an equal energy rule over a range of durations. At durations shorter than the lower limit of this range (of order 15 to 50 msec), the detectability drops in a manner that may be related to the spread of energy outside of the critical band centered at the carrier. At durations exceeding the temporal integration time, increasing the duration does not affect the threshold if the peak level is held constant, while the detectability decreases if the energy is held constant.

The noise and tone bursts used in these early studies were not representative of typical impulse noise, and they were limited to isolated bursts. Moreover, most of the emphasis was on threshold behavior. However, during the ensuing decades, these and other aspects of impulse noise psychoacoustics have begun to be addressed.

4.4.3 Psychoacoustical Effects of Type A Impulse Noise

4.4.3.1 Overview. During the late 1960s and early 1970s there was a surge of interest in the psychoacoustical effects of isolated type A impulses such as sonic booms and weapons fire. As was discussed in Chapter 2, both of these sources produce a simple shock waveform, but the rise times and durations of sonic booms are typically one to two orders of magnitude higher than those of weapons fire impulses. In psychoacoustical experiments, sonic booms are typically studied using synthetic N-waves with durations of order 100 msec. Weapons fire impulses are often simulated using impulses with a triangular waveform (rather than an N-wave) but of much shorter duration.

4.4.3.2 Sonic Booms. One of the earliest comprehensive studies on the loudness of synthetic sonic booms was performed by Zepler and Harel in 1965. They studied the effects of varying the total duration of the impulses, and of varying the rise time of the impulses while holding either the peak level or the slope of the rising edge constant. The subjects performed loudness balances with a continuous sine wave at 400 Hz. At impulse durations above 50 msec, the loudness was independent of duration. At durations below 50 msec, the two "clicks" due to the steep rising edges of waveform (one at the onset of the N-wave; and the other at the end, because of the rapid return to ambient pressure) were perceived as a single entity, resulting in a 3 dB increase in loudness.

The effect of varying the rise time of the booms (at fixed overall duration) depended on whether the peak level or the slope was held constant. At constant peak pressure (and also approximately constant energy), increasing the rise time from 200 μ sec to 13 msec yielded a 17 dB drop in the loudness level, which is approximately 2.8 dB per doubling of the rise time. On the other hand, when the slope of the rising edge was held constant, increasing the rise time also increased the peak level, and the loudness level increased by between 2 and 3 dB for each doubling of the rise time.

Johnson and Robinson (1969) explored the dependence of the loudness of sonic booms on their spectral content. Their model for the loudness of sonic booms will be discussed in section 4.5.

In 1978, Niedzwecki and Ribner published the results of several experiments on the loudness of synthetic sonic booms. Their data (1978a) showed a decrease in the loudness of synthetic N waves of approximately 2.4 dB per doubling of the rise time, in good agreement with the data of

Zepler and Harel (1965). However, in contrast to their results, Niedzwecki and Ribner (1978a) observed an abrupt increase in the loudness of a sonic boom with a 1-msec rise-time as its duration was increased from 200 to 250 msec. Niedzwecki and Ribner (1978b) also explored the loudness of "minimized booms" which are characteristic of long aircraft in the midfield region (i.e. after the boom has propagated for moderate distances). The two types of waveform are illustrated schematically in figure 8.

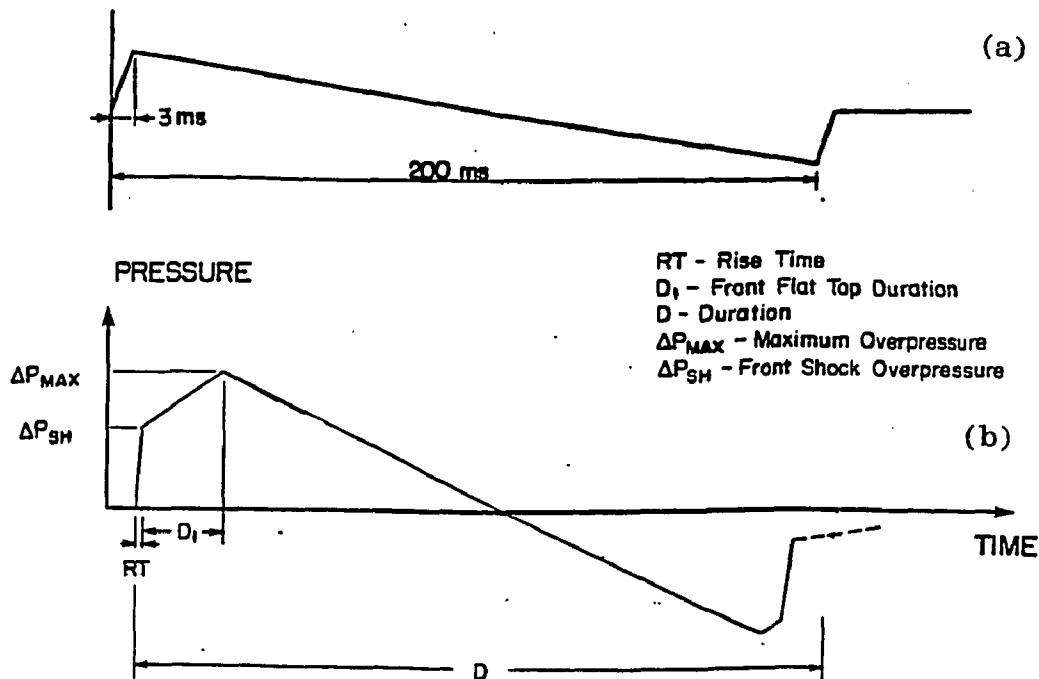


Figure 8. Sonic boom waveforms: a, ordinary N-wave (Niedzwecki and Ribner 1978a); b, "minimized" sonic boom. (Niedzwecki and Ribner 1978b).

They found that a minimized boom with a flat top is perceived to have the same loudness as an ordinary N-wave of a lower peak level, ΔP_N , according to the relation

$$(4.1) \quad \Delta P_N = \Delta P_{\text{shock}} + 0.11 \times \Delta P_{\text{max}}$$

where ΔP_{shock} is the level of the front shock of the minimized N-wave, and ΔP_{max} is the level at the maximum. Thus at equal peak amplitudes, the minimized waveform is perceived as less loud than the ordinary N-wave.

In summary, the loudness of sonic booms depends on the steepness of their rising edges. Halving the rise time increases the loudness by 2.5-3 dB over a range from 200 μsec to 20 msec. Loudness increases with increasing peak level but seems to be relatively insensitive to duration. In fact, the sonic boom can be thought of as two separate events (the rising transients at the leading and trailing edges) separated by several hundred msec. It will be seen below that the situation is quite different for the short impulses produced by firearms.

4.4.3.3 Short-Duration Type A Impulses. In 1970, Fidell et al measured the noisiness of short type A impulses using the PEST technique (see section 4.3). However, the definition of the term "noisiness" that was given to the subjects included the word "annoyance". One experiment demonstrated that alterations in the phase of the waveforms did not affect their noisiness. The second experiment, which explored the noisiness of filtered noise bursts, will be discussed in the section on type B impulse noise. A third experiment explored the effect of varying the interval between two impulses. This experiment was performed with an "ideal"

N-waveform (one with steep rising edges) with a duration of 26 msec, and a doublet waveform (a singular positive excursion, followed 13 msec later by a singular negative excursion). Increasing the interval between pairs of impulses from 33 msec to 1000 msec did not significantly affect the noisiness. However, increasing the total number of impulses in each trial did affect the noisiness, which followed an equal energy rule (3 dB doubling) as the number of impulses was increased from 1 to 8 at a repetition rate of 3 Hz.

A study of the loudness of short triangular transients designed to simulate weapons fire impulses was reported by Carter in 1972. The impulses were 1 msec in duration, had rise times varying from 0.05 to 0.5 msec, and were repeated at rates ranging from 1 Hz to 256 Hz. It was found that doubling the repetition rate lowered the peak level needed to reach the point of subjective equality (PSE) with the white noise reference stimulus by an average of 2.4 dB. Increasing the rise time from .05 msec to 0.5 msec increased the PSE by about 5 dB (i.e. impulses with the shorter rise times were perceived as louder).

Another early study explored the effect of reverberation on the annoyance of repeated impulses with a duration of 500 usec (Thiessen and Subarao 1962). The repetition rate was fixed at 4 Hz and the presentation level varied from 30 to 115 dB SPL. The reverberation was electronically simulated and had a decay time of 1.1 seconds. The increase in energy of the test signals due to the reverberation was between 0.4 and 0.9 dB, but the increase in annoyance that was observed was as much as 3 dB at presentation levels between 70 and 100 dB SPL.

All of the above studies of short type A impulses were performed

with synthetic stimuli. A number of studies have also been done using actual weapons fire impulses. Gustafson (1974) has studied the loudness of gunfire as a function of peak level by the ratio scaling method. The impulses had an A-duration of 50 msec, a rise time of 0.2 msec, and a spectrum that peaked near 500 Hz. An increase of the peak level by 7.5 dB was found to correspond to a doubling of the loudness.

The loudness of weapons fire impulses was also studied by Berglund et al. (1986). The impulses were produced by a variety of weapons and were presented at levels ranging from 40-90 dBA. The weapons impulses were also reproduced backwards, so that there was a long rising edge and short trailing edge. The data were fit by determining the combination of time weighing (peak, fast, or impulse) and frequency weighing (A or C) that best agreed with the loudness data from each weapon. This method yield a linear relation between the loudness and the peak level, with a slope of 9 dB per doubling of the loudness. Fitting all the data with a single time and frequency weighing worked best when the C weighing network was combined with either the peak or the fast time constant. It was also found that the impulses that were presented in reverse order were louder than their unreversed counterparts. The difference was greatest at higher presentation levels and amounted to about 5 dB on average.

The annoyance of weapons impulses has been extensively studied by Vos and collaborators (Vos 1990; Vos and Guertson 1987; Vos and Smoorenburg 1985), and by Ritterstadt (1985). In the experiments by Vos and Smoorenburg (1985), subjects rated the annoyance of gunfire and traffic noises at L_{Aeq} levels ranging from 30 to 60 dB in the presence of background noise (road traffic) at 35 and 55 dB. From these

data, an "impulse penalty" was derived. The penalty was highest (10-12 dB) at an L_{Aeq} of 30 dB, and dropped to about 8 dB at an L_{Aeq} of 60 dB. Increasing the background level to 55 dB increased the penalty at low levels but decreased it slightly at high levels. Ritterstadt (1985) also examined the dependence of the annoyance of impulse noise on the relative level of fluctuating background noise due to traffic as part of a social survey sponsored by the Commission of European Communities (CEC). In this study, the annoyance of the impulse part of the noise was most highly correlated with the difference between the L_{eq} of the impulses and the L_{eq} of the background noise.

A group of recent experiments by Vos (1990) has suggested that the annoyance penalty for weapons fire noise is level dependent and is highest at low levels. It was also found that the penalty was different for different firearms, suggesting the need to develop a more sophisticated procedure that accounts for both the spectral and the temporal features of impulse noise.

The effect of variations in the peak level in a train of repeated gunfire impulses has been studied by Vos and Guertson (1987). Impulses from nine different firearms used presented in 45-sec groups of 20 impulses. The peak level within these groups varied by up to 12 dB. The subjects used the method of adjustment to find the level of each stimulus that was as annoying as the reference stimuli (gunfire noise at $L_{eq} = 40$ dB, and traffic noise at $L_{eq} = 45$ dB). Overall, L_{Aeq} was found to be an adequate predictor of the annoyance of the impulse trains. The annoyance of impulse trains which had a small fraction of very high level impulses (12 dB above the reference) was underestimated by L_{Aeq} .

It is evident that the above studies on the psychoacoustical effects

of short-duration type A impulses using synthetic and real stimuli have yielded two different sets of information. The systematic studies which have been performed with synthetic stimuli have shown that, as in the case of sonic boom impulses, the loudness of short triangular transients is decreased with increasing rise time. The rate of increase is of 1-2 dB per doubling of the rise time, compared with 2.5-3 dB per doubling in sonic booms. Increasing the peak level by about 7 dB was found to double the loudness of short triangular transients.

The effect of duration on the loudness of short type A impulses has not been studied. According to Carter, increasing the repetition rate of impulses increases the loudness by about 2.3 dB, and Fidell has found that doubling the number of impulses increases the noisiness according to an equal energy rule.

In contrast, the studies on real impulses have primarily demonstrated that the annoyance engendered by weapons fire impulses is greater at lower levels, and exceeds that due to equivalent levels of fluctuating or steady continuous noise. The addition of fluctuating background noise appears to increase the annoyance of the combined noise at low levels, but the annoyance of the impulsive component is actually reduced as the relative level of fluctuating background noise is increased. Both the A-weighted equivalent continuous sound pressure level, L_{Aeq} , and various combinations of time and frequency weightings have been proposed to predict the psychoacoustical impact of weapons fire, but more work is needed in characterizing the impulses as to duration, rise time, and spectral content in order to devise a workable procedure.

4.4.4 Psychoacoustical Effects of Type B Impulse Noise

4.4.4.1 Overview. The psychoacoustical effects of type B (impact) impulse noise have been studied more extensively than the type A impulse noise discussed above, and there are some fundamental differences in the perception of the two types of impulse noise. Some of the studies that will be described in this section were performed using real impulse noise. Others were performed with a wide variety of synthetic stimuli that simulate the characteristics of type B impulse noise to varying degrees, but nevertheless are more closely related to the type B waveform than they are to the type A. These include, for example, tone bursts with either rectangular or exponentially decaying envelopes, and noise bursts with rectangular, triangular, trapezoidal, or exponentially decaying envelopes.

4.4.4.2 Psychoacoustical Effects of Isolated Type B Impulse Noise.

The majority of the experiments on the psychoacoustical effects of isolated type B impulses have been loudness measurements on tone bursts using the method of adjustment. As in the early experiments described in section 4.2.2, one of the main goals of these studies has been to determine time constants for temporal integration of the impulses. Other questions addressed by these studies include the effect of the shape of the envelope (rise time, duration, and the presence or absence of a plateau), and the effect of varying the carrier frequency of tone bursts or the center frequency of filtered noise bursts.

In 1970, Fidell et al. measured the noisiness of octave band filtered noise bursts with durations ranging from 10 msec to 1.0 sec compared to the noisiness of a 1.0-sec burst of filtered noise with band limits of

600-1200 Hz. The data approximately followed a 3 dB increase in noisiness per doubling of duration up through durations of 333 msec, with very little subsequent change between 333 msec and 1.0 sec.

Gustafson (1974) studied the loudness of exponentially decaying tone bursts as a function of duration, rise time, and carrier frequency. Doubling the duration of 1-kHz tone bursts with a peak level of 97 dB yielded an increase in loudness level of 1.5 dB (rather than the three dB that would be expected from an equal energy rule) over a range of durations from 40 to 800 msec. Over a range of rise times from 0.3 to 10 msec, the increase of loudness level with decreasing rise time corresponded to a 425-fold decrease in the rise time per doubling of the loudness. Impulses with rise times less than or equal to 1.5 msec were perceived as equally loud. Thus the loudness of the tone bursts in this study was much more strongly determined by duration than by rise time. In contrast, the loudness of type A impulses of comparable duration (sonic booms) discussed in the last section has been found to depend more on the rise time rather than on the duration.

Gustafson (1974) also found that the loudness of the tone bursts varied less than would be expected from the A-weighting curve when the carrier frequency was varied from 100 Hz to 4000 Hz. However, the A-weighting curve is based on the equal loudness contour for steady pure tones at 40 dB SPL, and the equal loudness contours for levels comparable to those used in the experiment are much flatter than the A-weighting curve.

The loudness of isolated type B impulses was also studied as a part of the round robin study on the loudness of impulse noise (Pederson, Lyregaard, and Poulsen 1977) which was sponsored by International

Standards Organization (ISO) working group 43. Both real impact noises (such as forging impacts) and tone bursts were included in the stimuli. As will be discussed in section 4.5, the loudness of the isolated real impact stimuli was best fit by applying the loudness calculation procedures of either Zwicker (1966) or Stevens (1971). The data on the isolated tone bursts at 95 phon were consistent with an auditory temporal integration time of 80 msec. At 75 and 55 phon, a drop in loudness relative to the predictions of the equal energy relation was observed at durations below 20 msec, in accord with the findings of Plomp and Bouman (1959) and Green, Birdsall, and Tanner (1957) which were discussed in section 4.4.2.

Poulsen (1978) followed up on these results by performing additional experiments on the loudness of tone bursts at relatively low presentation levels. A paired comparison technique was used to balance the loudness of pairs of tone bursts in which the duration of the second burst was exactly half that of the first. The durations ranged from 5 msec to 640 msec. Poulsen developed an auditory temporal integration model with two time constants to fit the data (see section 4.5).

The loudness of isolated tone and noise bursts was also studied in three sets of experiments by Kumagai, Ebata and Sone (1981, 1982a, 1982b). The first study (Kumagai, Ebata, and Sone 1981) explored the dependence of the loudness of tone bursts on peak level, rise time, and fall time using the method of adjustment. The tone burst stimuli were compared to a reference tone burst with rise and fall times of 60 msec. The main finding of this study was that the loudness of the impulse noise test stimuli relative to the reference stimulus was largely determined by their peak level rather than their energy, as is shown in figure 9.

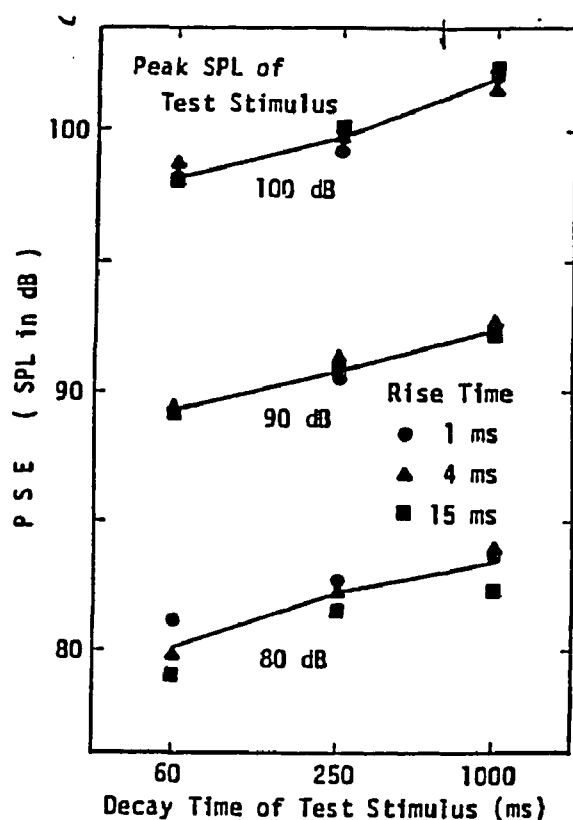


Figure 9. PSE for loudness of triangular tone bursts (Kumagai, Ebata, and Sone 1981).

It can be seen from figure 9 that increasing the peak level by 10 dB while keeping the energy constant yielded a 6 dB increase in the loudness level. Decreasing the rise time also slightly increased the loudness level, and this effect was largest at a 2-kHz tone burst frequency, and negligible at 500 Hz. Increasing the fall-time resulted in a 1 dB increase in loudness per doubling of the fall-time, but this is far less than the 3 dB expected from the equal energy relation.

The second study by Kumagai et al. (1982a) compared the loudness of tone bursts with triangular and trapezoidal envelopes. The subjects

performed loudness balances on trapezoidal waveforms with a rise time of 4 msec, a fall time of 60 msec, and plateau durations varying from 1 to 60 msec. The comparison stimulus was a trapezoidal impulse with a 200-msec plateau. The impulses with the shortest plateau durations (1-15 msec) were between 1 and 5 dB louder than would be predicted from the equal energy relation. These trapezoidal impulses were then compared with triangular impulses of comparable energy in a second experiment. The authors found that the longer triangular impulses had lower PSEs than the trapezoidal impulses of the same energy, and were therefore less loud than would be predicted on an equal energy basis.

Both of these results may have been due the fact that stimuli with durations exceeding the auditory integration time were compared on an energy basis to stimuli that were shorter than the integration time. In the experiment on the trapezoidal impulses, most of the energy of test stimuli may have integrated, whereas much of the energy of the 200-msec trapezoidal reference stimulus was probably not integrated. Thus, considered on an energy basis, the short-duration test stimuli were effectively louder than the 200-msec reference stimulus. Similarly, the triangular impulses of long duration may have been rated less loud than the trapezoidal impulses of the same energy because, in the case of the triangular impulses, the durations were well over 200 msec.

The third study by Kumagai et al. (1982b) involved comparison between tone bursts and bursts of white and pink noise. Both triangular and trapezoidal impulses were used, and the results were in agreement with those of the previous two studies.

Shortly after the publication of the above experiments, a round robin study on the loudness of impulse noise was conducted by eleven

psychoacoustical research teams in Japan (Kuwano et. al 1984, 1987; Sone et al. 1987; Suzuki et. al 1984.) The round robin included both repetitive impulse trains, which will be discussed in section 4.4.4.3, and isolated impulses. The isolated impulses used in the round robin were quite similar to those of the studies by Kumagai, et al. (1981). The impulses had rise times of 1 msec, fall times of 30, 100, and 300 msec, and steady durations of 30 and 100 msec (trapezoidal impulses), and 0 msec (triangular impulses). There were two carriers: a 1-kHz sine wave and an asymmetric rectangular wave.

The results of Kuwano et al. (1984, 1987) in the Japanese round robin suggest that the A-weighted sound exposure level, L_{AE} , is an effective predictor of the loudness of isolated impulses. When the data were analyzed on the basis of L_{AE} , there was no significant effect due to the envelope shape or duration. The results also appeared to be independent of the two "carrier" conditions (the sine wave and the rectangular wave).

Kuwano et al. (1984, 1987) also reported on the effects of amplitude modulation of the envelope of exponentially decaying impulses. Isolated 1-kHz tone bursts with an exponential decay time of 50 msec were amplitude modulated at rates of 10, 15, and 20 Hz with a modulation depth of 50 and 75 percent. A small but statistically significant increase in the loudness level (about 1 dB) was observed for the two higher modulation rates at the 75 percent modulation depth.

Suzuki et al. (1984) reported results similar to those of Kuwano et al. in the round robin study, in that there was good agreement between the measured sound exposure level of the test stimuli, L_{AE} , and the point of subjective equality for loudness. However, they found that the stimuli

with the shortest durations were perceived as one to two dB louder than the prediction based on the sound exposure level, as shown in figure 10.

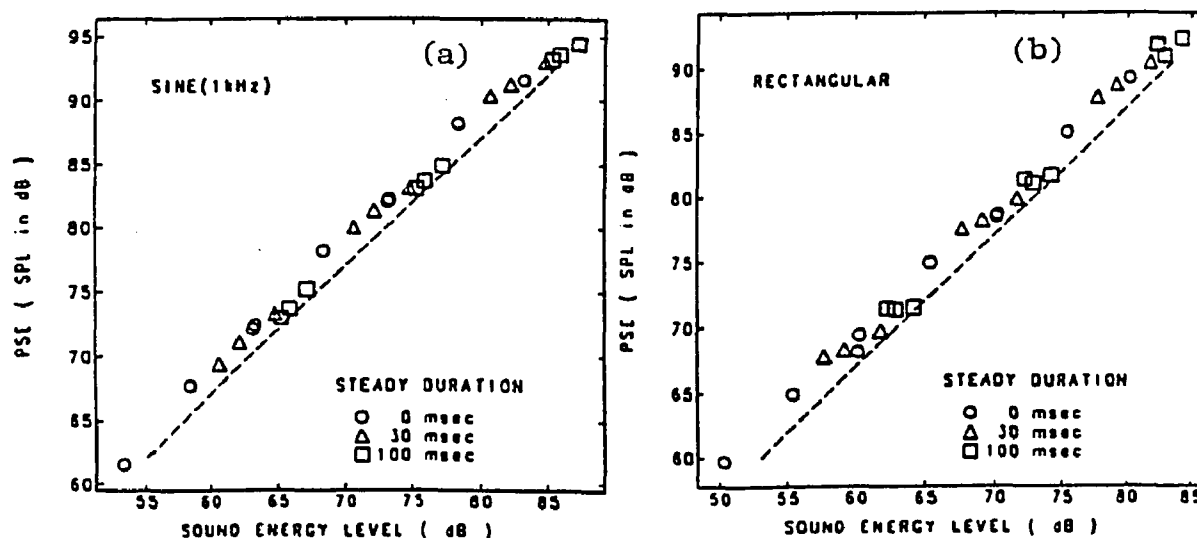


Figure 10. PSE of test stimuli as a function of their sound exposure level (Suzuki et al 1984). The dashed diagonal line is the equal-energy prediction.

Two other research teams have also studied the loudness of isolated type B impulses during the past decade. Tachibana and collaborators (Ishizaki and Tachibana 1985; Tachibana, Ishizaki, and Yoshihisha 1987; Tachibana, Yoshihisha, and Ishizaki 1984) have studied the loudness of both tone bursts and noise bursts as a function of level, frequency, and envelope shape. Namba and collaborators (Namba, Hashimoto, and Rice 1987; Hashimoto, Namba, and Rice 1984) have studied the loudness of exponentially decaying tone bursts as a function of level and decay time.

The first experiments of the Tachibana group (Tachibana, Yoshihisha, and Ishizaki 1984; Tachibana, Ishizaki, and Yoshihisha 1987) were performed using tone bursts with durations ranging from 4 to 256 msec. Loudness matching was performed using a 1-kHz, 16-msec tone

burst as the reference stimulus. Figure 11 shows the equal loudness contours that were obtained.

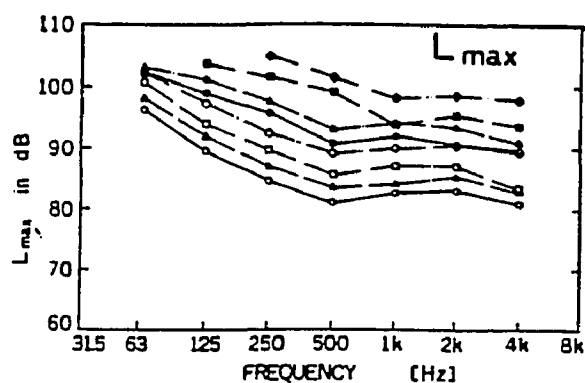


Fig.-7 Loudness contours by $L_{\max}$

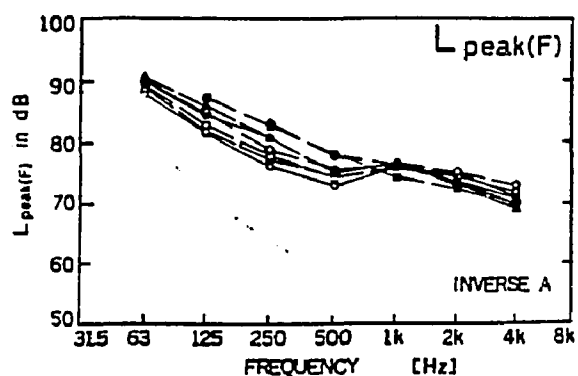


Fig.-10 Loudness contours by $L_{\text{peak}}(F)$

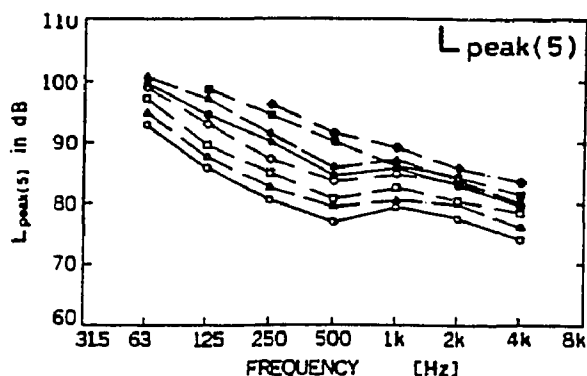


Fig.-8 Loudness contours by $L_{\text{peak}}(S)$

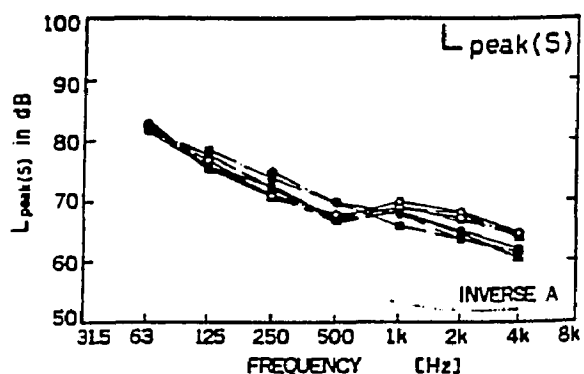


Fig.-11 Loudness contours by $L_{\text{peak}}(S)$

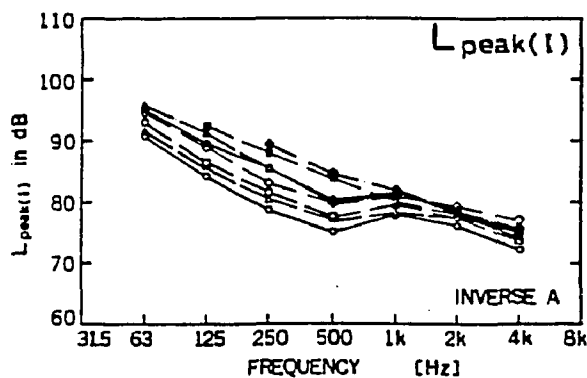


Fig.-9 Loudness contours by $L_{\text{peak}}(I)$

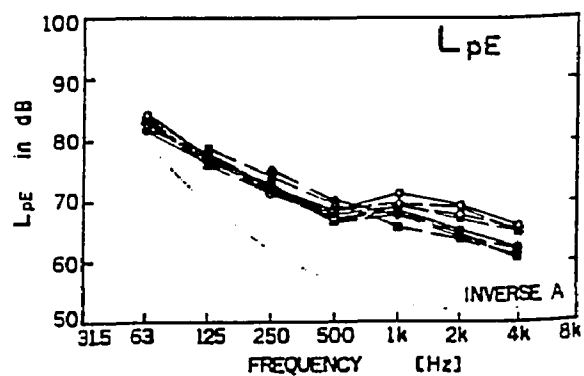


Fig.-12 Loudness contours by L_{pE}

Figure 11. Equal loudness contours for tone bursts as a function of duration (Tachibana, Yoshihisha, and Ishizaki 1984).

The equal loudness contours in figure 11 are reported in terms of several different quantities including the sound exposure level of the reference stimulus at PSE, and the peak sound pressure level of the reference stimulus at PSE determined using exponential averaging with a variety of time constants: slow (1 sec), fast (250 msec), impulse, and 5 msec. As in the case of the experiment by Gustafson described above, the contours are somewhat flatter than the A-weighting curve. This may be due in part to the fact that the level was higher than the 40 dB SPL of equal loudness contour which is used for A-weighting.

The contours for the different durations are quite separate at the 5-msec time constant, and they overlap more fully as the time constant is increased. Since measuring the peak levels of the test stimuli with a 5-msec time constant yields values very close to the instantaneous peak levels, these results imply that the loudness was better predicted by sound exposure level than by the peak level, i.e. that the equal energy relation holds for the loudness of isolated type B impulses, in agreement with the data of the Japanese round robin but in contrast to the results of Kumagai et al. (1981) above.

Repeating the above experiments with octave bands of filtered noise yielded similar results (Ishizaki and Tachibana 1985). Another experiment by this same research group demonstrated that variations in envelope shape have little effect on the perceived loudness of isolated impulses (Tachibana, Yoshihisa, and Ishizaki 1987). However, reproducing an impulse of short rise time and long decay time in reverse order was found to increase its loudness by one to two dB.

The other major set of experiments on isolated type B impulses was performed by Namba and collaborators (Namba, Hashimoto, and Rice

1987; Hashimoto, Namba, and Rice 1984). Their data on the loudness of exponentially decaying tone bursts compared to trapezoidal reference stimuli with varying plateau durations are shown in figure 12.

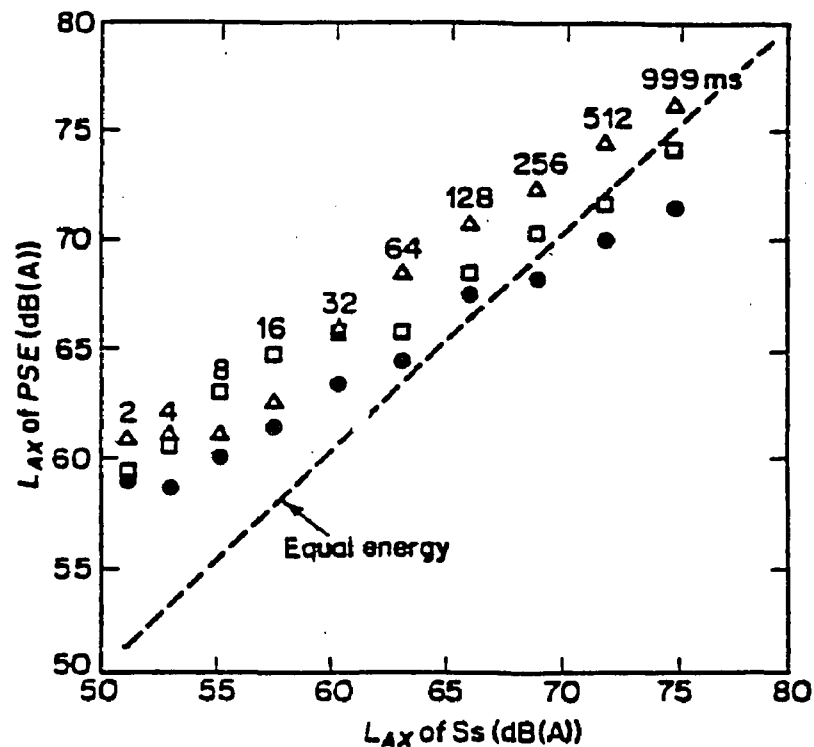


Figure 12. PSE of isolated triangular tone burst stimuli relative to three different trapezoidal reference bursts as a function of stimulus burst duration: triangles, 500-msec reference stimulus; squares, 330-msec reference stimulus; circles, 100-msec reference stimulus (Namba, Hashimoto, and Rice 1987).

It can be seen in the figure that the sound exposure level of the test stimulus at the point of subjective equality did not decrease with decreasing duration according to an equal energy relation, and that it depended on the plateau duration of the reference stimulus. At durations below 60 msec, the triangular impulses were louder than would be expected on an energy basis, and less loud than would be predicted

from the peak level. The loudness levels compared to the 500-msec reference stimulus were 2-3 dB higher than those obtained with the 100-msec reference, possibly because the duration of the former exceeded the integration time for loudness.

In considering the results of all of the above studies, the following general conclusions may be drawn. In contrast to the case of type A impulses, rise time has relatively little influence on the loudness of isolated type B impulses. The dependence of loudness on duration appears to follow the equal energy relation (doubling the duration at a constant peak level increases the loudness level by three dB) over a range of durations. The data of Kumagai et al. (1981) are consistent with an auditory temporal integration time of 100 msec, while the data from the Japanese round robin (Kuwano et al. 1984, 1987; Suzuki et al. 1984) imply an integration time of at least 300 msec.

At durations below about 50 msec, however, the results are contradictory. Poulsen's (1978) results suggest that shorter impulses are perceived as less loud than what would be expected from an equal energy rule, the data of Tachibana et al. (1984, 1987) continue to follow an equal energy rule, and the data of Namba et al. (1987) imply that the impulses with shorter durations are louder than would be expected from the equal energy relation.

There is general agreement that differences of one to two dB in loudness level may be obtained by varying the envelope shape of the impulses. Kumagai et al. (1982a) have found that trapezoidal impulses are perceived as louder than triangular impulses with the same sound exposure level in cases where the duration of the triangular impulses exceeds the auditory integration time. The data of Namba et al.

(1987) suggest that the opposite is true when the impulses are of shorter durations than the integration time.

Tachibana et al. (1987) have shown that reversing the order of an impulse with a long rise time and short fall time increases the loudness slightly. (A similar result, but larger in magnitude, was obtained for weapons fire impulses by Berglund et al. (1986), see section 4.4.3). The effect on loudness due to amplitude modulation of the envelope of isolated type B impulses was found by Kuwano et al. (1984, 1987) to be of the same order of magnitude.

Both Fidell et al. (1970) and Tachibana et al. (1984) have found that the equal loudness contour for short tone bursts is flatter than the A-weighting curve, but neither has performed an exact comparison with the equal loudness contours corresponding to the levels at which the experiments were performed.

4.4.4.3 Psychoacoustical Effects of Repetitive Type B Impulse Noise

Without Background Noise. Numerous experiments have been conducted on the psychoacoustical effects of repetitive type B impulse noise. As in the case of the isolated impulses, a major goal of these studies has been to explore the role of the duration, rise time, level, and carrier frequency or spectral content in determining the psychoacoustical effects of the noise. Experiments have also been conducted to determine the effect of varying the repetition rate or inter-impulse interval, and the effect of repeating the impulses at a variable rather than a constant repetition rate. The question of the effect of adding continuous background noise will be discussed separately in section 4.4.4.3.

Some of the early studies that were performed in order to determine

the time constants for the impulse sound level meter circuit were done with repetitive trains of type B impulse noise (see section 2.6.2.2). For example, Zwicker (1966) measured the loudness of 2-kHz tone bursts as a function of both duration and repetition rate. In keeping with some of the data on isolated impulses, he found that increasing the duration of each of the repeated impulses above 100 msec yielded no increase in loudness. At shorter durations, a tenfold increase in duration was found to double the perceived loudness. (This is equivalent to the equal energy rule if one equates a doubling in loudness with a change of about 10 dB in level, as is observed for continuous noise (Kryter 1970)). Doubling of the loudness was also obtained by a tenfold increase in repetition rate for repetition rates above 10 Hz. At rates below 10 Hz, the loudness was found to be independent of repetition rate.

Another study on the loudness of trains of type B impulses was reported by Boone (1973). He measured the loudness of repeated tone bursts compared to a sustained sine wave of the same frequency at 72 dB SPL. The interval between impulses (and hence, the repetition rate) was controlled but the number of impulses in the test stimulus and the duration of the reference stimulus were determined by the subjects, who were able to switch back and forth between the test reference stimuli at will. After the loudness balance was achieved for each stimulus pair, the level of the sustained portion of the impulses was measured. Since the impulses were effectively rectangular in shape, the product of this level and the duration is a good estimate of the energy of the impulse. The difference between this level and the reference level was measured as a function of the duration and the time interval between impulses.

The results of Boone's experiment suggest that the equal energy

relation is followed for 1-kHz impulses at a low repetition rate (3 Hz) for durations up to an auditory integration time of about 120 msec, as shown in figure 13a. The data obtained as a function of "off time" (inter-impulse interval) at a carrier frequency of 4 kHz with duration as a parameter are shown in figure 13b.

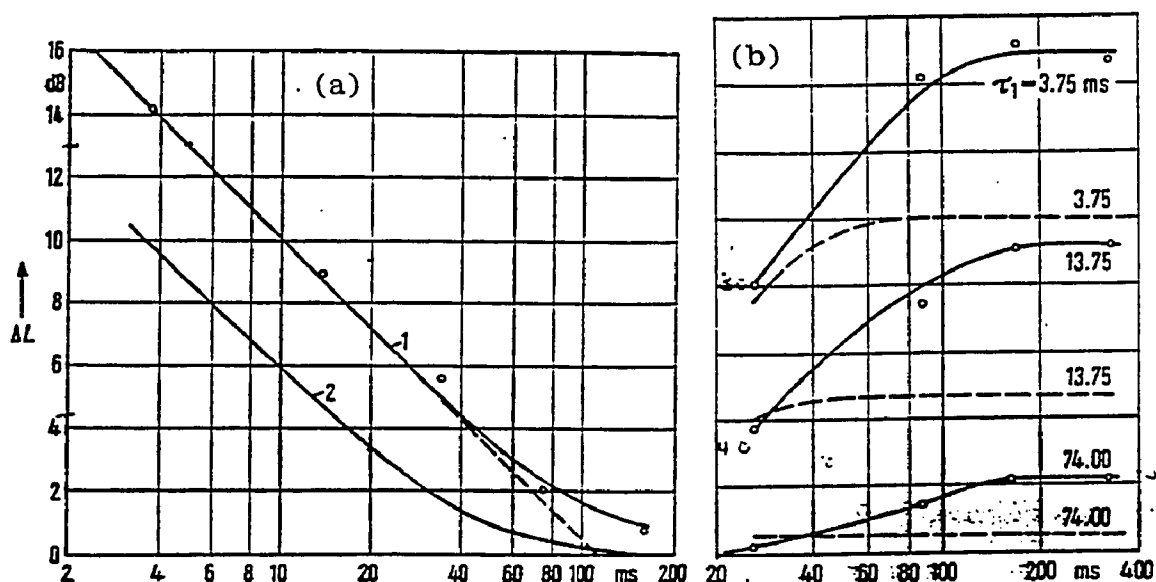


Figure 13. Loudness of repeated tone bursts: a, curve #1: Loudness of 1-kHz tone bursts at a repetition rate of 3 Hz as a function of duration; curve #2: readings of the impulse sound level meter; dashed line: predictions of equal energy law; b, solid lines: loudness of 4-kHz tone bursts as a function of the burst duration and the interval between impulses; dashed lines: readings of the impulse sound level meter. (Boone 1973).

In figure 13b, the PSE for loudness decreases as the "off-time" increases. At 4 kHz however, a plateau is reached in the vicinity of 150 msec (between 5 and 10 Hz). The difference in PSE at low repetition rates (after the plateau is reached) corresponds to equal energy

behavior. For example, the 3.75-msec and the 13.75-msec curves are about 6 dB apart, and $10 \log (13.75/3.75) = 5.6$ dB. At higher repetition rates, the loudness level increases less rapidly than would be expected from the equal energy rule.

The loudness of repetitive impulse trains was also studied as part of the ISO-sponsored round robin study on impulse noise (Pederson, Lyregaard, and Poulsen 1977). The test stimuli were recorded from industrial machinery which produced impact noises at low repetition rates. One-second bursts of the impulse noises were compared to a one-second burst of octave band filtered noise at 55, 75, and 95 dB SPL by a variety of methods at the participating laboratories. The data were analyzed in terms of the agreement with physical measurements of the stimuli using various time and frequency weightings, and with the results of applying steady state loudness calculation procedures to the spectrum as measured with a variety of time constants, as will be discussed in section 4.5.

Recently, several other studies on the psychoacoustical effects of repeated impulses have been reported. In general, these experiments were performed with impulses of longer duration and lower repetition rates than those of the Boone study. In some cases, the results may have been affected by the choice of the reference stimulus and the way in which its level was reported.

Kumagai, Suzuki, and Sone (1982, 1984) studied the loudness of tone bursts with a rise time of 4 msec and fall times of 60, 120, and 240 msec. The bursts were presented in isolation and also in trains of 2, 4, or 8 impulses at intervals of 100, 200, or 400 msec. The results were similar to those reported for isolated impulses by Kumagai et al. (1981) in

that doubling the duration only increased the loudness level at PSE by one dB, and increasing the peak level by 10 dB while holding the impulse energy constant caused a 5 dB increase in the loudness level. Doubling the energy by doubling the number of impulses yielded a 1.1 to 1.3 dB increase in the loudness level. Varying the interval between impulses from 100 to 400 msec had little effect, but the loudness level of the 100-msec condition tended to be just slightly higher. As the authors point out, the data reflect temporal integration by the auditory system under a saturation condition because the durations of the test stimuli exceeded the integration time.

Another experiment involving repeated impulses of lower repetition rates and longer durations was reported by Nakamura et al. in 1984. The impulses were triangular bursts of one-third octave-band noise at 4 kHz with durations of 500 and 750 msec. Trains of 1, 2, 4, or 6 of these impulses were presented at "off-times" (inter-impulse intervals) of 500 msec and 1 sec, and both loudness and noisiness were measured by a scaling method. Overall, both the loudness and the noisiness data followed an equal energy rule. The loudness data were well correlated with the L_{eq} of the impulses computed without including the off-time (which is therefore equivalent to the L_{eq} of a single impulse). The noisiness data were best fit by the sound exposure level, L_E , measured over a 5-second interval.

Sakai (1986) has also measured both the loudness and the noisiness of repeated bursts of long duration. White and pink noise bursts with durations ranging from 138 to 1100 msec were presented in 8-second trains at repetition rates ranging from 1.25 to 10 Hz. A possible source of bias in the results is that the reference stimulus was always

presented first in each trial, leading to an enhancement of the loudness of the test stimulus due to the "sequence effect" (see section 4.3.1). Also, a design with two separate groups of six subjects (of unspecified otological status) was used, rather than a repeated measures design. The results did not appear to vary systematically with duration or repetition rate. It was found, however, that loudness and noisiness were linearly related with a slope of unity and an intercept of 2.5 dB. This relation appeared to hold for real impulse noises as well.

The loudness and noisiness of repeated impulses were also measured as part of the Japanese round robin study that was described in section 4.4.4.1. The data on repeated impulses were reported in a separate paper (Sone et. al. 1987). Impulses of 30, 100, and 300 msec duration were presented at 85 phon in two-second bursts at repetition rates of ranging from 0 Hz (isolated) to 30 Hz. The data obtained with the 1-kHz tone bursts are shown in Fig 14. A line with a slope of 0.63 (rather than the slope of unity that would be expected from the equal energy relation) has been fit to the data, and the agreement appears excellent.

However, if the data are examined more closely, it becomes clear that the characteristics of this regression line are an artifact of the way in which the data were reported. The data at the lower repetition rates, and for isolated impulses, do in fact follow an equal energy law for duration. A line drawn through the 3 open circles (1 Hz), for example, would have a slope of approximately unity but would be displaced by about 10 dB from the equal exposure line.

This cause of this displacement may be the fact that the reference stimulus was much longer than the temporal integration time (which is of order 100-200 msec), and yet the results were reported in

terms of sound exposure level. The measured PSE seems to correspond to the level at which the sound exposure in the 200-msec integration time interval was comparable to that of the test stimulus.

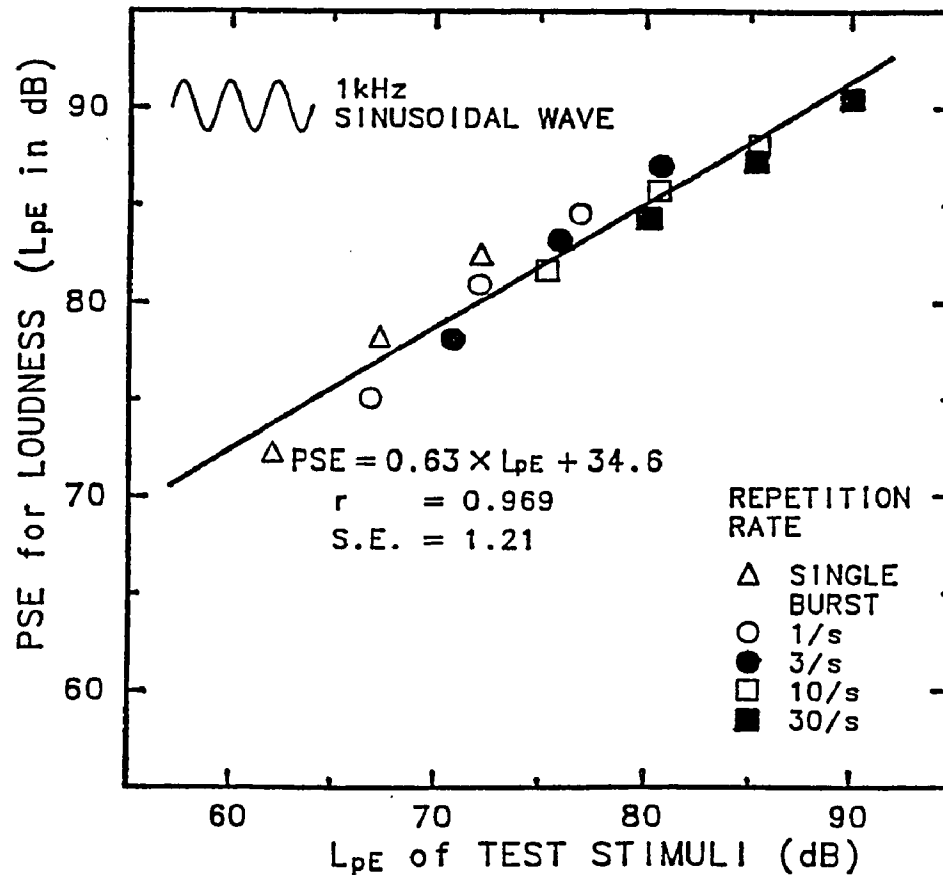


Figure 14. Loudness of repeated noise bursts as a function of sound exposure level and repetition rate. At each repetition rate, the left-most point of the three is the impulse with a 30 msec fall time, the center point corresponds to a duration of 100 msec, and the right-most point, to a fall time of 300 msec (Sone et al 1987).

On the other hand, the stimulus consisting of the 300-msec impulses at 30 Hz is essentially a continuous noise due to overlap of the impulses. The mean PSE for that stimulus (the right-most filled square) falls on the

equal exposure line. In this case, the subjects probably compared the energy in the 100-200 msec integration time window for both cases, and this yielded equal exposure because the overall durations of the test and reference stimuli were almost the same. The data at the intermediate repetition rates can be seen to form a continuum between these two extreme cases. This result is quite similar to the pattern seen in the data of Boone (1973). As was discussed earlier in this section, his data also followed an equal energy rule for duration at repetition rates below about 5 Hz, but the change in PSE was less than that predicted by the equal energy relation at higher repetition rates.

Thus the slope of the overall regression line that was obtained in the Japanese round robin on repeated impulses is a consequence of both the way in which the test conditions were selected and the relative durations of the test and reference stimuli. In fact, it appears that the slope is dependent on repetition rate, and varies from about 0.63 at 30 Hz to unity at 1 Hz. In contrast, the slope of the noisiness data was consistently close to unity at every repetition rate studied, suggesting (in agreement with the data of Fidell (1970) and of Nakamura et al. (1984)), that the integration time for noisiness comparisons is much longer than for loudness.

An extension of the round robin experiment on repeated type B impulses was reported by Sone et al. in 1989. The stimulus burst duration was varied from 2 to 50 seconds so that repetition rates as low as to 0.2 Hz could be studied. They found that the PSE at each repetition rate increased with increasing overall stimulus burst duration.

Several conclusions may be drawn from the above studies on the loudness and noisiness of repeated type B impulse noise: First, at low

repetition rates, the loudness data are comparable to those obtained by the same experimenters for isolated impulses. For example, equal energy behavior was observed, with an integration time window of order 100 msec, by Zwicker (1966), Boone (1973), and in the Japanese round Robin (Sone 1987). In the data of Kumagai et al. (1982), on the other hand, peak level (rather than energy) was the best predictor of the loudness of the repeated impulses, in agreement with their earlier results for isolated impulses (1981).

Second, as the impulse repetition rate is increased, the equal energy rule for duration ceases to hold, and there appears to be a psychoacoustical transition between isolated impulses and quasi continuous noise at repetition rates of order 3-10 Hz. Such a transition might be expected to occur in this region, because, if the auditory integration time is 100-300 msec, then more than one impulse occurs within the ear's temporal window once the repetition rate exceeds 3-10 Hz.

For example, in the data of Boone (1973) (figure 13b) there is a plateau which commences at repetition rates of between 3 and 10 Hz depending on the duration. At lower repetition rates, the equal energy rule is followed for duration as shown in figure 13a. Above 3-10 Hz, the three curves in figure 13b begin to converge on the reference (zero) level, so that loudness increases more slowly than the equal energy prediction.

Zwicker (1966) has also observed a transition in the loudness data for tone bursts at a repetition rate of 10 Hz. Loudness was independent of repetition rate at rates below 10 Hz, and it increased according to the equal energy relation as the repetition rate was increased above 10 Hz.

The presence or absence of a psychoacoustical transition between isolated impulses and quasi continuous impulse noise is more difficult to assess in the data from the Japanese round robin. Overall, the loudness level increased by two dB per doubling of the duration. However, the data at 1 and 3 Hz appear to follow the equal energy rule with increasing durations, while at 10 Hz and 30 Hz the slope is more gradual, suggesting that there is a change in auditory processing in the vicinity of 3 to 10-Hz repetition rate.

Another factor that may affect the psychoacoustical transition between isolated impulses and quasi continuous impulse noise is the roughness effect. Concerns about the possibility of an artifact due to the roughness effect at repetition rates above 10-20 Hz were raised by Reichardt and Niese (1970). However, the data discussed above do not seem to show an abrupt increase in loudness level at the higher repetition rates. For example, in the results of the Japanese round robin (figure 14), there is a smooth, gradual change in the slope of the data as the repetition rate is increased from 3 to 30 Hz. The data of Boone (figure 13b) also show smooth, orderly behavior as the repetition rate is increased from about 5 Hz (inter-impulse interval of 200 msec) to about 30-40 Hz (inter-impulse interval of 30 msec).

One can also conclude from the experiments on repeated type B impulses that, in contrast to the situation with loudness, the integration time for noisiness exceeds 1 second and may be as much as 5 seconds, in agreement with the results of Fidell et al. (1970). This is evident in the data of Nakamura et al. (1984) and in the noisiness data of the Japanese Round Robin study (Sone 1987).

So far, all of the studies discussed in this section have involved

measurements of loudness and/or noisiness. In the past decade, a series of experiments on the annoyance and impulsivity of repeated type B impulse noise has also been performed by several cooperating laboratories as part of a project on the measurement, rating, and psychoacoustics of impulse noise which has been sponsored by the Commission of the European Communities (CEC) (Rice 1989).

The dependence of the annoyance of repetitive type B impulse noise on several fundamental parameters has been studied by Berry (1985, 1987) as part of the CEC project. Initially, the annoyance of recorded impulse noises (e.g. pile driver, pneumatic drill, dump truck) and a fluctuating noise (road traffic) were studied. The annoyance ratings of the impulses noises increased with increasing presentation level. The pile driver noise had a much higher rating throughout, but increased in annoyance less rapidly with increasing level. The annoyance rating of the fluctuating traffic noises exceeded that of the pile driver at 70 dB L_{eq} .

Berry (1987) also measured the annoyance of synthetic impulse noises with durations of 10 msec at repetition rates of 2, 4, 8, and 16 Hz, and durations of 100 msec at repetition rates of 2, 4, and 8 Hz. The annoyance ratings of all of the impulse noise stimuli exceeded those of the reference noise stimuli (traffic noise and steady white noise) and there was a significant interaction between the repetition rate and the duration of the impulses. At the 2-Hz repetition rate, the 100-msec impulses had higher annoyance ratings than the 10-msec impulses, while the opposite was true at the 8-Hz repetition rate. From these data, impulse penalties (relative to the annoyance of traffic noise) that ranged from 16.0 dB at an L_{eq} of 35 dB to 4.2 dB at an L_{eq} of 65 dB were determined.

(Inspection of the data shows that the rapid increase in annoyance that

was observed for the traffic noise with increasing level causes the large variation in penalty with level).

Berry (1985, 1987) also studied the dependence of annoyance on irregular impulse repetition rates. The annoyance of 100-msec impulses with repetition rates that fluctuated in the ranges: 0.2 to 1 Hz, 1 to 4 Hz, and 4 to 8 Hz was compared to the annoyance of uniform impulse trains at 1, 4, and 8 Hz. For each range of repetition rates, the annoyance of the train with the fluctuating repetition rate did not differ significantly from that of its steady counterpart.

The next step in the CEC project was to measure the subjective impulsivity of impulse noise and to correlate the impulsivity ratings with annoyance data. Brambilla and Caretti (1988, 1989) have carried out experiments in which subjects rated a variety of environmental impulse noises (including some type A impulse noises), and fluctuating and steady noises at presentation levels of 40, 55, and 70 dB L_{Aeq} . The subjects were asked to rate how annoying and how impulsive the noise was, how annoying they found the impulsive component of the noise, and also to state whether or not the noise was "clearly impulsive".

Overall, the perceived impulsivity of the impulsive noises was higher than that of the nonimpulsive noises, and it increased with increasing L_{Aeq} . There was a strong dependence of both annoyance and impulsivity on noise type; for example, a type A noise, gunfire, at 70 dB L_{Aeq} was rated slightly less impulsive than hammering at 40 dB L_{Aeq} , but the annoyance rating of the gunfire at 70 dB was higher than that of the hammering at any of the levels. One of the surprising findings of this study was that the rate of increase of impulsivity with increasing L_{Aeq} was independent of noise type, even for nonimpulsive noises. The

authors developed an impulsivity criterion based on the increment descriptor which will be discussed in the next section, and they derived a level-dependent penalty for impulse noise that estimates the annoyance compared to that of road traffic noise. The penalty, which is of the same order of magnitude as those of Berry (1987) and of Vos (1990), is given by the expression:

$$(4.2) \quad P = 24.7 - 0.35 \times L_{Aeq}$$

Where P is the impulse penalty which must be added to the level L_{Aeq} of the impulse noise to determine the level of traffic noise that would be equally annoying. The penalty is about 11 dB at impulse noise levels of 40 dB L_{Aeq} and drops to zero at about 70 dB L_{Aeq} .

Thus, while the loudness level of a repetitive type B impulse noise is lower than that of a steady noise of the same L_{eq} , the annoyance rating is typically higher than that of a steady or fluctuating noise of the same L_{eq} . The relative annoyance decreases with increasing level, and the rate of decrease is higher when the reference is a fluctuating rather than a steady noise. The level-dependence of the annoyance penalty of type B impulse noise is qualitatively similar to that of type A impulse noise (section 4.4.3). However, unlike the case of type A impulse noise, the duration and repetition rate of repeated type B impulses to interact in determining the overall annoyance.

The experiments discussed above have helped to clarify the psychoacoustical boundary between isolated impulses and quasi continuous impulse noise, as well as the dependence of that boundary on the impulse duration. In order to develop a means of predicting the

loudness of quasi continuous impulse noise, another psychoacoustical boundary must be explored; namely the transition between continuous noise and impulse noise as the relative level of a continuous or fluctuating background noise is varied. This topic is addressed in the next section.

4.4.4.4 Psychoacoustical Effects of Repetitive Type B Impulse Noise With Continuous Background Noise. Research studies on the psychoacoustical effects of repetitive impulse noise with added background noise may be divided according to whether loudness, noisiness, or annoyance were measured. In many of these studies, the background level was varied systematically, and simple models have been proposed to account for the results.

The loudness of real machine noises with high levels of background noise and repetition rates ranging from 2 to 20 Hz was studied by Banner et al. (1976) and by Engstrom and Nordby (1979). A key feature of these experiments is that the loudness of each test stimulus was measured compared to a steady reference stimulus that was spectrally shaped to match the test stimulus. Banner et al. (1976) performed a preliminary experiment on ten recorded machine noises using the method of adjustment at a reference stimulus level of 60 dBA. The peak-to-background ratio of the background noise was neither controlled nor reported, but it appears (from oscillograms in the report) to have been between 0 and 10 dB. The measured loudness levels of the impulse noise test stimuli were from 0.71 to 2.94 dB above those of the spectrally-matched steady reference stimuli. However, the test stimulus was always presented after the reference stimulus during each trial, and thus this finding may have been due at least in part to the "sequence effect"

discussed in section 4.3.1.

A follow-up experiment was performed by Engstom and Nordby (1979) by the ratio estimation technique using the same stimuli. The test and reference stimuli were presented several times in succession, but, as in the previous experiment, the last presentation in each sequence was always the test stimulus. Analysis of the results included several significant main effects including test stimulus level and reference stimulus level, and several interactions. A subjective annoyance penalty was derived from the data. In contrast to the results of Brambilla and Caretti (1988, 1989), and of Berry (1987) this penalty increased with increasing presentation level (from 0 dB at a presentation level of 55 dB, to 10 dB at 65 dB).

Berry (1987) studied the annoyance of synthetic impulse noise as a function of the relative level of steady white background noise at repetition rates of 2, 4, and 8 Hz by magnitude estimation. The impulses had durations of 10 msec and peak-to-background ratios of 10, 20, and 30 dB. The annoyance of pile driver noise and traffic noise was also measured in order to derive an impulse penalty.

Overall, the annoyance ratings of the noises with a peak-to-background ratio of 10 dB were lowest and were comparable to that of traffic noise at the same level, while the annoyance ratings of the 30-dB condition were highest and were similar to that of pile driver noise. At peak-to-background ratios of 20 and 30 dB, the 4-Hz repetition rate condition was most annoying, then 8 Hz, then 2 Hz. The impulse penalties (compared to the annoyance of traffic noise at the same L_{eq}) varied from approximately 9 dB at the 30-dB peak-to-background ratio to about 1 dB at the 10-dB peak-to-background ratio. Berry concluded that, unlike

some of the other parameters that were studied, the peak-to-background ratio had a "clear and consistent effect" on the annoyance (Berry 1987, 53).

Similar results were obtained quite recently by Flindell et al. (1989). They conducted a pilot study to measure the impulsivity and the annoyance of synthetic impulse noise with a 1-Hz repetition rate and durations of 53, 95, 180, and 350 msec. Background noise was added at peak-to-background ratios of 0, 10, and 20 dB. Increasing either the overall level or the peak-to-background level of the stimuli increased the annoyance ratings, which were not well correlated with ratings of impulsivity. The annoyance was most strongly related to the differences between the impulse peak levels and the background level.

The dependence of noisiness on peak-to-background ratio was studied by Yano et al. (1989) using trains of 100-msec bursts of pink noise at a 3 Hz-repetition rate, with overall stimulus durations from 2 to 32 sec, and peak-to-background ratios from 0 to 40 dB. Noisiness comparisons were performed between these stimuli at constant peak levels of 50, 60, 70, and 80 dBA and an 8-sec burst of steady pink noise at 70 dBA.

The results of this study are shown in figure 15. The noisiness ratings increased with decreasing peak to background ratio, in contrast to the annoyance data of Berry. However, since the data were reported in terms of the peak level of the impulses, stimuli of very different L_{eq} values are being compared because the background noise increases the L_{eq} significantly for the 0 and 10-dB conditions. If the data were compared on an equal L_{eq} basis, the curves in figure 15b would practically be superimposed. It is also interesting to note that the

noisiness continued to increase linearly with increasing duration up through durations of 32 seconds (figure 15c), compared to the value of 5 seconds obtained by Nakamura et al. (1984).

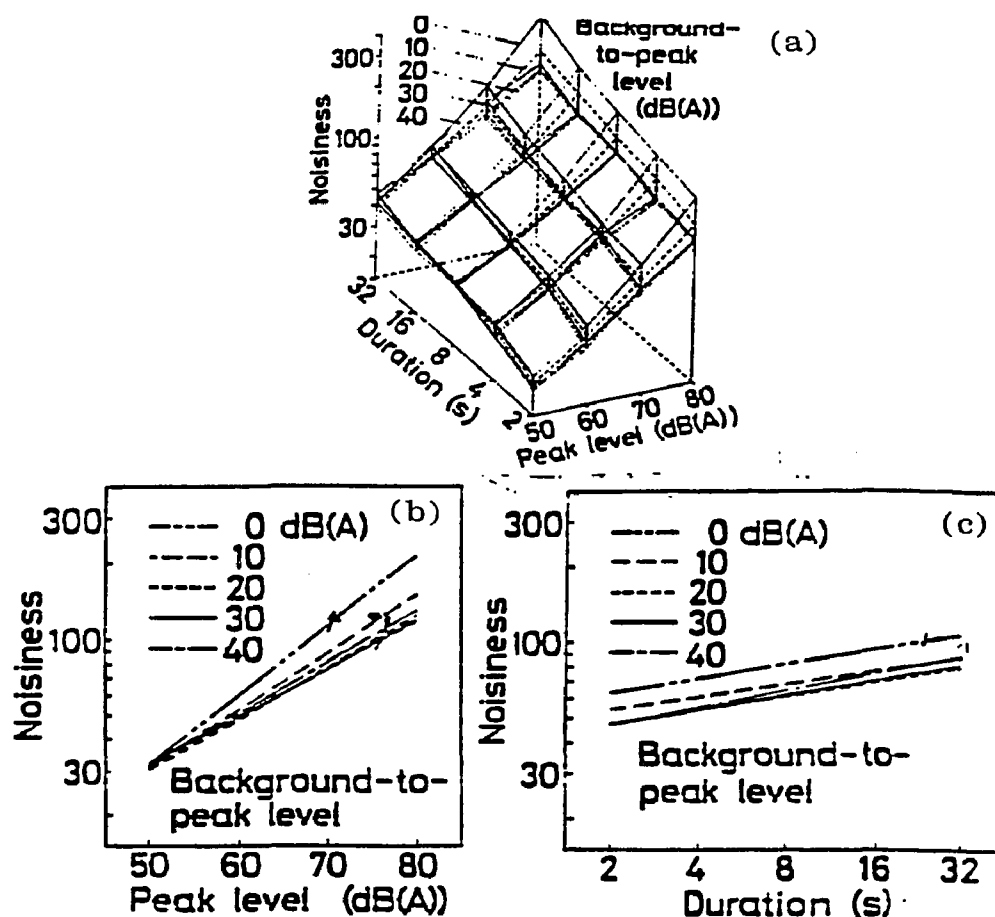


Figure 15. Results of experiment by Sone et al. (1989): a, Noisiness as a function of peak level and duration, with peak-to-background ratio as a parameter; b, Noisiness averaged over duration as a function of peak level, with peak-to-background ratio as a parameter; c, Noisiness averaged over peak level as a function of duration, with peak-to-background ratio as a parameter.

A second study by Yano et al. (1990) extended these findings to the annoyance of real impulse noise (pile hammer) and fluctuating background

noise (road traffic). The disturbance caused by these noises separately and in combination (at fixed overall levels L_{eq} of 60 and 70 dB, but varying relative levels) was measured by magnitude estimation.

The results for the separate noises are in qualitative agreement with those of Berry (1987) and of Vos (1990); the disturbance due to the traffic noise was lower than that of the pile hammer at low L_{eq} values (40 and 50 dB), but exceeded that of the pile hammer at 70 dB, as shown in figure 16a. It can be seen in figure 16b that, as the peak-to-background ratio was varied, the disturbance ratings at each level varied between

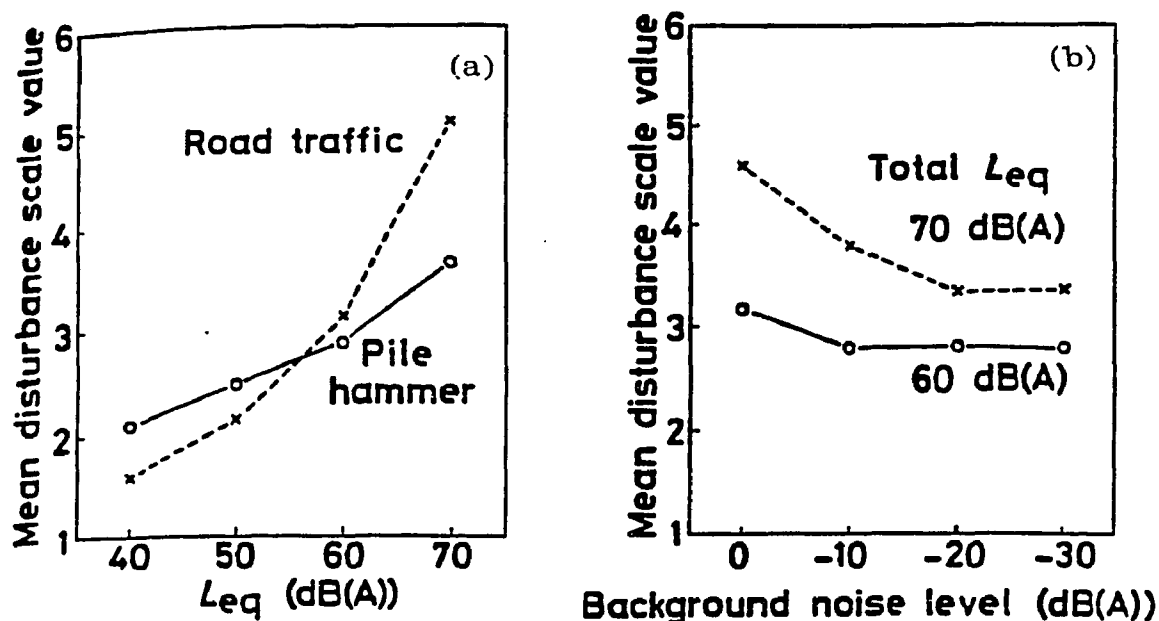


Figure 16. Results of experiment by Sone et al. (1990): a, disturbance ratings of separate fluctuating and impulsive stimuli as a function of presentation level; b, disturbance of combined impulsive and continuous noises, as a function of peak-to-background ratio, at overall L_{eq} of 60 and 70 dB.

the ratings obtained for the component noises at the same L_{eq} values. For example, at 70 dB L_{eq} , the disturbance due to the combined noise is almost identical to the value for the traffic noise alone at a peak-to-background ratio of 0 dB, and it drops monotonically to a value comparable to that of the pile driver alone at a peak-to-background ratio of 30 dB. These results were best fit by a regression model based on the annoyance of the separate noise components.

In summary, the limited evidence discussed above suggests that the peak-to-background ratio of repetitive impulse noise does affect the psychoacoustical response. However, the full range of effects of these combined noises seems to be predictable from the responses to their steady and impulse components. This is in contrast to the case of physiological effects, in which adding background noise increases the hazard of the combined noise beyond that of either of its components at comparable levels (Henderson and Hamernik 1986).

4.5 Psychoacoustical Models of the Perception of Impulse Noise

4.5.1 Introduction

Numerous models for estimating the psychoacoustical effects of impulse noise have been proposed, but none has proven completely satisfactory (Pedersen, Lyregaard, and Poulsen 1977), a fact which is not surprising in view of the variety of stimulus parameters, measurement quantities, and test methods that pertain to impulse noise. The motivating force behind much of the early work on the psychoacoustics of impulse noise was the development of the impulse sound level meter circuit. This circuit was intended to simulate the subjective response to

impulse noise (see discussion in section 2.6.2.2). It has since become clear that the circuit which has been standardized as a result of that effort (International Electrotechnical Commission 1973, 1979) is unable to predict fully the loudness of even isolated impulses, let alone quasi continuous impulse noise, any more than the A-weighted Sound Pressure Level completely predicts the loudness of steady-state sounds. In the case of steady-state sounds, procedures for calculating loudness and noisiness have been developed (International Standards Organization 1975, Kryter 1970). These and other models, (such as models of temporal integration, which were introduced in section 4.4.2), have been applied to impulse noise with varying degrees of success.

The psychoacoustical models that have been applied to impulse noise may be grouped into several categories according to the degree to which they incorporate the temporal and spectral aspects of the noise. Nearly all of these models are loudness models; models for noisiness and annoyance have not been extensively developed for either continuous or impulse noise.

The simplest temporal models are merely the application of various time weightings (e.g., with a sound level meter). This method does not take the spectral content of the impulse noise into account, except perhaps by applying a frequency weighting to the input. More complex models of temporal integration involving multiple time constants or simulation of physiological phenomena such as stimulus overshoot have also been applied to impulse noise. Another approach based on purely temporal information is the use of the descriptors that were defined in chapter 2, such as crest factor and kurtosis.

The other main class of models consists of spectrally-based

calculation procedures. Some of these models, such as that of Johnson and Robinson (1969) were specifically developed for use with impulse noise, while others, such as the procedures of Zwicker (1966) and Stevens (1971) were initially developed for steady noise. In applying the latter models, the only way in which the temporal aspects of the impulse noise are incorporated is in the selection of the averaging time to be used in measuring its spectrum.

The ideal psychoacoustical model for impulse noise must account for all of those aspects of the impulse noise, both temporal and spectral, that influence its loudness. So far, two models have been advanced to fill this purpose (Sone 1989; Zwicker 1977), but they have not been fully tested as yet.

4.5.2 Temporal Models

4.5.2.1 Single-Time-Constant Models. The early research that first led to the development of temporal integration models was surveyed in section 4.4.2. It was clear from these experiments that the auditory system performs temporal summation of loudness within a time window of approximately 100-250 msec. Several models involving a single integration process have been proposed. These models differ in the functional form of that integration process.

The temporal integration models of this nature typically refer to the mean-squared pressure, $\bar{p}^2$, of a rectangular tone or noise burst at the listener's ear as an "intensity". This conventional terminology is misleading because the term "acoustic intensity" actually refers to the average rate of flow of the energy of a sound wave through a unit normal surface. However, for the sake of continuity with the literature,

the term "intensity" and the symbol "I" will be used throughout this discussion to refer to the mean-squared pressure of a rectangular impulse. A further point of confusion is the use of the symbol "t" to indicate both time and stimulus duration.

Garner and Miller (1947) proposed a linear integration model for threshold detection known as the "diverted input hypothesis". The model assumes that the auditory system does not integrate the total energy of the stimulus. Rather, only that portion of the stimulus that is above a threshold intensity I_L is linearly summed. The intensity, I_L , corresponds to the intensity of a burst of long duration that is just at the threshold of audibility. As such, it can be interpreted as the minimum intensity that can serve as an effective stimulus of the auditory system. According to the authors, the product of this minimum intensity, I_L , and the integration time constant of the auditory system, T , should be equal to the energy integrated (above I_L) when the input is an impulse of duration t , shorter than T , and threshold intensity, I :

$$(4.3) \quad (I - I_L)t = I_L T = \text{constant}$$

The exponential integration model of Plomp and Bouman (1959) has been more frequently applied to the perception of impulse noise. This model treats the auditory system as an exponential (RC) integrator. In other words, the portion of the total stimulus intensity that is integrated decreases exponentially with increasing stimulus duration. The auditory sensation that results from this integration process is assumed to be proportional to the integrated intensity. Thus the sensation, S , due to a rectangular impulse with duration, t , and mean-squared level, I , is:

$$(4.4) \quad S = K \int_0^t I \exp\{-t'/T\} dt'$$

where K is a constant, t is the impulse duration, and T is the exponential time constant, which is assumed to be equal to the auditory integration time. Integrating this expression over time and evaluating the result at the limits yields the model of Plomp and Bouman (1959):

$$(4.5) \quad S = kI (1 - \exp\{-t/T\})$$

where k is a constant. The stimulus is detected if the sensory effect, S , exceeds a sensory threshold level, S_0 . Two stimuli will be equally detectable (or equally loud) if they have the same sensory effect, S .

A schematic of an RC circuit that simulates this exponential integration model electronically is shown in Figure 17. When a voltage V_0 is applied to the circuit, the voltage across the capacitor, V_c , increases according to the expression

$$(4.6) \quad V_c = V_0 (1 - \exp\{-t/RC\})$$

where R is the resistance, and C is the capacitance. There is a direct analogy between this expression and equation (4.5). The voltage across the capacitor, V_c , is analogous to the sensory effect, and the time constant, RC , which determines the rate at which the voltage across the capacitor approaches its final value, is analogous to the auditory integration time T .

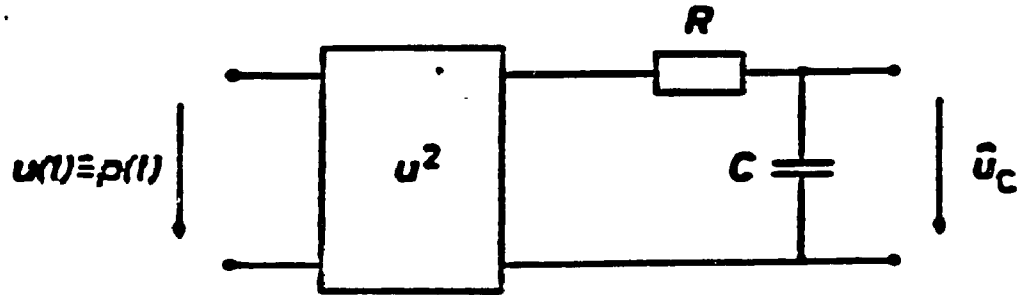


Figure 17. Single-time-constant RC Circuit model for the loudness of impulse noise (Port 1963a).

At short durations ($t \ll T$), the exponential in eq. 4.5 may be approximated as $(1-t/T)$ using a Taylor series expansion. Substituting this value back into eq. 4.5 yields the relation

$$(4.7) \quad S = kI (1 - \{1 - t/T\}) = \frac{kIt}{T}$$

Thus, in order to maintain equal loudness (or equal detectability) at short durations the product of I (the mean-squared pressure) and t (the duration) remain constant. Since this product is proportional to the energy of the stimulus, eq. 4.7 is an expression of the equal energy relation at durations $t \ll T$. In other words, the model predicts that the equal energy relation will be followed if the duration of the impulse is much less than the integration time, T .

At durations that are much longer than the integration time ($t \gg T$), eq. 4.5 asymptotically approaches the value $S_{\infty} = kI$, where S is the sensory effect due to an impulse of effectively infinite duration.

Denoting the intensity of this effectively infinite impulse as I_{∞} , and the intensity of an impulse of duration t as I_t , the ratio of the sensory effects due to these impulses may be written:

$$(4.8) \quad \frac{S_t}{S_{\infty}} = \frac{kI_t(1 - \exp\{-t/T\})}{kI_{\infty}}$$

If the sensory effects are equal, (i.e. at threshold, or at the PSE for loudness), eq. 4.7 may be rewritten as:

$$(4.9) \quad I_t = \frac{I_{\infty}}{(1 - \exp\{-t/T\})}$$

This expression gives the intensity, I_t , to which an impulse of duration t must be increased in order to produce the same sensory effect (e.g., threshold detection, loudness) as a stimulus of effectively infinite duration and level I_{∞} . For example, the threshold of an impulse of duration t may be calculated in terms of the threshold of a steady stimulus.

Thus, the single-time-constant exponential integration model predicts that the threshold (or loudness) will follow an equal energy rule for durations that are shorter than the integration time constant $T=RC$, and that loudness will be independent of duration for impulses that are much longer than T .

An approximate equal energy relationship between level and duration was evident in many of the loudness experiments discussed in section 4.4. The time constants that were deduced from these data, however, varied from approximately 35 msec to 800 msec. At durations shorter than the auditory integration time, the data may be adequately fit by either

the "diverted input" hypothesis (eq. 4.3) or the exponential integration model (eq. 4.5). The latter expression appears to be superior at durations approaching the integration time T (Moore 1982, 51).

However, there is some evidence that the single-time-constant model is inadequate at extremely short durations (below about 20 msec). In the data of Plomp and Bouman, for example, the rate of increase in the auditory threshold at these short durations was higher than the 3 dB per halving of the duration that is predicted by both of the single-time-constant models. Thus, it appears that the auditory system is unable to integrate all of the stimulus energy if its duration is too short.

Plomp and Bouman (1959) attributed this incomplete integration to the spreading of the impulse spectrum outside of the critical band at short durations. A similar deviation from the equal energy relation at short durations has been observed by Green et al. (1957) and by Poulsen (1978). One way to model this effect is to introduce an additional time constant into the exponential integration model, as will be seen below.

4.5.2.2. Two-Time-Constant Models. There are two different types of models of auditory temporal integration that involve two time constants. One of these types was developed to explain the results of temporal integration experiments on impulses of extremely short duration. These models have a response that depends on the impulse duration and are referred to here as the "duration" models. In the other type of model, here referred to as the "rise-fall model" the response to the rising edge of an impulse differs from the response to the trailing edge. The duration model is supported by the work of Zwislocki (1961), who has suggested the presence of several characteristic time constants in the

auditory system. The rise-fall model is an extension of the single-time-constant model of exponential integration with the inclusion of a peak detector and is the basis for the impulse sound level meter circuit. The duration models divide the range of impulse durations into three regions rather than two by the use of two time constants, T_1 and T_2 . For durations that far exceed the shorter time constant T_1 , the models predict the same behavior as the single-time-constant model with a time constant $T=T_2$; namely that the equal energy trading between duration and intensity will be followed for durations much less than the longer time constant T_2 , and that the loudness will be independent of duration for impulses whose duration is long compared to T_2 . The models attempt to account for the fact that the loudness of impulses with durations less than T_1 is lower than what would be expected on an equal energy basis.

The duration model proposed by Green et al. (1957) is based on the simple application of a straight-line fitting procedure to the trapezoidal "detectability versus duration" data that were obtained for equal-energy tone bursts. As was discussed in section 4.4.2, the detectability of an impulse of constant energy that follows the equal energy relation will be independent of duration, forming the plateau of the trapezoid. The two time constants, T_1 and T_2 , are defined as the durations at which the plateau commences and ceases. At durations shorter than T_1 , which was between 10 and 20 msec for most subjects, the detectability declined with a slope of 1.5 dB per halving of the duration. At durations longer than T_2 , which was between 100 and 275 msec for most subjects, the detectability declined at the rate of 1.5 dB per doubling of the duration.

One of the advantages of this model over the single time-constant exponential integration model is that it accounts for that fact that

impulses of duration ($t < T_1$) are less loud than would be predicted from the equal energy relation. However, the model also predicts an abrupt transition in the behavior at duration $t = T_2$ (the point at which the equal-detectability plateau ceases). The exponential integration model of Plomp and Bouman (1959) is a far more accurate description of temporal integration in this region.

Poulsen (1978) has developed a model that incorporates this exponential behavior at the transition from equal energy behavior to complete integration near T_2 . The model also predicts an exponential dependence for durations comparable to the short integration time T_1 . Poulsen's model was originally developed to explain deviations from equal energy behavior at short durations in his measurements on the loudness of isolated tone bursts, which were performed as an extension of the ISO-sponsored round robin study (Pederson, Lyregaard, and Poulsen 1977). He initially applied the single-time-constant model of exponential integration (eq. 4.5) to obtain the following relation between the levels of a burst of duration t and one of duration $2t$ at the PSE for loudness:

$$(4.10) \quad \frac{I_t}{I_{2t}} = \frac{(1 - \exp\{-2t/T\})}{(1 - \exp\{-t/T\})}$$

where T is the exponential time-constant. Using the fact that

$$(4.11) \quad 1 - \exp\{-2x\} = (1 - \exp\{-x\})(1 + \exp\{-x\})$$

eq. 4.10 can be rewritten as

$$(4.12) \quad \frac{I_t}{I_{2t}} = (1 + \exp\{-t/T\})$$

Thus far, this model is identical to the single-time-constant model of exponential integration, but it is expressed explicitly in terms of the ratio of the intensities obtained at the PSE when the duration of an impulse is doubled. At durations ($t \ll T$), this ratio approaches a value of 2 (3 dB) as expected.

Poulsen improved upon this model by assuming that auditory temporal integration in the vicinity of the short time constant, T_1 , and the long time constant, T_2 , has the same exponential dependence as the single-time-constant model, and that the two exponential terms are multiplicative:

$$(4.14) \quad S = kI(1 - \exp\{-t/T_1\})(1 - \exp\{-t/T_2\})$$

Thus, in analogy with eq. 4.10, the ratio between the sensory effect due to an impulse of duration t and that due to an impulse of duration $2t$ is:

$$(4.15) \quad \frac{S_{2t}}{S_t} = \frac{kI_{2t}(1 - \exp\{-2t/T_1\})(1 - \exp\{-2t/T_2\})}{kI_t(1 - \exp\{-t/T_1\})(1 - \exp\{-t/T_2\})}$$

Applying eq. 4.11 twice in the above expression yields:

$$(4.16) \quad \frac{I_t}{I_{2t}} = (1 + \exp\{-t/T_1\})(1 + \exp\{-t/T_2\})$$

Eq. 4.16 expresses the relation between the intensity (mean-squared pressure of a rectangular impulse) of an impulse of duration t and that of an impulse of duration $2t$ at the PSE. At durations short compared to both T_1 and T_2 , the two terms in eq. 4.16 each approach a value of 2, yielding an upper limit of 6 dB decrease in loudness level per halving of the duration, rather than the 3 dB predicted by the equal energy relation. At long durations ($t \gg T_1$), the term involving T_1 approaches

unity, and the dependence on duration becomes equivalent to that of the single-time-constant exponential model with time-constant $T=T_2$.

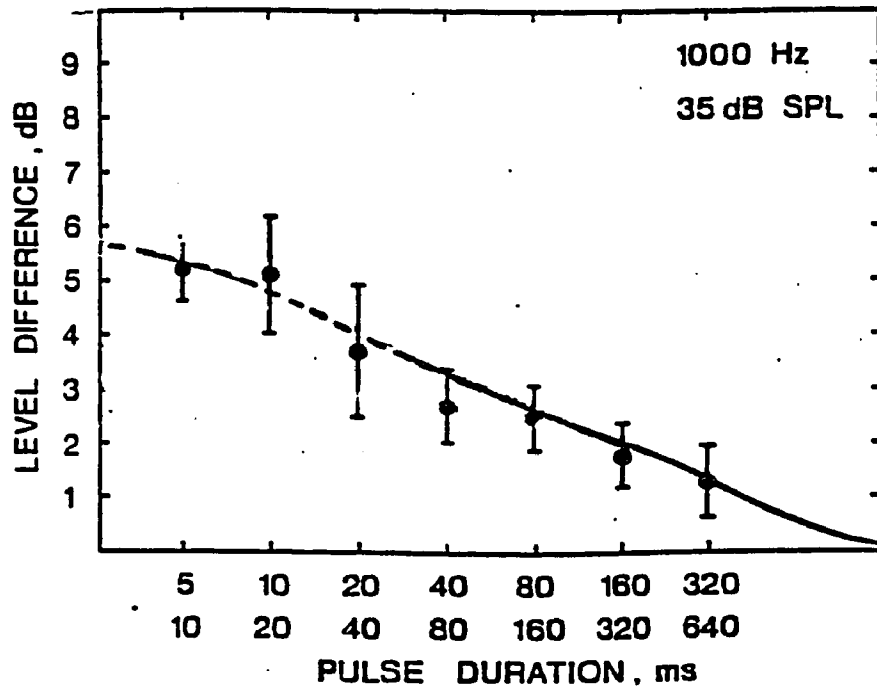


Figure 18. Agreement between the model and data of Poulsen (1978).

The agreement between the Poulsen model and the loudness data for 1-kHz tone bursts is shown in Figure 18. This model gave the best agreement with the data using integration time constants, T_1 and T_2 , of 10 msec and 100 msec, respectively. The change in loudness level per doubling of the impulse duration is plotted as a function of the durations (t and $2t$). Therefore, equal energy behavior appears as a value of 3 dB on the plot. Halving the duration from 10 to 5 msec, for example, decreased the loudness level by just over 5 dB rather than the 3 dB predicted by the single-time-constant model.

Thus, the "duration" models involving two time constants predict the loudness level of isolated tone bursts at a broad range of durations,

including the deviation from equal energy behavior both at durations less than the short time constant, T_1 , and at durations exceeding the long time constant, T_2 . However, there is not enough experimental evidence to determine which of the two duration models (the model of Green et al. (1959), or the model of Poulsen (1978)) provides the best overall description of temporal integration.

The other type of two-time-constant model, the "rise-fall" model, is equivalent to the single-time-constant model of Plomp and Bouman (eq. 4.5) except that the integration time constant depends on whether the input is increasing or decreasing in level.

A schematic diagram of the equivalent circuit for this model is shown in Figure 19. This circuit is identical to the single-time-constant RC circuit of Figure 17 except that an element consisting of a resistor, R_2 , in parallel with a diode has been added between the resistor, R_1 , and the capacitor, C . This element is the so called "leaky peak detector" that is used in the impulse sound level meter.

When voltage is applied to this circuit, the current flows in a forward direction through the diode, which has negligible resistance compared to R_2 . Thus, as long as the input signal is increasing, the voltage across the capacitor increases exponentially as in eq. 4.7 with a time constant R_1C . However, once the input signal begins to decrease (on the falling edge of the impulse), current must flow in a reverse direction through the peak detector. The impedance of the diode in the reverse direction is effectively infinite. Thus, if the resistor R_2 were not in the circuit, the capacitor would continue to hold the peak voltage until such time as the input level exceeded it again, i.e. it would function as a lossless peak detector. However, the shunt provided by R_2 allows the

capacitor to discharge. Since the current passes through R_1 and R_2 in series when flowing in the reverse direction, the discharge time constant for the leaky peak detector is $(R_1 + R_2) \times C$.

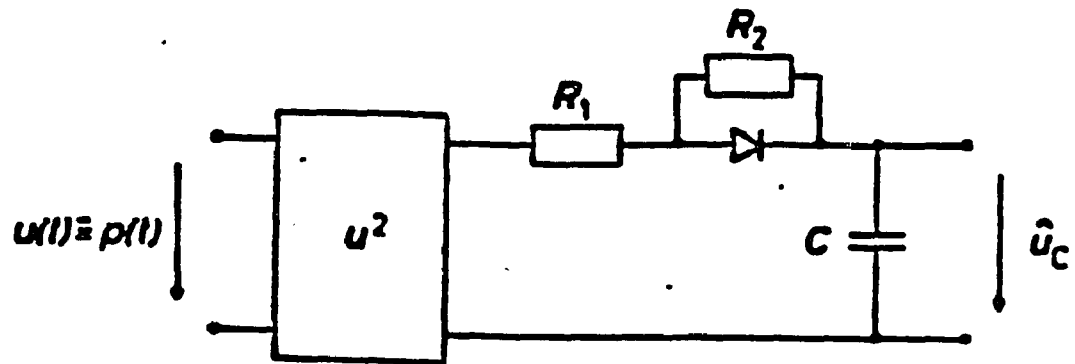


Figure 19. Two-time-constant RC Circuit model for the loudness of impulse noise (Port 1963a).

The net effect of the peak detector element on the performance of the circuit depends on the relative values of the two time constants. If R_2 is much greater than R_1 , the circuit will initially follow the behavior of the single time constant model, but then will hold for a comparatively long time at the highest peak level that was reached during the integration. This is how the impulse sound level meter performs.

However, in its original conception by Port (1963a, 1963b), the two time constants were designed to be comparable. In this case, the meter holds the peak level for such a short time that, if the input is a train of short impulses, the output will be a sawtooth pattern. The degree to which the circuit follows the rising and falling of an input train depends on values of the impulse duration and inter-impulse interval relative to the two constants. If the duration is less than either of the time constants, the peaks of the output will be much lower than the, input as

would be expected from the single-time-constant model. As can be seen from the simulations in figure 20, if the inter-impulse interval is short compared to the fall time constant, the output holds at a fairly constant level. If the inter-impulse interval is long compared to the time constant, the sawtooth returns to the base level between impulses.

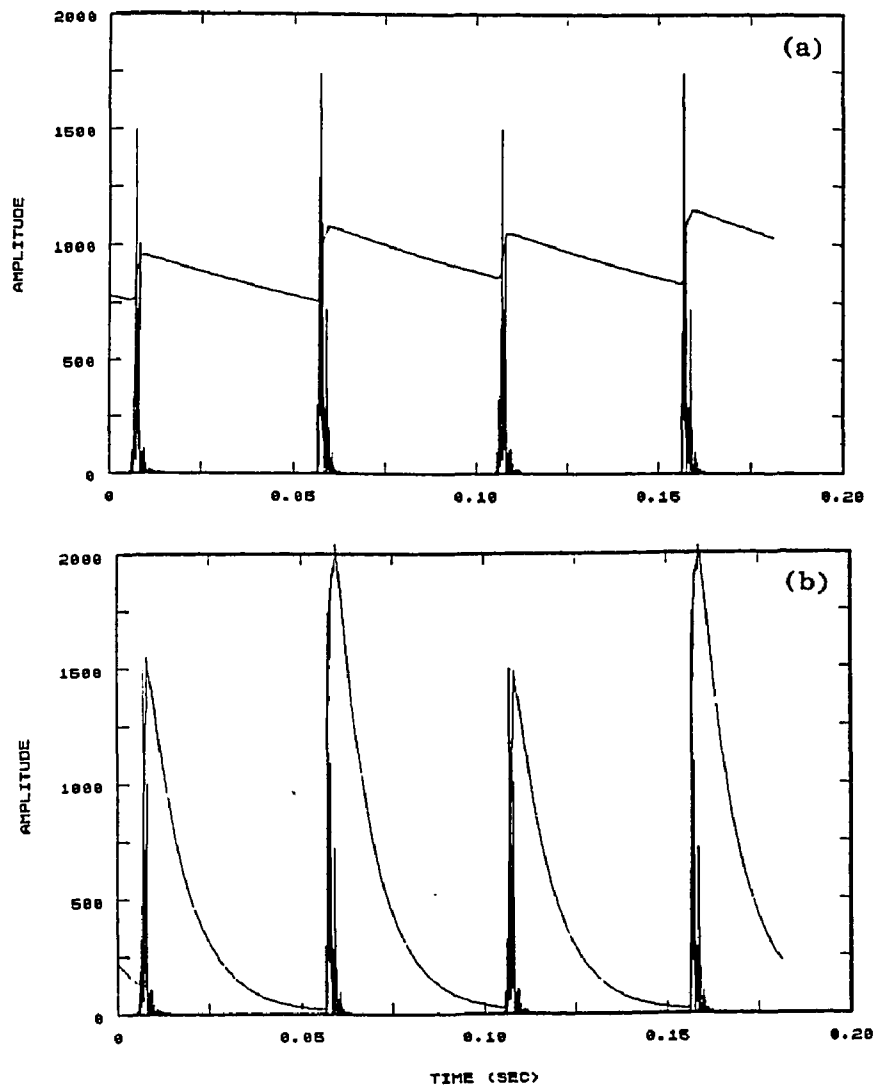


Figure 20. Simulated response of the rise-fall model with a short rise time to an impulse train: a, fall-time constant long compared to impulse repetition period; b, fall-time constant short compared to repetition period. The impulse train is identical in both a and b.

Thus, the rise-fall model is fundamentally different from the duration models in that the addition of the peak detector element simply allows the model to hold (for a time determined by the fall time constant) the peak level obtained during the loudness integration process as determined by the single-time constant formula with a time constant equal to the rise time. Under no circumstances does this model predict the behavior that has been observed at extremely short durations, which is explained by the duration models of Green et al. (1957) and Poulsen (1978).

The agreement between the rise-fall model and various experimental results was discussed in Chapter 2 in the context of the development of the impulse sound level meter circuit. Although most of the data from those experiments were adequately fit by an exponential integration model with a single time constant, the data of Port (1963a, 1963b) were best described by a rise-fall model with time constants of 70 and 200 msec.

The rise fall model is, in effect, applied with time constants of 35 msec and 1.5 seconds whenever loudness data are compared to readings obtained with an impulse sound level meter circuit. For example, in the ISO-sponsored round robin study (Pederson, Lyregaard, and Poulsen 1977), the subjective results were compared with objective measurements obtained with a variety of time and frequency weightings. The agreement between these measurements and the data is shown in figure 21. The log of the mean squared error for the isolated impulses is shown in figure 21a, and for the repeated impulses in figure 21b. (The agreement obtained using the loudness computation procedures of Stevens and Zwicker, also shown in the figure, will be discussed below). In the case of the isolated impulses, the agreement between the loudness data and the

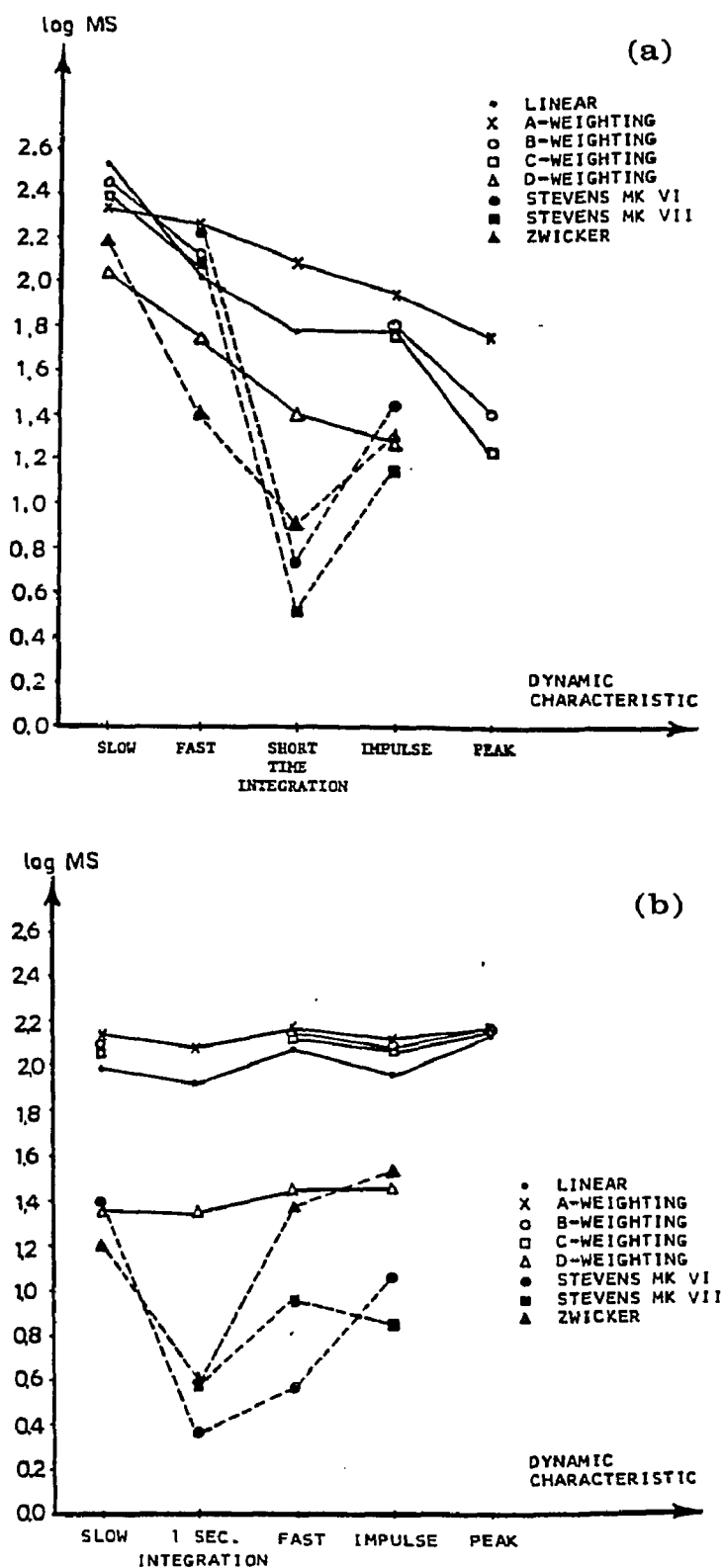


Figure 21. Agreement between the data of the ISO round robin study and various objective measures of the impulse noise stimuli: a, isolated impulses; b, repeated impulses (Pedersen, Lyregaard, and Poulsen 1977).

output of the impulse circuit with linear, C, or D weighting was superior to the agreement obtained with longer time constants, but even better agreement was obtained with the peak level peak level measurements obtained with these same frequency weightings. In figure 21b it is clear that the mean squared error for the quasi continuous impulse noises was even higher, and that the impulse circuit was no more successful than the other time weightings at predicting the subjective response.

The rise-fall model was applied with somewhat more success to the data on isolated impulses obtained by Namba et al. (1987) and on both isolated and repeated impulses by Kumagai et al. (1981). In the data of Namba et al. (1987), equal energy behavior was observed for impulse durations above 60 msec. However, at shorter durations, the loudness level increased more rapidly than would be expected from the energy law, but less rapidly than would be predicted on the basis of the peak level, when the duration was increased. These data were qualitatively predicted by the readings of the impulse sound level meter.

Kumagai et al. (1981) found that the loudness of isolated impulses so strongly on peak level, that increasing the peak level by 5 dB at constant energy yielded a 3 dB increase in loudness level. The best agreement with these data was obtained using a rise-fall model with a rise time of 5 msec, which approximated the peak levels of the impulses even more closely than would the standard impulse sound level meter, which has a 35-msec rise time.

Kumagai et al. (1984) extended the rise-fall model by proposing a model involving two rise-fall circuits, as shown in figure 22. The 16-dB attenuation was introduced into the model so that it could be applied to all types of stimuli ranging from continuous noise to isolated impulses.

Kumagai et al. (1984) obtained good agreement between loudness data for impulses ranging 60 to 1000 msec in duration at repetition rates varying from isolated impulses to 10 Hz and the predictions of this model.

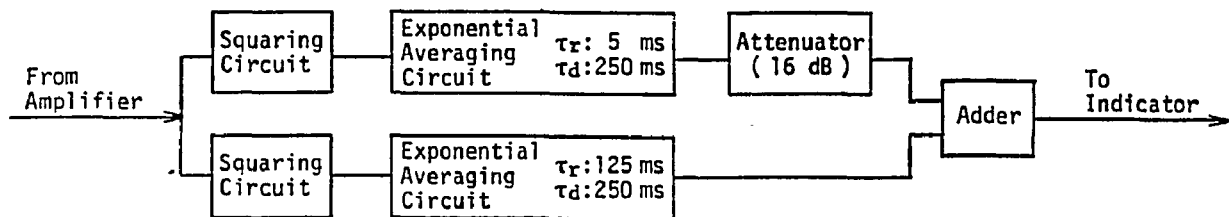


Figure 22. Model for the loudness of impulse noise using two rise-fall circuits (Kumagai, Suzuki, and Sone 1984).

However, as was seen in the earlier discussion, most of the data obtained on both isolated and repeated impulses in this range of durations indicate that the loudness is related to impulse energy and has little dependence on peak level. Thus these data are best fit by either the single time-constant model, or alternatively by a two time constant "duration" model rather than the "rise fall" model or its variants.

4.5.2.3 Physiological Models.

All of the models discussed so far are predicated upon relatively simple assumptions about the auditory system. Temporal integration is

assumed to behave according to certain laws, but the physiological rationale for these assumptions is not addressed. Although sophisticated models of the physiological processes of the auditory system have been developed, they have not generally been used to predict the psychoacoustical response to impulse noise.

However, one relatively simple model with physiological underpinnings has recently been developed by Namba et al. (1987), using the results of their own investigations of nonsimultaneous masking. The model predicts the loudness of isolated, type B impulse noise by estimating the effects of stimulus overshoot and suppression. A physiological excitation pattern is calculated and added to each impulse noise stimulus in order to obtain the total "physiological energy" of the test and reference stimuli used in the experiment. The agreement between the predictions of the model and the data is excellent for impulse durations from 2 to 128 msec.

4.5.2.4 Waveform Descriptors. An alternative means of modeling the response to impulse noise based on purely temporal factors is to use waveform descriptors such as those defined in section 2.3. The appeal of this approach is that these descriptors may be easily determined, allowing the assignment of a single number index of psychoacoustical aversiveness to any impulse noise. The challenge, of course, is to select the correct descriptor. As in the temporal integration models, the descriptor method ignores the spectral aspects of the noise except insofar as they are reflected by the time waveform. Ideally, one could define indicators based on those aspects of the waveform that reflect its important spectral aspects as well (e.g. focusing on the sharpness of a rising edge which

might also be an indicator of bandwidth). However, there is not a simple, one-to-one correspondence between the characteristics of impulse noise in the time and frequency domains. In practice, therefore, impulse noise descriptors have been developed and applied empirically. Typically, a correlation analysis is performed between the subjective data and the physical descriptors of the stimuli.

This approach has been used by the cooperating laboratories of the CEC project on impulse noise (Rice 1989), using the annoyance and impulsivity data discussed in section 4.4.4. Initially, Berry (1985, 1987) compared the results of the experiments on the annoyance of repeated, type B impulse noise with six different waveform descriptors of the test stimuli: kurtosis, $L_{AeqT} - L_{Aeq}$, crest factor, the ISO descriptor, and the standard deviation and salience indicators (see section 2.3). Both the kurtosis (Erdreich 1986) and the difference $L_{AeqT} - L_{Aeq}$ were ruled because of excessive scatter in the data. Particularly striking was the number of noises that were not impulsive according to the ISO criterion ($L_{AeqT} - L_{Aeq}$ less than 4 dB (International Standards Organization 1988)) but nevertheless had annoyance penalties exceeding three dB, as shown in figure 23. The four remaining descriptors were compared with the subjective data using a third-order polynomial fitting procedure. Of these four, the ISO descriptor agreed best with the subjective data.

In the next phase of the CEC project, data on the annoyance and impulsivity of real impulse noise stimuli (Berry 1989; Brambilla and Caretti 1988, 1989) were analyzed. In addition to the indicators mentioned previously, Berry (1989) also introduced and applied a new indicator, the "increment". Figure 24 illustrates the distinction between the increment and the salience indicators. Both are based on the short-

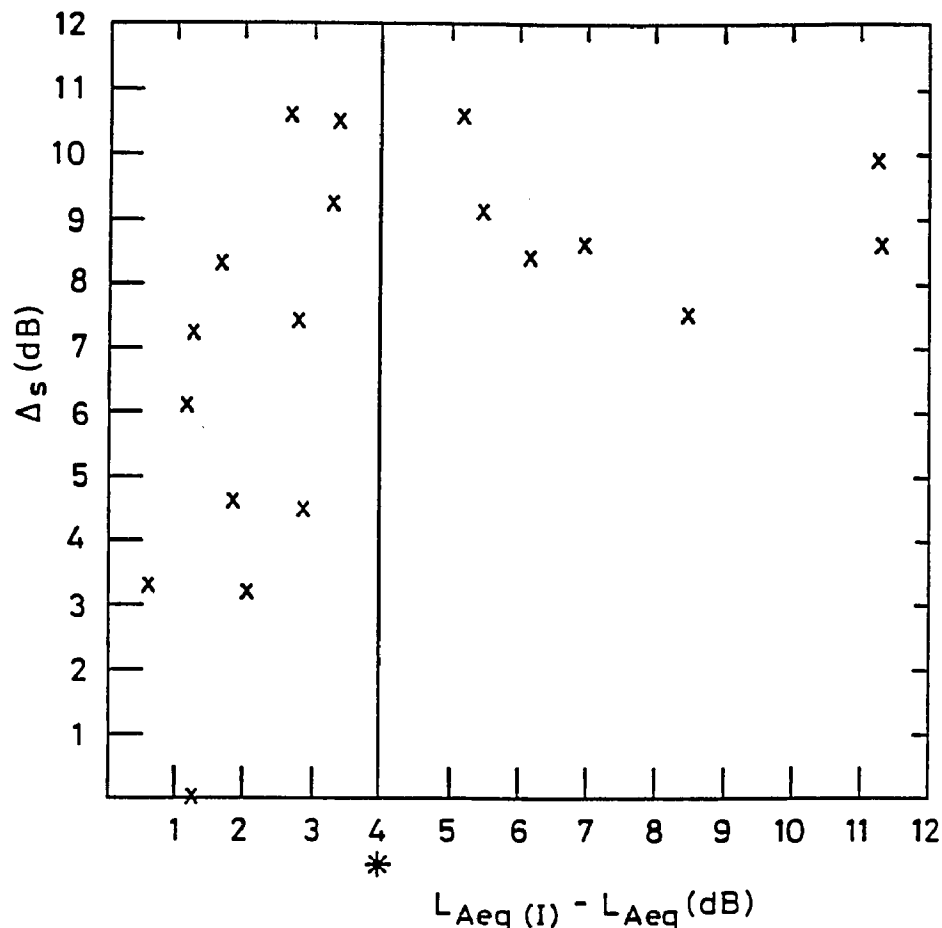


Figure 23. Agreement between the annoyance penalties and the impulsivity indicator $L_{Aeq(I)} - L_{Aeq}$ of the impulse noise test stimuli used by Berry (1977). The solid line represents the demarcation between impulsive and nonimpulsive noise according to ISO 7779 (1988).

L_{Aeq} (10 msec) time series. The salience is the difference between the maximum value of the L_{Aeq} (10 msec) time series and the average value in each one second interval (a crest factor, in essence). The increment is simply the largest difference between two successive values in the L_{Aeq} (10 msec) time series in each one-second interval.

The subjective data to which these indicators were applied consisted of responses to four separate questions about the annoyance and the impulsivity of the noise in the CEC study (Brambilla and Caretti 1988,

1989). All of the participating laboratories found a clear advantage to using the increment indicator. For example, the correlation between the increment descriptor and the "annoyance of the impulsive part of the noise" varied from 0.556 to 0.673, while the correlation with the other indicators was significantly lower. The increment indicator also performed best in predicting the impulsivity of the noises, and in predicting the overall annoyance of the stimuli, although the correlation coefficients for overall annoyance were quite low.

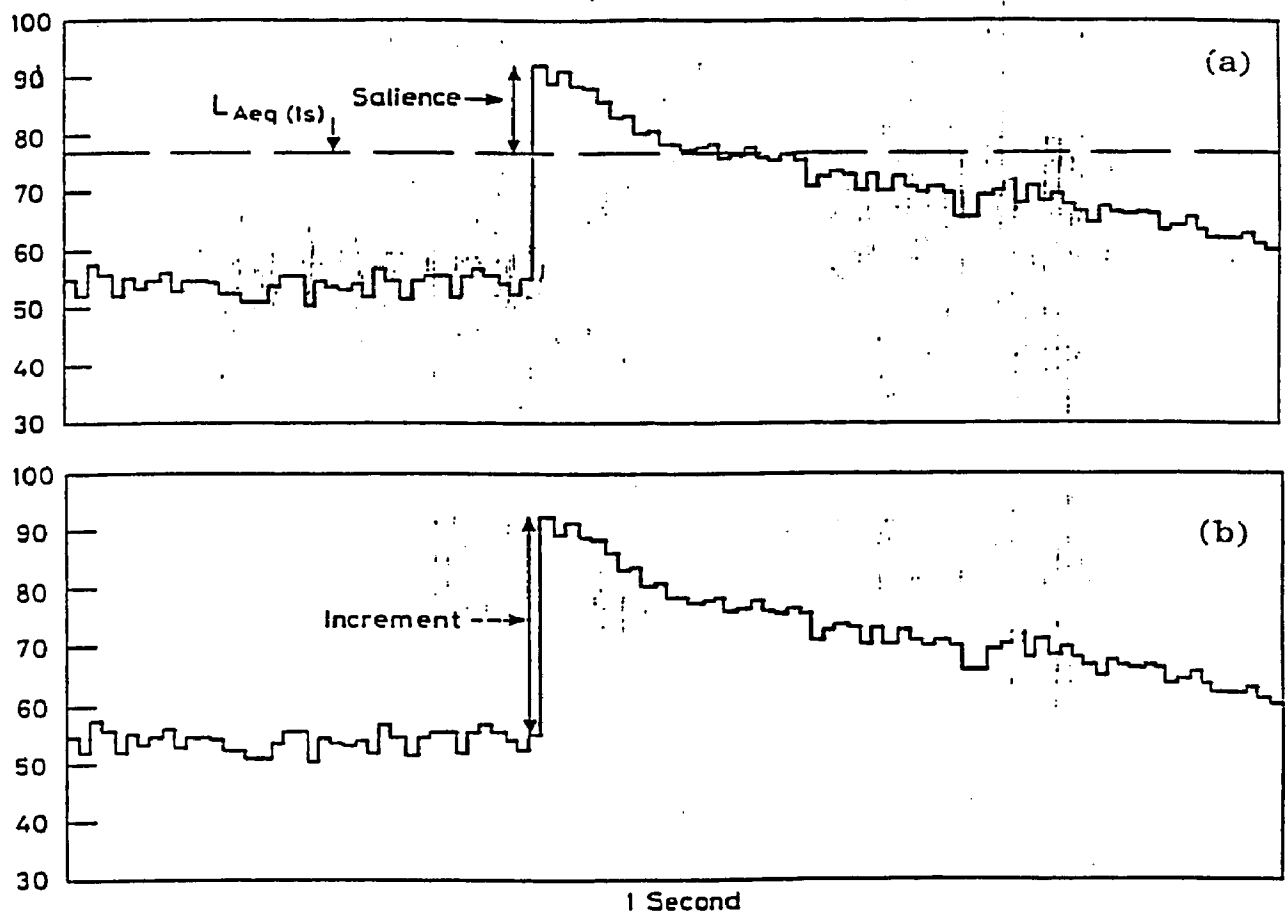


Figure 24. The increment and salience indicators of impulsivity (Berry, Wallis, and Rozwadowski, 1989).

4.5.3 Spectral Models

The two purely spectrally based loudness calculation procedures that have been applied to impulse noise most frequently are the methods of Zwicker (1960, 1984) and of Stevens (1971). Both of these procedures are designed to estimate the loudness of complex, steady-state sounds. The Zwicker procedure is applied to one-third octave-band spectra, which are intended to approximate the critical bands of the auditory system. The level in each one-third octave-band is adjusted to account for upward spread of masking in the cochlea. This procedure is performed either graphically (Zwicker 1960) or numerically (Zwicker 1984). Then, the adjusted levels are summed to obtain the total loudness level in phons.

The Stevens procedure (1971), on the other hand, is applied to octave-band spectra. The loudness is calculated using a sone scale relative to the loudness of a pure-tone reference. The model assumes that loudness has a power law dependence on the level in each octave band, that each band should be frequency weighted according to measured equal loudness contours, and that the band with the highest level will play a primary role in determining the loudness of complex sounds. The procedure has undergone several revisions during the past few decades. The improvements of the most recent version, Mark VII, over the Mark VI version include new frequency weighting curves and a change of the reference frequency for the sone scale to 3150 Hz.

The simplest means of applying either of the above methods to impulse noise is to treat the measured spectrum as though it were that of a steady noise. However, the choice of measurement time constant for the impulse spectrum can be critical. Both Port (1963a) and Reichardt (1965)

have suggested that the loudness of impulse noise be estimated by measuring the spectrum over a time interval corresponding to the rise time constant of the impulse sound level meter circuit (35 msec).

The results of ISO-sponsored round robin study on impulse noise (Pederson, Lyregaard, and Poulsen 1977) were compared to the predictions of both the Zwicker and the Stevens models, as shown in figure 21. The spectra were measured using a variety of time constants. The predictions of the loudness of the stimuli obtained from the Zwicker and Stevens models using these spectra were superior to those obtained from simple frequency and time-weighted level measurements for both isolated impulses (figure 21a) and repeated impulses (figure 21b). However, the time constants with which the best agreement was obtained differed for the two cases. The data on isolated impulses were best fit by the Stevens mark VII method using a "short" integration time (20-50 msec). The loudness of the repeated impulses, on the other hand, was best predicted by applying the Stevens Mark VII method to the spectrum measured with a 1-second (slow) time constant.

The methods of Stevens and Zwicker were applied to loudness data on type A impulse noise by Carter (1972). The loudness of the impulse trains was predicted from calculated spectra and compared to loudness predictions determined from the measured spectra of the steady reference noise stimulus. Both the Stevens and the Zwicker procedure overestimated the loudness of the impulse trains at low repetition rates (1-4 Hz), and provided agreement with the loudness data to within 3 dB at the higher repetition rates. However, the measured A-weighted sound pressure level predicted the loudness more accurately. The variation in loudness with rise time was not as well predicted by the Stevens method

as it was by either A-weighting or the Zwicker method.

A variation of the Stevens method has been used by Johnson and Robinson (1969) to predict the loudness of sonic booms. The modification was required because the spectra of sonic booms typically includes the high levels in the low-frequency bands (below 50 Hz). After applying a correction for the low frequency bands, the Stevens Mark VI procedure was used. The model was used to predict the loudness of sonic booms from a variety of aircraft.

A completely different approach to impulse noise characterization on the basis of spectral information has been developed by Bisping (1989) as part of the CEC project on impulse noise (Rice 1989). Bisping used the Prony technique (Kay and Marple 1981), which is fundamentally different from the Fourier analysis used to obtain conventional spectra, to predict the impulsivity of noise. Three measures of the Prony spectrum of the L_{Aeq} (10 msec) time series were developed and compared with subjective measures of impulsivity obtained on the same set of noises (Brambilla and Caretti 1988, 1989). These measures explained between 52 and 71 percent of the variance of the subjective data, compared to values ranging from 24-55 percent (Berry 1989) for the waveform descriptors discussed in section 4.5.2.4.

4.5.4 Mixed Temporal and Spectral Models

Recently, Sone et al (1989). proposed combining two of the models discussed above in order to fit their data on the loudness of trains of repetitive type B impulse noise (see section 4.4.4.2, above). They first applied the Zwicker loudness model to their impulse noise stimuli, then applied the "rise-fall" model of exponential integration with time

constants of 100 msec and 5 seconds to the frequency weighted spectrum, and then summed the components to obtain a loudness prediction. The effect of varying the repetition rate was accounted for by the following formula:

$$(4.9) \quad L_{PSE} = C \log (1+R/R_0) + L_{PSE0}$$

where L_{PSE} is the PSE for a noise of repetition rate R , L_{PSE0} is the PSE for an isolated impulse of the same duration and peak level, and the repetition, R_0 , which is determined graphically, represents the reciprocal of duration of the sensory effect due to the impulses. One of the unexplained features of this experiment is that the values of R_0 that were obtained imply a duration of the sensation of approximately three seconds, even though the measurements were of loudness, not noisiness. However, once the formula was applied, the data were well fit by the combination of the steady-state Zwicker procedure with the rise fall model.

Zwicker (1977) has extended his original steady state loudness calculation procedure to time varying sounds. Unlike the approach used by Sone et al. (1989), this model attempts to account for the dynamic behavior of the auditory system, including forward and backward masking as well as the dependence of auditory temporal integration constants on impulse duration.

The model was developed from temporal masking experiments, and from loudness data on impulse noise. The masking data were used to determine auditory masking patterns for transient sounds that are analogous to those of the steady state model. The time constants

for the increase and the decay of loudness sensation in each critical band are determined by the reciprocal of the critical bandwidth at low frequencies. A lower limit of 2 msec is set at the higher frequencies. The model performs a nonlinear conversion from band level to loudness level. The levels in each band are then summed, filtered, and rectified to yield a time-varying loudness function.

Recently, Berry and Zwicker (1986) applied a prototype loudness meter based on the time-varying Zwicker procedure to the noises that were used in the first phase of the CEC project on impulse noise (Berry 1987). A comparison was made between the loudness-time functions of the 10-msec impulses at repetition rates of 2 and 8 Hz at equal L_{Aeq} . It had been found previously that the annoyance penalty of the stimulus at the 8-Hz rate was about 3 dB higher than that of the 2-Hz stimulus.

Because the output of the transient Zwicker model is a time-varying function, it was unclear how to compare the results for the two stimuli. Since they were at equal equivalent sound pressure levels, the 2-Hz impulse noise stimulus had a much higher peak level than the 8-Hz stimulus, and consequently a higher peak value of the loudness time function, even though the 2-Hz stimulus was rated less annoying. It was found that the subjective data agreed with the "N₂₀" values of the loudness time functions, i.e. the loudness level that was exceeded 20 percent of the time. Since this choice of N₂₀ was based on obtaining agreement with a rather small data sample, and since the comparison was with annoyance data rather than loudness data, further testing of the transient Zwicker model seems to be indicated before it may be generally accepted.

CHAPTER 5

HYPOTHESES AND EXPERIMENTAL DESIGN

5.1 Hypotheses

The foregoing discussion demonstrates that attempts to develop a comprehensive loudness prediction method for impulse noise have not been entirely successful. There does not appear to be a single model or descriptor that accurately predicts the loudness of all types of impulse noise. One can conclude from the literature reviewed in Chapter 4 that characteristics such as the duration, repetition rate, spectral content, and envelope characteristics of the impulses, and the relative level of continuous background noise all interact in determining the total psychoacoustical impact. These variables are only partially incorporated into the various indicators defined in Chapter 2, and they are interrelated in a complex fashion. Moreover, there appear to be fundamental differences between the perception of isolated impulses and the perception of quasi continuous impulse noise.

The primary hypothesis of this study was that the point of subjective equality (PSE) for the loudness of quasi continuous impulse noise relative to a steady reference stimulus with a comparable spectrum (averaged over one second) could be predicted by a simple model. The elements of the model are parameters of the impulse waveform and the background noise. Using the model, the loudness of quasi continuous

impulse noise could be predicted in a two-step process. First, one of the steady-state, spectrally based loudness calculation procedures such as that of Zwicker (1960) would be applied to the measured time-averaged spectrum of the impulse noise. This would yield a loudness prediction (in phons) for the spectrally matched reference stimulus at the same equivalent continuous sound pressure level. Next, the model would be applied to predict the additional increase or decrease in loudness level that would occur due to the temporal features of the impulse noise.

An additional hypothesis was that the spectral shape of the background noise would affect the loudness of the impulse noise, and that this factor could be incorporated into the model.

5.2 Experimental Design

5.2.1 Overview

Loudness was selected as the quantity to measure because it is less dependent on non-acoustic factors than are noisiness or annoyance, and it appears to be the dominant component in noisiness and annoyance judgments. Because this study focused on high-repetition-rate, quasi continuous impulse noise, it was decided to use the type B impact waveform rather than the type A (N-wave) impulse waveform that is characteristic of isolated explosions or sonic booms in free field conditions.

Another key decision was whether to use tone bursts or noise bursts. In actual practice, impact noise is somewhat of a hybrid between the two. The loudness of tone bursts has been more extensively studied than the loudness of broadband noise bursts. Broadband noise was chosen for this experiment because its time-averaged spectrum (over

a period greater than the impulse repetition period) is relatively unaffected by amplitude modulation (Miller and Taylor 1948). Moreover, broadband noise bursts appear to be more representative of actual sources in the field, both spectrally and temporally, than are tone bursts. Furthermore, the background noise in the settings in which type B impulse noise occurs, such as industrial sites, is typically broadband rather than tonal. It seemed that subjects would be more likely to treat the quasi continuous impulse noise as a fused unit if the impulses and the background noise were spectrally similar.

Since the impact (type B) waveform was chosen, the classic impact waveform with exponentially decaying envelope was used (see figure 1b). The impulses were produced by numerically gating broad-band, Gaussian noise. The gating envelope was a double-sided exponential with a 500 μ sec rise time.

$$\begin{aligned}
 (5.1) \quad E(t) &= \exp \left(\frac{t-t_0}{T_r} \right) & t < t_0 \\
 &= \exp \left(-\frac{t-t_0}{T_f} \right) & t \geq t_0
 \end{aligned}$$

where t_0 is the time at which the impulse reaches its maximum level, and T_r and T_f are the rise and fall time constants, respectively. The explicit rise-time of 500 μ sec was included in the envelope because otherwise the rise-time would have been controlled by the random behavior of the digitized Gaussian noise that was used to produce the impulses. In principle, the rise time could have been as short as the time interval between successive samples of the digitized Gaussian source noise (which

was 22.7 μ sec) if the amplitude of the source noise were high just at the onset of the impulse. As was seen in chapter 2, a 500- μ sec rise time is typical of type B impulse noise. It is also significantly shorter than any of the fall-times used in the study, as will be seen below, so that the classic type B envelope shape (sharp rise followed by a long exponential decay) was preserved.

The durations and repetition rates of the impulses were varied by changing the fall time, T_r , and the occurrence times, t_o , of the envelope function. These gated impulses were then digitally mixed with the spectrally shaped, steady Gaussian background noises at several different peak-to-background ratios. The study was divided into two experiments. In experiment 1, the repetition rate, duration, and peak-to-background ratio of white noise impulses with steady white background noise was studied. The spectral shape of the background noise was varied in the second experiment.

In addition to the two main experiments, two sets of measurements on steady noises were designed, one involving steady white noise at different levels, and the other using the spectrally shaped steady background noises at a single level. The white noise measurements were planned in order to check the calibration of the testing system. The steady background noises were studied as a baseline for experiment 2, in which these noises were combined with impulse noise.

5.2.2 White Noise Calibration

The calibration stimuli were identical to the steady white noise reference except that they were synthesized with different amplitudes.

Thus, when presented at the same playback level parameter (same gain) as the reference stimulus, the stimuli differed in level by increments of three dB over a range from 48 to 72 dB L_{eq} . This range was chosen because it was assumed that the levels to which the stimuli were adjusted by the subjects in order to reach the point of subjective equality (PSE) with the reference stimulus would fall within plus or minus 12 dB of the reference level, and therefore it was essential to establish linearity over that range.

In principle, it was possible to perform exact loudness balances between the calibration stimuli and the reference stimulus because they were identical in all respects except for their amplitude. If the testing system was linear, the change in playback level parameter (in dB) of each test stimulus required to achieve PSE with the reference stimulus should correspond exactly to the magnitude of the initial level difference between that test stimulus and the reference stimulus. Therefore, the results of these loudness balances would provide baseline data on any bias in the testing system as well as on the variability and repeatability of the results.

5.2.3 Steady Background Noise Stimuli

Four steady background noise stimuli with different spectral shapes were used in this experiment. These four stimuli were mixed with impulse noise in order to produce the test stimuli for experiment 2. The frequency ranges of the background noise stimuli are given in table 1. The steady white background noise stimulus was identical the reference stimulus except that separate sequences (sampled at different times) were used.

TABLE 1
FREQUENCY RANGES OF STEADY BACKGROUND NOISES

Spectral Shape	Lower Freq. Limit	Upper Freq. Limit
White	20 Hz	20.0 kHz
Low-pass	10 Hz	3.15 kHz
Band-pass	500 Hz	3.15 kHz
High-pass	2 kHz	20.0 kHz

5.2.4 Experiment 1

The first experiment was intended to explore the loudness of white impulse noise stimuli with steady, white background noise as a function of impulse repetition rate, impulse duration, and the peak-to-background ratio of the background noise. The repetition rates and durations were chosen in order to explore the transition between isolated impulses and quasi continuous impulse noise. The peak-to-background ratios were intended to cover the range from an effectively background free condition to a condition where there was a psychoacoustically significant amount of background noise.

The first main decision involved the selection of the repetition rates to be used in this experiment. Most of the previous work on impulse trains has involved low repetition rates (0.25-10 Hz) and relatively long durations (50-500 msec). However, some impulse sources, particularly impact printers and typewriters, operate at much higher repetition rates. Moreover, since the goal of this study was to explore the loudness of impulses in the transition region between isolated impulses and continuous noise, repetition rates ranging from 5 Hz (effectively isolated impulses) to 100 Hz were selected in order to span this region. The range of durations that could be used at each repetition rate was constrained by two factors. First, if there was too much overlap between the impulses,

the noise would be less impulsive, as reflected by measures such as crest factor and kurtosis which, regardless of their psychoacoustical utility, do provide a physical measure of the impulsiveness of the noise. Second, one of the important aspects of this design was to vary the peak-to-background noise ratio over a range of 30 or 40 dB. Too much overlap between the impulses would make it impossible to generate impulse noise with the higher peak-to-background ratios. This concern set an upper limit on duration ranging from about 2 msec at 100 Hz to 40 msec at 5 Hz. At the other extreme, if the impulses were too short, there would have been too much variability in peak levels of the digitized signals due to the small number of data points within the envelope (44/msec). The practical lower limit was about 1.5 msec with a 500 msec rise time under these conditions.

The above constraint on the overlap between the impulses suggested that the use of a parameter related to the product of repetition rate and duration might be a convenient way to compare the data obtained under different conditions. For example, the overlap constraint yielded a maximum allowable duration of 2 msec at 100 Hz and 40 msec at 5 Hz. In both cases, the product of the repetition rate and the fall-time constant of the impulses is the same (0.2), while the absolute durations and repetition rates are quite different.

Conventionally, the product of the repetition rate and the duration (or equivalently, the ratio between the duration and the repetition period) of a train of rectangular impulses is referred to as the "duty factor" because it is a measure of the percentage of time that the signal is "on duty" during a given interval. However, in cases where the time-waveform of the repetitive signal is not rectangular, a more accurate duty

factor may be calculated by computing an effective duration, i.e. the duration of a rectangular impulse having the same energy and peak level as the impulse, and multiplying this effective duration by the repetition rate.

The effective duration of an impulse is obtained by integrating its squared pressure envelope and dividing by the peak level, I_P .

$$(5.2) \quad t_{eff} = \frac{1}{I_P} \int_0^{\infty} p(t)^2 dt$$

In the case of an isolated impulse occurring at time t_0 , with peak pressure, P_P , and an exponentially decaying envelope characterized by a decay time, $T_\#$,

$$(5.3) \quad p(t) = P_P \exp\{-(t-t_0)/T_\#\}$$

it can be shown that the effective duration equals the decay time constant of the mean-squared pressure envelope, which is one-half the decay time constant of the pressure envelope, T_r . The squared pressure envelope is given by

$$(5.4) \quad p(t)^2 = I_P \exp\{-2t/T_\#\}$$

where I_P is the square of the peak pressure of the envelope, and the time t_0 at which the envelope peaks has been set to zero for convenience. Therefore, the effective duration is:

$$(5.5) \quad t_{eff} = \frac{1}{I_P} \int_0^{\infty} I_P \exp\{-2t/T_\#\} dt$$

Evaluating this integral yields:

$$(5.6) \quad t_{eff} = \frac{1}{I_p} \left[-\frac{T_f}{2} (0 - I_p) \right] = T_f/2$$

The effective durations of the impulse trains used in the experiments (in the absence of background noise) were quite close to one-half the decay-time constant of the pressure envelope because there was little overlap between impulses.

The effective duration of a single impulse in a train of repeated impulse may also be defined by eq. 5.2 but with the repetition period of the impulse train, $\tilde{T}$, substituted as the upper limit of the integration. Therefore, the duty factor, DF, (product of repetition rate, F, and effective duration) may be written:

$$(5.7) \quad DF = \frac{F}{I_p} \int_0^{\tilde{T}} p(t)^2 dt$$

where $\tilde{T}$ is the repetition period of the stimulus.

With the above constraints on maximum and minimum impulse durations in mind, the repetition rates and durations of the test stimuli were chosen to allow comparisons on the basis of the duty factor of the impulses. Table 2 shows the combinations that were chosen, together with duty factors computed from the effective durations of the stimuli according to equation 5.4. As is clear from the table, these envelope functions have three distinct duty factors (within a few percent). All three values are represented at 20, 10, and 5 Hz, while only the two higher factors were feasible at 50 Hz, and the highest at 100 Hz, because of the considerations mentioned above. With this range of duty

TABLE 2
PARAMETERS OF IMPULSE NOISE TEST STIMULI
FOR EXPERIMENT 1

Repetition Rate (Hz)	Duration (msec)	Duty Factor
100	1.5	0.105 (High)
50	1.5	0.055 (Medium)
50	3.5	0.987 (High)
20	2.0	0.025 (Low)
20	5.0	0.055 (Medium)
20	10.0	0.105 (High)
10	5.0	0.028 (Low)
10	10.0	0.053 (Medium)
10	20.0	0.103 (High)
5	10.0	0.026 (Low)
5	20.0	0.051 (Medium)
5	40.0	0.101 (High)

factors, peak-to-background ratios of up to 30 dB were attainable. In most cases, it would have been possible to increase to a 40 dB peak-to-background ratio. However, from pilot work that had been performed, it was clear that there would have been little or no perceptible difference between 30 and 40 dB. Moreover, the indicators such as kurtosis and crest factor that were calculated for the two conditions were not different enough to warrant studying an additional level of the peak-to-background ratio parameter. The lower limit on the peak-to-background ratio was taken as 10 dB, because at levels below 10 dB the kurtosis values and crest factors of the test stimuli approached that of the steady background. The full series of 36 stimuli (12 rate-duration combinations at 3 peak-to-background ratios) was studied at a reference level of 60 dB Leq.

5.2.5 Experiment 2

The second experiment was designed to explore the effects of the spectral shape of the background noise. It was assumed that the background noise might either reduce loudness through a masking

process, or add to the loudness of the impulses, depending on the spectral shape of the background noise and on the relative importance of the different regions of the frequency spectra of the impulses in determining their overall loudness. Four different conditions were selected in order to test this assumption: white noise, and high pass, band pass, and low pass filtered white noise. The frequency ranges of the filtered noises were listed in table 1. These noises were added at peak-to-background ratios of 10 and 20 dB. The 30 dB peak-to-background ratio was not used because it corresponded to an essentially background-free condition. A subset of the rate-duration combinations of experiment 1 were studied at a reference level of 60 dB L_{eq} .

5.3 Selection of Test Method

The advantages and disadvantages of a variety of psychoacoustical testing procedures were briefly discussed in section 4.3. Clearly, the experiments described above involve the performance of suprathreshold loudness determinations. The first decision was whether to use a classical method (e.g., the method of adjustment), a scaling procedure, or an adaptive technique. Since the goal was to develop a model based on the loudness of a steady state sound of comparable spectrum, a scaling procedure was ruled out. If loudness scaling were to be used, it would be necessary to obtain data on the steady, white reference stimulus and use that data to convert all the loudness measurements to a difference in L_{eq} between the test stimuli and the reference stimuli at the PSE. With the classical method of adjustment or an adaptive technique, the difference in L_{eq} between the test and reference stimuli at PSE would be obtained directly. Ideally, these differences could then be correlated with

the differences obtained using a simple model based on physical measures of the stimuli.

The next decision, therefore, was whether to use a classical method of adjustment or an adaptive procedure to determine the PSE (see section 4.3). This decision was straightforward because of the advantages of the adaptive method for efficiency and the possibility of automating the testing procedure. A simple two-alternative forced-choice (2AFC) up-down method was chosen rather than a transformed procedure so that the 50 percent point on the psychometric function (i.e. the conventional PSE) would be determined. In order to improve efficiency, a variable step size was used in a manner similar to the PEST procedure. The step size was not increased after two negative responses, but it was decreased upon reversal (see section 7.3.1 for full details of the testing program).

The number of reversals in each trial was set at five, which is a compromise between obtaining an accurate estimate of the PSE and keeping the testing time to a minimum. After eliminating the first reversal level, which usually deviates from the PSE by an unacceptable amount, the reversal levels were averaged to obtain the means of each run between the minima and maxima of the subject's responses.

Another concern was whether or not appropriate test and reference stimulus durations could be selected in order to avoid the measurement problems mentioned in section 4.3.2. Ideally, the stimulus durations in a 2AFC up-down method should be short enough that the psychoacoustical impression due to the first stimulus in each pair does not fade appreciably during the presentation of the second stimulus. Otherwise, there is a systematic difference in the results depending on the presentation order, here termed the "sequence effect", which was

discussed in section 4.3.1. On the other hand, the durations must be long enough that the psychoacoustical impression is fully built up during the presentation. For example, the data reviewed in Chapter 4 suggest that noisiness builds up over a period of 5 seconds or more, leading to stimulus durations that are unworkable for a 2AFC paradigm. In the case of loudness, however, full integration appears to occur within 250-500 msec, and certainly within 1 second, for all of the stimuli that have been studied.

It was also shown in Chapter 4 that problems can arise if the durations of the test and reference stimuli are very different, especially if the durations exceed the integration time for loudness and the data are reported in terms of sound exposure levels. Quasi continuous impulse noise lends itself well to the 2AFC method chosen here because the impulse noise test stimuli and the steady reference stimulus can be short bursts of identical overall duration.

With these considerations in mind, the stimulus duration chosen for this study was 1.05 seconds. This time included a gated rise and fall time of 25 msec to prevent a click at the onset and offset of the stimulus. The timing of the impulses in the train was adjusted so that the gating envelope was at its maximum when the first impulse in the train was presented. An interstimulus interval of 250 msec was selected because it was as short as possible (to minimize the sequence effect) but exceeded the measured time constants for forward and backward masking (Moore 1982). Further details of the testing procedure are given section 7.3.3.

CHAPTER 6

SYNTHESIS AND CHARACTERIZATION OF IMPULSE NOISE STIMULI

6.1 Overview

The majority of experiments on the psychoacoustical effects of impulse noise have been performed on two classes of stimuli: real environmental impulse noise, and idealized impulses produced by either analog or digital methods in the laboratory. Stimuli obtained by the former method generally do not vary systematically, making it difficult to study the effect of varying a single parameter. Synthetic impulse noise stimuli are more controllable, particularly if the synthesis is performed digitally, but the results of the studies on synthetic stimuli may not be as easily generalized to practical situations. This is particularly true in the case of the tone burst stimuli that have been used for much of the research on impulse noise psychoacoustics. In this study, the use of a broadband noise source was combined with digital synthesis techniques so that the temporal and spectral parameters of the impulse noise stimuli could be varied as independently as possible, while closely simulating the physical characteristics of impulse noise. Specialized hardware was assembled and software was written to generate the impulse noise test stimuli, which were characterized using a variety of techniques.

6.2 Synthesis of Impulse Noise

6.2.1 Overview

A system based on the IBM Audio Capture and Playback Adapter (ACPA card or Audio card) and an IBM PS/2 Model 50 computer was used to synthesize the impulse noise test stimuli. The stimuli were generated numerically from source noises (filtered steady Gaussian white noise) that had been digitally recorded by the audio card. The recorded source noises were read into an APL2 workspace (a numerical language environment in which programs may be written and run without compiling) and converted from binary to decimal form. These source noises were then normalized, gated and mixed to produce the impulse noise test stimuli. Various waveform statistics were recorded during the synthesis and the completed stimuli were reconverted into binary form and stored on diskettes. The details of the audio card and other apparatus, the associated APL2 programs, and the synthesis technique will be described below. Printouts of the APL2 programs that were written to perform the synthesis may be found in Appendix B.

6.2.2 Details of the Synthesis System

A block diagram of the synthesis system is shown in figure 25. The audio card consists of a Texas Instruments TMS320C25 digital signal processing chip, several memory registers, and analog-to-digital (ADC) and digital-to-analog (DAC) converters with 16-bit resolution and a sampling rate of 88.2 kHz. The incoming signals are digitized and transferred to a region of shared memory on the audio card. The computer has access to the digitized signals over the bus. The process is reversed for playback. The card can be programmed in assembly language to perform digital signal processing on the stored data.

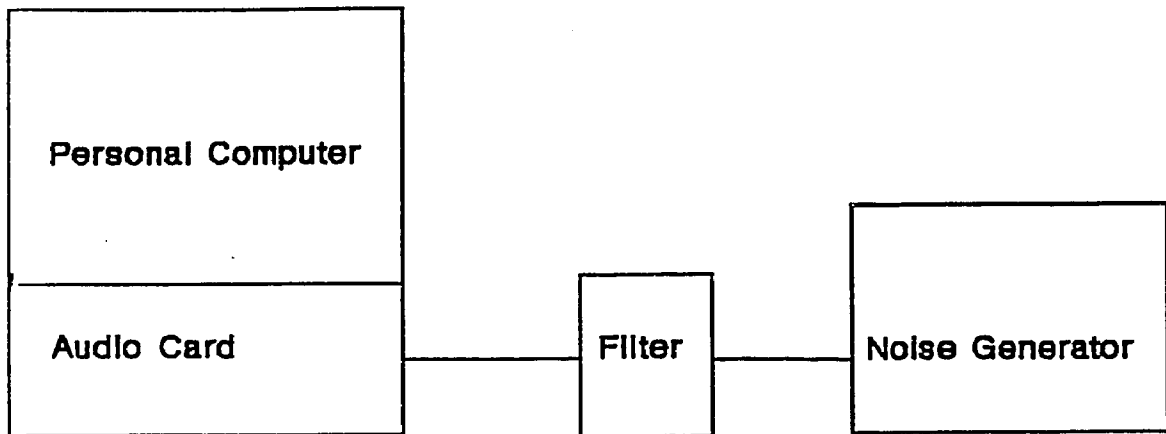


Figure 25. Block diagram of synthesis system

In order to manipulate the data in the audio files, an IBM C software package (The Audio Application Program Interface, or AAPI) was used as an interface to the audio card. The AAPI consists of a compiled C library containing subroutines for creating audio data files, prototype functions for playing and recording audio data, and digital signal processor code to drive the audio card. The functions were used to record the source noises for the synthesis, and to listen to the results. The play function code was incorporated into the psychoacoustical testing program that will be described in Chapter 7. Because the AAPI package was used, the audio card was essentially operated as a ADC/DAC rather than a signal processor. It contained an anti-imaging filter at 20 kHz (3 dB per octave) and interpolation and decimation routines so that the effective sampling rate in the computer was 44.1 kHz rather than 88.2 kHz. Normally, the AAPI performs pulse code modulation (PCM) to save disk storage space,

but this also reduces the effective sampling rate to about 11 kHz (and hence, the useable bandwidth to about 5 kHz) and complicates the data encoding. Therefore, a version without PCM was used.

In order to record and play data with the audio card, a "virtual disk" must be defined in the extended random access memory of the computer since the hard disk is unable to keep pace with the TMS320C25 data transfer. Because the data are uncompressed, each 16-bit data point requires 2 full bytes of storage and therefore each second of (monophonic) recording uses about 90 kilobytes. The AAPI actually creates two files with the same filename but different extensions when recording: a large "escape" file (with the file extension `!.ad`) that contains records of audio data separated by brief headers, and a separate header file (with the file extension `!.au`) with information about the data. Both files are then copied to the hard disk or diskette for storage. The header files are not used in the synthesis, but each data file must retain its corresponding header file for playback. The data files are in binary form with twos-complement notation. In each byte, the most significant bit is first, but the order of the two bytes that comprise each 16-bit value is reversed, i.e. the least significant byte is first. The structure of the data files is as follows:

Initial Header	-	42 words	(84 bytes)
Record 0	-	551 words	(1102 bytes) all zeros
Header	-	13 words	
Record 1	-	551 words	- first real data
Header	-	13 words	
Record 2	-	551 words	

and so on for the rest of the file. The sampling rate is 44.1 kHz, which corresponds to 22.7 μ sec per data sample. Thus each record of 551 samples has a duration of 12.494 msec. Eight records comprise 0.099955

seconds and form a string of 4408 samples when read into APL2. This is the largest string that could be handled conveniently in APL2 on the computer. Therefore, the synthesis was performed in units of eight records (approximately 0.1 seconds) at a time. The synthesis method is explained in more detail in the next section.

6.2.3 Synthesis Method

The steady source noises were produced by a General Radio Model 1382 noise generator and an Ithaco Model 1282 band-pass filter set with a slope of three dB per octave. The filter settings for the white noise that was used to produce the impulses were 20 Hz and 20 kHz. The low-pass filtered noise had a low-frequency cut-off of 10 Hz and a high-frequency cut-off of 3.15 kHz. The band-pass filtered noise was produced by setting the filters at 500 Hz and 3.15 kHz. The high-pass filtered noise had a low-frequency cut-off of 2 kHz and a high-frequency cut-off of 20 kHz. These source noises were recorded on audio tape using a Sony Model WM6-DC cassette deck. The line output of the tape deck was later used as the input to the audio card in order to transfer the noises into audio data files on the computer. This did not introduce any extraneous noise because of the high signal levels on the audio tape. However, it was observed that, when the noises were recorded by the audio card, there was an initial offset in the ground level of the digitally recorded noises, which declined to zero during the first 100 msec of recording. In order to eliminate this artifact, the first eight records of each audio data file were eliminated by transferring the rest of each file into a new "dummy" file. (The dummy files were readily created by recording on the audio card with no input.)

The final result was five audio data files of approximately 1.5 seconds duration: the steady white reference noise (which was also the noise that was gated to produced the impulse noises) and the four steady background noises described above. The white background noise sample was taken from a different portion of the recording than the white reference stimulus so that it would not be correlated with the impulses. A sine wave for calibration purposes was also synthesized. As opposed to the customary calibration frequency of 1 kHz, the frequency of the calibration tone was chosen so that each record of audio data would contain an integral number of cycles in order to simplify the synthesis. Therefore a frequency of 800.363 Hz was used for the calibration tone.

The way in which the impulse noise stimuli were synthesized from the steady noise source files is illustrated schematically in figure 26. The source noises were read into APL2, decoded from binary to decimal form, numerically gated, mixed with the desired level of background noise, renormalized, re-encoded into binary, and then written into dummy audio data files. In the ensuing discussion of the procedures that were followed, the names of the APL2 subroutines are included (in upper case) to facilitate referral to the APL2 programs in Appendix B.

The first step in synthesizing the impulse noise stimuli was to select an appropriate RMS level for the signals such that even those with the lowest duty factor and the highest peak-to-background noise ratio would not exceed the 16-bit range of the DAC. A 16-bit range corresponds to a range of values from -32,768 to +32,767. After some trial and error, a mean squared level of 2.5×10^6 (i.e. an average magnitude of 1,580) was chosen because this yielded a peak level of approximately 20,000 for the impulses that had the highest peak levels (i.e. the shortest impulses

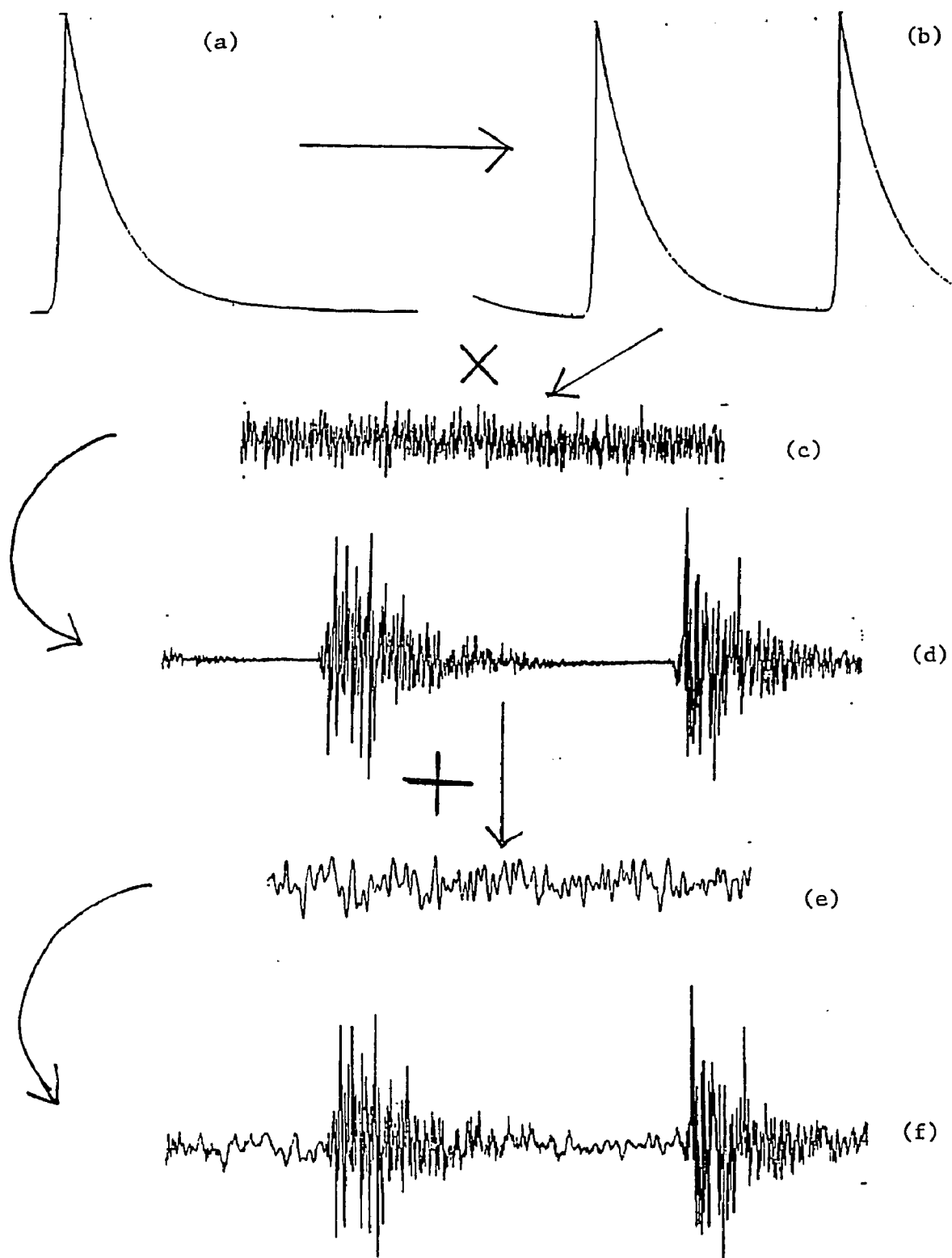


Figure 26. Schematic illustration of the synthesis process: a, envelope of single impulse; b, gating envelope produced by superimposing the single impulse envelope at the desired occurrence times and renormalizing; c, steady white source noise is multiplied by gating envelope (b) to produce impulse train, d; e, desired level of background noise is added to yield final result, f.

at the lowest duty factor). Thus most of the range of the D/A was used, but there was no risk of peak clipping.

The five recorded noise samples and the sine wave were then adjusted to this mean squared level of 2.5×10^6 . Several 0.1 second samples of each noise file were read into APL2 (using the GETIMP program), and the average of the RMS levels of these samples were calculated (using the PRMS program). The normalization factor was obtained by taking the square root of the ratio of the actual RMS level and the target level of 2.5×10^6 . The IMPIO program was used to transfer each steady noise into the a new file with an RMS level of 2.5×10^6 by setting the BASE parameter to 1 (i.e. all background noise, no impulses) and the FACT parameter to the normalization factor that had been calculated for each noise.

Once the noise samples were normalized, the main synthesis program, NEWIO, was used to generate impulses and mix them with the appropriate background noise. As was mentioned in Chapter 5, the gating function was a double sided exponential:

$$\begin{aligned}
 (5.1) \quad E(t) &= \exp \left(\frac{t-t_0}{T_r} \right) & t < t_0 \\
 &= \exp \left(-\frac{t-t_0}{T_f} \right) & t \geq t_0
 \end{aligned}$$

where t_0 is the occurrence time of the impulse. The envelope parameters were the repetition rate, the burst rise-time constant, T_r (500 μ sec), and the burst fall-time constant, T_f .

Before starting the NEWIO program, the background level and overall normalization parameters had to be determined for each noise

stimulus. This was done by calculating the envelope function that would be used to gate the white noises (thus forming the impulse part of the noise) using the SINTH program. The program operated on units of 0.1 second at a time because, with the sampling rate of 44.1 kHz, using longer sequences was impractical in APL2. Since all of the noise stimuli, (with the exception of those at a 5-Hz repetition rate) had a gating envelope that repeated every 0.1 second, working with 0.1-second segments was practical. Minor changes had to be made in the programs to synthesize the 5-Hz stimuli.

The gating envelope was a normalized superposition of double-sided exponentials, each of which had the form given in eq. 6.1. The duration was controlled by varying the fall time, T_r . The repetition rate was controlled by setting the occurrence times, t_o , of the impulses (using the TOS parameter in the program). For example, for a 20 Hz repetition rate, the TOS parameter was set to 0.025 and 0.075 seconds, since two impulses in 0.1 second would correspond to 20 impulses in 1 second. In cases where the impulse decay time was long enough that the decaying exponential envelopes from the previous 100 to 200 msec might not have completely fallen to zero, those previous intervals were included in the calculation. For example, for the 10-Hz repetition rate and 20-msec duration, the occurrence time parameters that were used were 0.025 and -0.125 seconds. The SINTH program summed all of the impulses in the 0.1-second interval and normalized the result to a peak value of unity.

Once the envelope had been synthesized, both the background level needed to obtain the desired peak-to-background ratio and the overall normalization constant needed to obtain a mean squared level of

2.5x10exp6 were determined using 0.1 second samples of the steady white source noise and the chosen steady background noise. (Ideally, the entire noise sample should have been used, but this would have been extremely time-consuming. Instead, the 0.1-second sample with an RMS level closest to the RMS level for the entire sample (2.5x10exp6) was used in each case). The MAX and SFACT programs were used to set the parameters efficiently. The MAX program calculated the peak-to-background noise ratio using a 1-msec sample of the first impulse envelope peak, and a 1-2 msec sample located in a valley between peaks. The background level parameter was adjusted until the desired peak-to-background ratio was achieved. Then, the correct overall normalization for the impulses plus the background noise was calculated using the SFACT program.

After the parameters were set, the source and target files were opened and the NEWIO program was called. For each 0.1-second segment, the NEWIO program read in a 0.1-second segment of the white source noise, multiplied it by the impulse envelope function, and then read in and added a 0.1-second segment of the desired background noise. This was performed record by record; there were eight records in each 0.1-second segment (see section 6.1.3). Waveform statistics such as the RMS level, kurtosis, and crest factor were calculated (using NEWSTAT) and stored in a matrix. The envelope waveform was retained but different impulse and background noise sequences were used for each 0.1-second segment. Each segment was then encoded into twos-complement binary notation and written into the prerecorded audio "dummy" file. The completed stimuli were transferred to the hard disk and to backup diskettes for use in the experiments. Some modifications were required to

synthesize the 5-Hz stimuli because the impulses were placed only in every other 0.1-second interval. The APL2 programs used for this were FIVIO, MAX5, and SETFACT, (see Appendix B), but the principles are the same. The program, NEWBIO, was written to allow synthesis of two stimuli at a time as long as the parameters were identical for both with the exception of the background noise level. This program saved considerable computer time.

6.3 Calibration

The calibration of the playback system used for the experiments served several purposes. It was necessary to confirm the relation between the input voltage to the headphone and the resulting sound pressure levels, to verify that the output of the audio card and headphone varied linearly with playback level parameter on the audio card, and to confirm that the impulse were not being distorted by the headphone. It was also of vital importance to be able to correlate the value of the playback level parameter of each impulse noise stimulus with its physical level. As will be seen below, this was not a trivial problem.

A block diagram of the calibration set-up is shown in figure 27. The phono output of the ACPA card was connected directly to the TDH-49 headphone used in the experiments. A Bruel and Kjaer 1 inch microphone (Model 4132) and cathode follower were installed on a Bruel and Kjaer Model 4151 artificial ear (6 cc coupler). The follower output was connected to the microphone input of a Norwegian Electronics NE-830 analyzer. The analyzer gain was set with a pistonphone (124.0 dB at 250 Hz). Then the headphone was placed on the coupler and covered with a 500 gram weight. The calibration tone was reproduced by the audio card

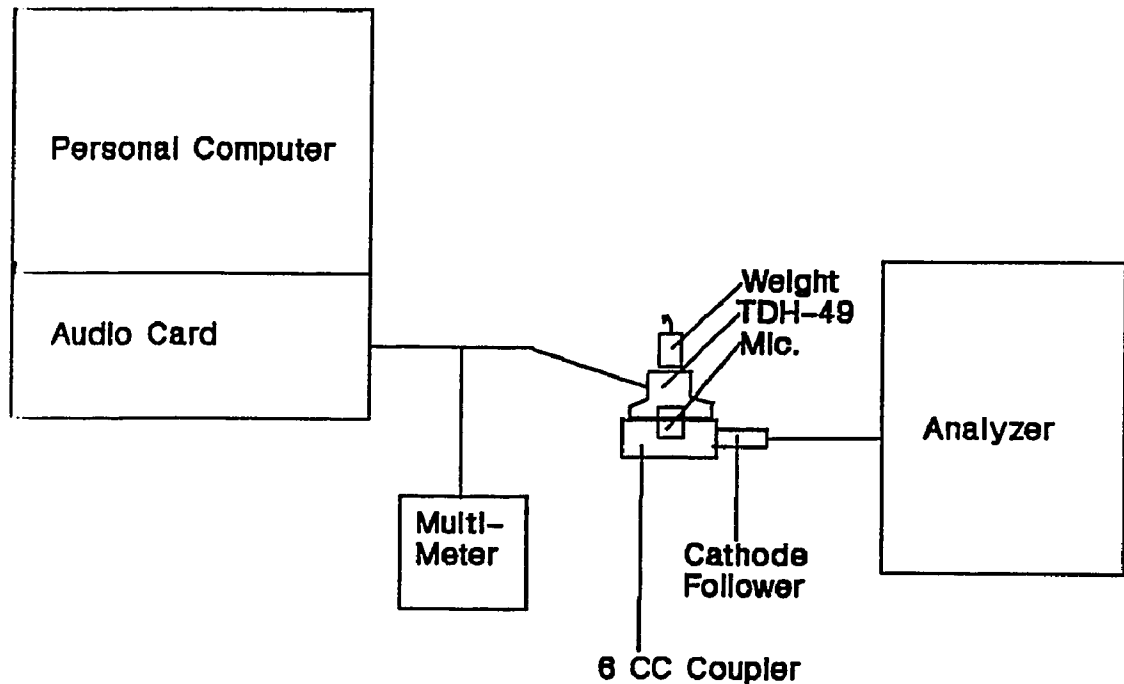


Figure 27. Block diagram of calibration apparatus.

at different playback levels and the level in the 800-Hz one-third octave-band was measured on the NE-830 analyzer. The voltage across the headphone was monitored with a Hewlett Packard 3438A digital multimeter. At a playback level of "89" (10 dB above that used in the experiments), the level in the 800-Hz one-third octave-band was 72.3 dB. The one-third octave-band spectrum of the sine wave is shown in figure 28. The voltage across the headphone was 3.29 mV. This is in good agreement with the calibration given by the manufacturer of the TDH-49

headphone of 115 dB at 500 mV, which would yield 71.4 dB at 3.29 mV.

At this stage, the upper limits of the output of the system were checked in order to ensure OSHA regulations on the levels of potentially damaging levels of noise would be complied with at all times during the testing of the subjects. First, the voltage across the headphone was measured while reproducing one of the test stimuli at full volume (playback level parameter = 100). The voltage across the TDH-49 headphone when connected to the phono output of the audio card was 10 mV, which yields an output of 81 dB SPL with the TDH-49 headphone on a standard 6 cc coupler. Thus the ceiling on the average level of the impulses that could be produced on this system (using the synthesized waveforms with an RMS value of 2.5×10^{-6} and the phono output to the TDH-49 headphone) was 81 dB SPL.

Next, the maximum peak output was checked with a sine wave that employed the full 16-bit range of the ADC. This sine wave produced a 100 mV signal on playback which corresponded to 101 dB SPL through the headphone on a 6 cc coupler. Since the peak level of a sine wave is 3 dB higher than its RMS value, this meant that the maximum peak level was 104 dB SPL. Current OSHA regulations limit the level of an eight-hour daily noise exposure to 90 dBA and the peak level of impulses to 140 dBA (Kundert 1977). Thus the stimuli used in the experiments were below the OSHA limits by a wide margin even for extended test sessions. (In order to reduce the levels of 60 Hz noise from the audio card, the line output from the audio card was amplified and used in the experiments rather than the phono output. However, the gain was adjusted so that the conditions mentioned above were still met.)

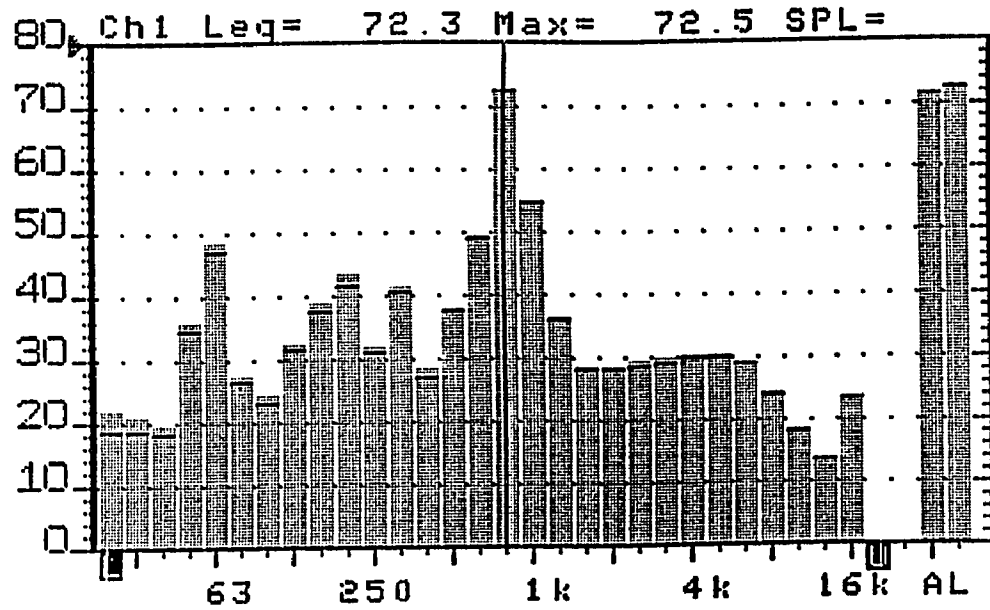


Figure 28. One-third octave-band spectrum of calibration tone.

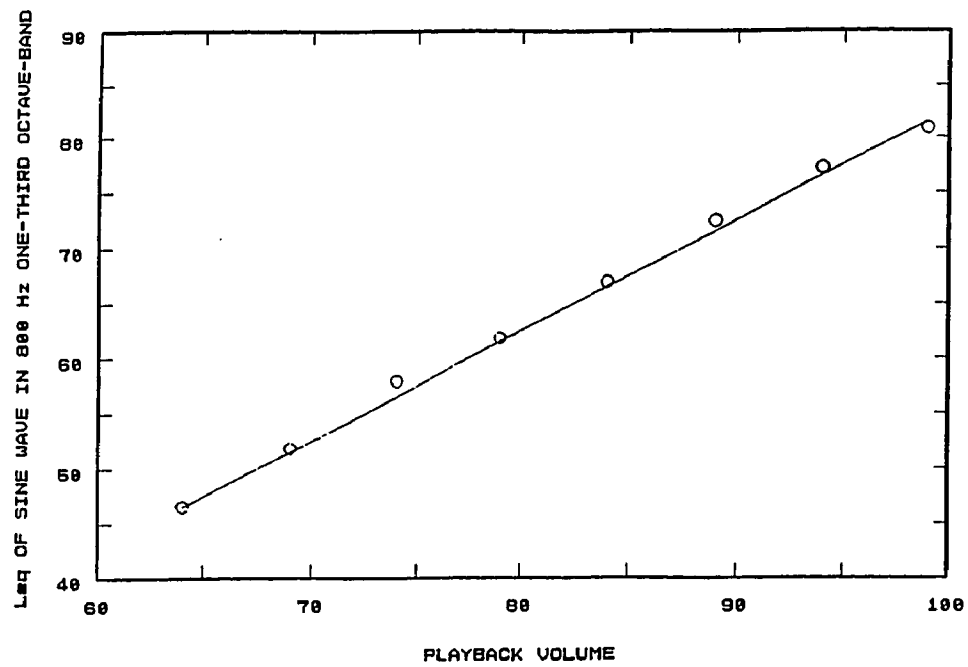


Figure 29. Level of calibration tone (in 800 the Hz one-third octave-band) as a function of the playback level parameter of the audio card.

Next, the pressure-time waveforms of some of the more extreme impulse noise test stimuli were examined with a high speed oscilloscope, which confirmed that the headphone was not distorting the waveforms.

The linearity of the output of the audio card was verified by reproducing the calibration tone at a variety of levels and examining the level of the tone in the 800-Hz one-third octave-band, as well as the overall equivalent sound pressure level, L_{eq} . Over a 30-dB dynamic range, the output was quite linear, as is shown in figure 29. At lower levels, the background noise from the audio card began to interfere with linearity in the overall L_{eq} due to strong components in the 63-kHz one-third octave-band, while the level in the 800-Hz one-third octave-band continued to track linearly with playback level.

The next step was to calibrate the level of each of the impulse noise stimuli used in the experiment, i.e. to correlate the value of the playback level parameter in the testing program with the physical level L_{eq} produced by the headphone for each stimulus. There were two reasons to do this. First, even though the stimuli were synthesized at approximately equal RMS levels, there was slight variability because the parameters were selected based on a 0.1-second sample rather than the entire stimulus. Second, even if the RMS levels of the stimuli had been adjusted to be exactly equal during synthesis, the adjustment was performed with a full 20 kHz bandwidth, while the frequency response of the headphone dropped sharply at approximately 7 kHz.

Ideally, the above calibration should have been done with the headphone and a 6 cc coupler, so that the effect of the drop in the frequency response of headphone above 7 kHz could be measured exactly. However, there was too much low-frequency background noise in the

laboratory where the calibration was performed to get accurate measurements on the coupler. Therefore, this part of the calibration was performed using an electronic filter (Ithaco 4142) to simulate the frequency response of the headphone.

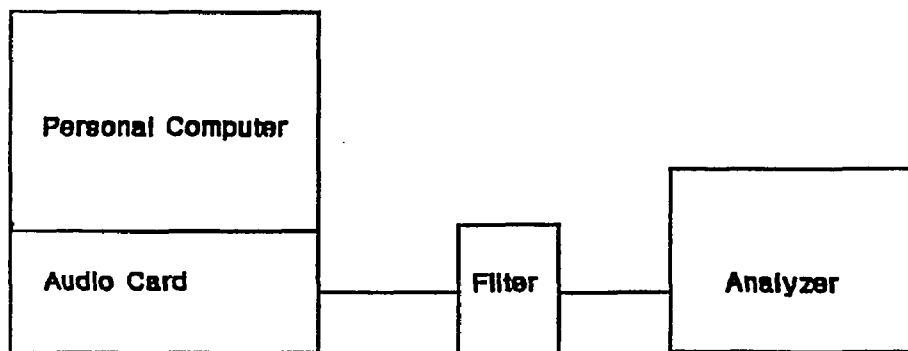


Figure 30. Apparatus used for converting playback level parameter to equivalent continuous sound pressure level.

The apparatus used for this stage of the calibration is shown in figure 30. The analyzer was recalibrated for line input from the audio card through the filter, (rather than a microphone input from the 6 cc coupler) using the 800-Hz calibration tone. The gain of the analyzer was adjusted so that the level of the 800-Hz calibration tone in the 800-Hz one-third octave-band was the same as had been measured previously through the headphone and coupler at the same playback level. The frequency response of the headphones was simulated by setting the Ithaco Model 4142 low-pass filter to 6.3 kHz with a slope of 24 dB per octave. Figure 31 shows a comparison between the one-third octave-band

spectra of the steady white noise reference stimulus as measured from the 6 cc coupler, and from the line input to the analyzer (after recalibration) with the Ithaco filter in place. The headphone clearly rolls off more sharply than the filter, but the difference between the two is only a few dB in the region where the filter and the headphone roll off (6.3-12 kHz).

Using this apparatus, the one-third octave-band spectra of all of the impulse noise test stimuli and the steady background noise stimuli were measured to determine the correspondence between playback level and actual L_{eq} (one-second measurement time, 250 msec "fast" time constant). The measured L_{eq} of the steady white reference noise at the playback level, V_0 used in experiments 1 and 2 was 60.5 dB. Almost all of the other stimuli used in the experiments had L_{eq} levels (at this same playback level) within 0.5 dB the reference level, but a few deviated by as much as 1.5 dB.

The results of these measurements were used to convert the experimentally determined playback levels of the stimuli at the point of subjective equality (PSE) to L_{eq} levels. For example, suppose that the measured L_{eq} level of a particular impulse noise test stimulus was 60.1 dB, (rather than the 60.5 dB of the reference stimulus), at the playback level, V_0 . If the measured playback level of the test stimulus at the PSE was 2.3 dB above the reference playback level, V_0 , a value of 2.3 dB would be added to the measured L_{eq} level of that test stimulus at V_0 , 60.1 dB, to obtain an L_{eq} at PSE of 62.4 dB.

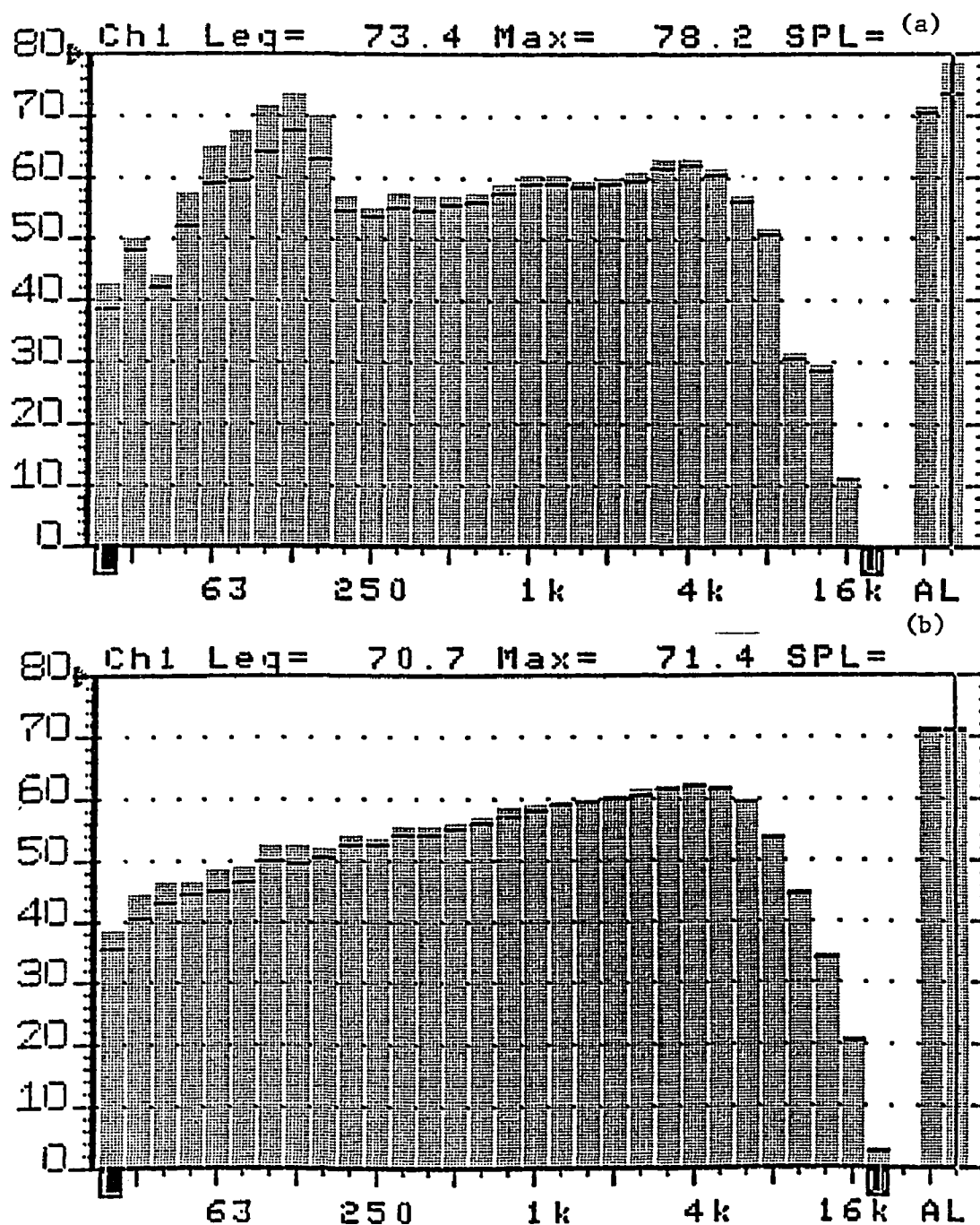


Figure 31. Simulation of the frequency response of the TDH-49 headphone. *a*, one-third octave-band spectrum of white noise measured using 6 cc coupler as shown in figure 25. *b*, one-third octave-band spectrum of white noise measured with Ithaco filter to simulate headphone, using the apparatus shown in figure 30.

6.4 Characterization of Impulse Noise Test Stimuli

6.4.1 Procedures

The physical characterization of the impulse noise test stimuli included the following procedures: measurement of one-third octave-band spectra and calculation of loudness according to ISO 532B (1975); and calculation of the following impulse indicators: peak level, crest factor, kurtosis, $L_{eqT}-L_{eqI}$, and $L_{AeqT}-L_{AeqI}$ (see Chapter 2). All measurements of the test stimuli were performed at the levels that corresponded to those measured in the experiments. For example, if the mean L_{eq} level at PSE (all subjects, all trials) for a particular stimulus in one experiment was 61.4 dB, the input levels and analyzer gain were adjusted so that the measured L_{eq} was also 61.4 dB.

The pressure-time waveforms were plotted directly from the digitized stimuli. The one-third octave-band spectra were measured using the NE-830 analyzer with the apparatus shown in figure 30. These spectra were saved and used as the input to a BASIC program that calculated the loudness level of each stimulus according to ISO 532B (1975) as if they were steady noises. One-third octave-band spectra with the impulse time constant were also obtained for all of the test stimuli so that the indicators $L_{AeqT}-L_{AeqI}$ and $L_{eqT}-L_{eqI}$ could be calculated.

Calculation of the crest factor and kurtosis indicators were performed in APL2 during the synthesis of each test stimulus. As each the synthesis was performed, record by record, the decimal values of the stimulus were saved and appended in segments of approximately 0.1 seconds (eight records or 4408 points). The indicators were calculated on each segment, stored in a matrix, and then averaged over all twelve

segments. In the case of the impulse noise test stimuli at a 5-Hz repetition rate, however, the segments were paired so that the indicators could be calculated on a 0.2-second segment. The maximum and minimum levels and the RMS level were also computed for each segment, and saved and averaged over all segments.

The peak levels of the impulse noise test stimuli were estimated using the results of sine wave calibration that had been performed previously. The peak amplitude of each test stimulus in digital form was estimated by averaging the maximum and minimum values of each 0.1-second segment (or 0.2 seconds, for the 5-Hz repetition-rate stimuli). The L_{eq} of the sine wave was known as a function of playback volume from the calibration, and therefore its peak level, which is 3 dB above the RMS level, was also known. The difference (in decibels) between the peak level of the digitized impulse noise and the digitized sine wave was computed, and this difference was added to the known peak level of the sine wave to obtain the peak level of the impulse noise at the headphones. This procedure was accurate except that it did not account for a possible lowering of the peak levels due to the high frequency cut-off of the headphones.

6.4.2 Results

The results of the characterization of the test stimuli are summarized in tables 3 and 4 and in the figures of Appendix C. Table 3 summarizes the parameters of all the impulse noise test stimuli used in experiment 1, (gated white-noise impulses with steady white background noise), including L_{eq} , L_{Aeq} , the impulse indicators $L_{AeqI}-L_{Aeq}$ and $L_{eqI}-L_{eq}$, and the crest factor, kurtosis, and loudness according to ISO 532B

(1975). Table 4 shows the same information for the stimuli with the high-pass, low-pass, and band-pass filtered steady background noise that were used in experiment 2.

The time-waveforms and one-third octave-band spectra of the four steady background noises are shown in figures 61 to 64 of Appendix C, and the results of the loudness computations by the Zwicker method are in figure 60. Figures 65-100 of Appendix C show the time-waveforms of the impulse noise test stimuli used in experiment 1. The spectra of these stimuli were too similar to one another to warrant presentation of all of the spectra. The one-third octave-band spectra of a subset of these noises are shown with the spectra of the stimuli used in experiment 2. Figures 101-124 of Appendix B show the time waveforms of the impulse-noise stimuli with spectrally shaped background noise. The one-third octave-band spectra of all the impulse noise test stimuli used in experiment 2 (including those with steady white background noise) are shown in figures 125-156 of Appendix C. The loudness computations according to ISO 532B (International Standards Organization 1975) are shown in figures 157-164. (The complete set of loudness graphs for the impulse noises with white background noises is not shown because of the similarities in the spectra.)

TABLE 3
CHARACTERISTICS OF IMPULSE NOISE TEST STIMULI
WITH WHITE, STEADY BACKGROUND NOISE

Rep. Rate	Dur. (msec)	Peak/ Backg	Leq -Leq	LAeq -LAeq	LeqI	LAeqI	Peak	Kurtosis	Crest Fact. (dB)	Loudness
100	1.5	10	59.8	60.0	1.0	0.8	76.5	6.0	15.6	13.9
		20	59.2	59.3	1.4	1.3	77.8	12.5	17.4	13.3
		30	58.3	58.3	1.4	1.4	77.2	13.8	17.7	12.5
50	1.5	10	60.2	60.2	1.2	1.1	78.2	7.7	17.0	14.3
		20	61.2	61.2	1.9	1.9	81.7	22.7	19.6	15.2
		30	58.9	58.9	2.4	2.4	80.2	27.6	20.0	13.1
50	3.5	10	60.0	60.1	1.2	1.1	77.0	6.6	15.8	14.1
		20	60.5	60.5	1.4	1.4	79.1	12.8	17.1	14.5
		30	60.0	60.1	1.7	1.5	79.0	14.2	17.3	14.1
20	2	10	60.6	60.7	2.0	1.9	79.6	9.1	16.9	14.6
		20	62.2	62.3	3.7	3.6	85.0	40.8	20.6	16.3
		30	63.6	63.7	4.1	4.0	87.1	57.0	21.5	17.9
20	5	10	61.0	61.1	1.9	1.7	79.2	8.2	16.5	15.0
		20	61.4	61.5	3.0	2.9	82.3	22.5	19.1	15.4
		30	61.1	61.2	3.0	2.9	82.4	26.6	19.6	15.2
20	10	10	61.2	61.3	1.8	1.7	78.5	7.1	15.8	15.3
		20	61.6	61.7	2.5	2.4	80.7	12.9	17.5	15.6
		30	60.9	61.1	2.4	2.3	80.1	14.1	17.7	15.0

TABLE 3. cont.

Rep. Rate	Dur. (msec)	Peak/ Backg	Leq -Leq	LAeq -LAeq	LeqI	LAeqI	Peak	Kurtosis	Crest Fact. (dB)	Loudness
10	5	10	60.2	60.3	1.5	1.3	78.6	5.9	15.8	14.3
		20	62.6	62.8	4.0	3.8	84.6	31.1	23.0	16.8
		30	63.2	63.3	4.8	4.6	86.8	49.8	24.1	17.4
10	10	10	60.2	60.4	2.3	2.1	78.4	7.5	16.5	14.3
		20	62.0	62.1	3.8	3.6	83.1	23.2	19.5	16.1
		30	61.9	62.0	3.9	3.7	83.5	27.9	20.2	16.0
10	20	10	60.8	60.9	2.1	2.0	78.2	6.7	15.8	14.8
		20	61.7	61.9	3.2	3.0	80.9	13.3	17.7	15.8
		30	61.2	61.4	4.1	4.0	80.5	14.5	17.9	15.3
5	10	10	60.7	60.8	1.4	1.3	78.1	4.4	15.8	14.7
		20	61.7	61.8	2.8	4.8	84.9	29.1	21.8	15.8
		30	63.1	63.2	6.1	6.1	87.3	53.0	23.2	17.3
5	20	10	60.5	60.6	1.7	1.6	77.4	4.4	16.3	14.5
		20	61.4	61.5	4.4	4.3	82.3	17.2	18.8	15.4
		30	61.6	61.7	5.3	5.2	83.7	26.8	21.2	15.6
5	40	10	60.2	60.3	1.9	1.8	77.1	4.5	15.8	14.2
		20	61.0	61.2	3.9	3.7	80.5	11.7	18.2	15.1
		30	61.1	61.3	4.3	4.2	80.6	14.2	18.9	15.2

TABLE 4
CHARACTERISTICS OF IMPULSE NOISE TEST STIMULI
WITH FILTERED, STEADY BACKGROUND NOISE

Rep. Rate	Dur. (msec)	Peak/ Backg	Leq -Leq	LAeq -LAeq	LeqI	LAeqI	Peak	Kurtosis	Crest Fact. (dB)	Loudness
Band-pass										
100	1.5	10	59.9	60.3	1.1	0.9	77.0	6.3	15.5	13.7
		20	59.5	59.6	1.4	1.3	78.3	12.9	17.5	13.6
50	3.5	10	61.1	61.5	1.1	0.9	77.0	6.1	15.0	14.7
		20	60.2	60.3	1.5	1.4	78.4	13.2	17.1	14.2
20	5	10	61.6	62.0	1.4	1.3	77.9	6.2	15.8	14.9
		20	61.3	61.4	2.5	2.7	82.2	22.1	19.1	15.3
10	10	10	62.3	62.8	1.5	1.3	78.0	5.2	15.2	15.5
		20	61.0	61.2	3.3	3.1	80.6	20.7	19.4	15.0
High-pass										
100	1.5	10	58.8	59.1	1.1	1.0	77.3	8.4	16.2	12.9
		20	58.4	58.5	1.4	1.2	77.4	13.2	17.5	12.6
50	3.5	10	59.9	60.2	1.1	0.8	77.5	7.5	15.6	13.8
		20	61.0	61.1	1.6	1.5	79.3	13.4	17.1	15.0
20	5	10	61.0	61.5	1.3	1.2	78.7	5.8	15.6	14.4
		20	60.1	60.2	2.8	2.7	81.5	20.9	19.1	14.1
10	10	10	60.6	61.1	1.7	2.0	78.1	5.7	15.8	13.9
		20	61.3	61.5	3.6	3.4	82.4	21.0	19.5	15.3
Low-pass										
100	1.5	10	60.4	60.4	1.0	0.9	75.7	5.8	14.7	14.2
		20	59.5	59.6	1.2	1.1	77.7	12.9	17.4	13.6
50	3.5	10	61.5	61.6	1.3	0.9	76.8	5.3	14.0	15.3
		20	60.8	60.9	1.4	1.2	78.6	12.2	16.8	14.8
20	5	10	60.0	60.0	1.5	1.4	76.5	5.2	14.7	13.7
		20	61.9	62.1	2.9	2.7	83.1	19.1	19.1	16.0
10	10	10	61.1	61.1	2.6	2.4	77.2	5.3	15.4	14.7
		20	61.2	61.3	3.3	3.1	81.7	19.2	19.2	15.2

CHAPTER 7

EXPERIMENTAL METHODS

7.1 Overview

The previous chapter covered the generation and characterization of the impulse noise test stimuli. In this chapter, the discussion focuses on the way in which these stimuli were presented to the subjects. Ten young normal hearing subjects were recruited and oriented. A testing program was written in C to conduct the automated two-alternative forced-choice (2AFC) up-down procedure and the testing system was calibrated. The stimuli were randomized, and a set of test procedures was developed for each experiment.

7.2 Subjects

Subjects were recruited from among the local population, and had no known history of otologic disease or hearing impairment as determined by an interview with the examiner. (The questions that were asked were typical of those found in a standard audiological interview (Katz 1985)). The subjects were screened at 20 dB HL (American National Standards Institute 1969) at audiometric frequencies from 250 Hz to 8 kHz with a Beltone model 9D audiometer. Several potential subjects were rejected on the basis of the interview, as was one subject that did not pass the audiometric screening. The ten subjects who completed the screening process ranged in age from 20 to 38 years. Seven were males and three

were females. One subject was a music producer, another was an amateur audio technician. None had participated previously in any kind of psychoacoustical testing.

7.3 Testing

7.3.1 Hardware and Software

A block diagram of the experimental apparatus is shown in figure 32, and a photograph of the testing environment in figure 33. A program for testing using the 2AFC procedure was written in C to conduct two sets of interleaved trials in which the test stimulus was first in one set, and the reference stimulus was first in the other. The reference level was held constant in each case, and the level of the test stimulus was adjusted using a simple, adaptive up-down procedure. The starting level of the test stimulus was randomly set to either 6 dB above or 6 dB below the reference level of 60 dB L_{eq} .

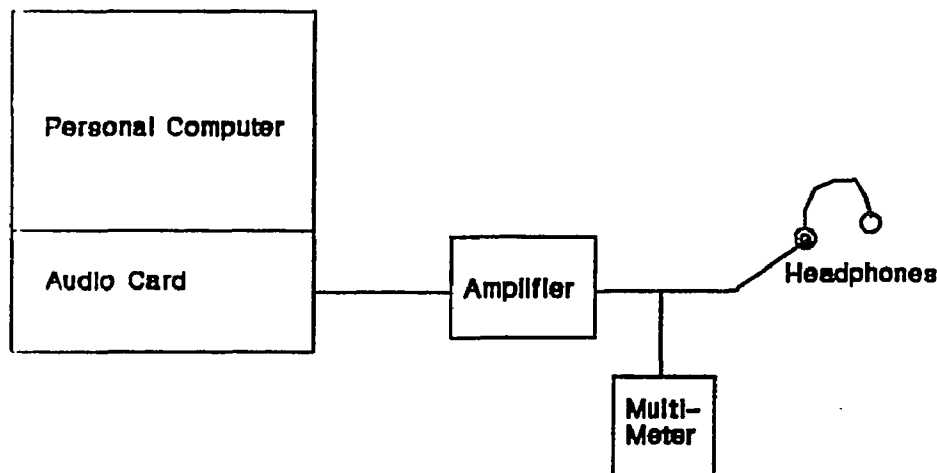


Figure 32. Block diagram of the apparatus used to conduct the psychoacoustical testing.

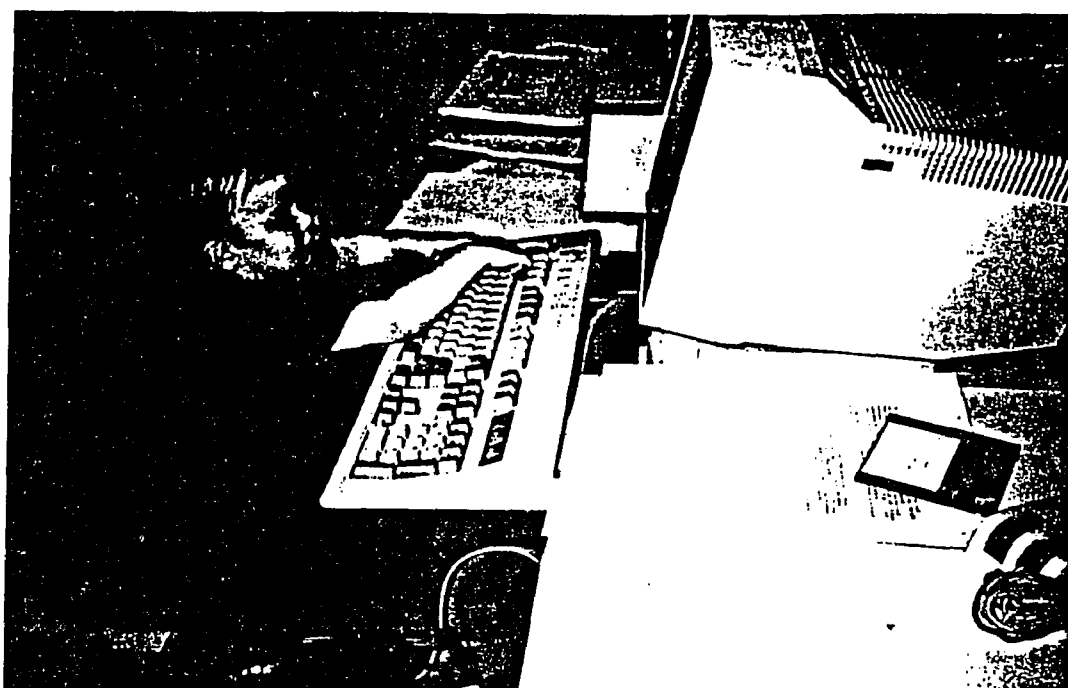


Figure 33. Photograph of the testing environment

The core subroutines for reproducing the stimuli were obtained from the AAPI package, modified to suit the test conditions, and incorporated into the C testing program INOISE. The input parameters of the program were the name of a file containing a list of the names and paths of the stimuli to be tested, the reference stimulus filename and level, and the number of reversals, which was five. The step size started at five dB and was reduced by one dB on each reversal to a minimum value of one dB. The stimulus duration was 1.05 seconds, with a 250 msec interstimulus interval and a gated rise/fall time of 25 msec. These times were controlled by adjusting the parameters in the C testing program. The volume was set to increase from 0 to the full level during the first 25 msec, then present the stimulus for 1.0 seconds, then fade down to 0 over 25 msec, and finally to present 250 msec of silence.

The operation of the testing program is illustrated schematically in figure 34. When the testing program was initiated, it first copied the reference stimulus to the virtual disk. Then, each impulse noise test stimulus listed in the input list file was copied in turn to the virtual disk for testing. Subjects were prompted by the computer to hit the enter key when they were ready to start testing. From then on, the computer would present each stimulus pair about one second after getting the response from the previous pair. Switching between the two sets of interleaved trials was controlled by a random number obtained from the internal time clock.

The program included a graphic display designed to assist the subjects in keeping their place during the testing. As the first stimulus in each trial was presented, a rectangle with a flashing number '1' appeared near the left side of the computer screen. A rectangle appeared on the right hand side with a flashing number '2' during the second stimulus. Then the words "Which was louder (1/2)?" appeared below the rectangles. The subjects responded by hitting either the 'c' or the 'm' key, which were labeled '1' and '2'. (These keys were used rather than the actual '1' and '2' keys because they are well spaced and easily reached). Once the subject's response was entered, the screen was erased. If the response was a reversal, i.e. the reference stimulus went from sounding louder than the test stimulus to sounding softer, or vice versa, the level of the test stimulus was stored in the appropriate result array, the step size was decreased by 1 dB, and the reversal counter was incremented. Trials continued until five reversals had been achieved in both the reference-stimulus-first and the test-stimulus-first trial sets. The program saved the reversal levels and the average of the levels of

PLAYBACK AND TESTING:

**C TESTING PROGRAM
COMPILED C SUBROUTINES
and ASSOCIATED STRUCTURES**

Hard Disk:

INPUT LIST FILE
path1\file1.*
path2\file2.*
.
.

OUTPUT FILE
Subject Info.
Test File names
Subject Responses

Virtual Disk:
Stimulus File
Reference File

Diskettes:
Audio Data Files

**ACPA
DSP CODE**

TDH-49 PHONES

**Subject Responses
(Keyboard)**

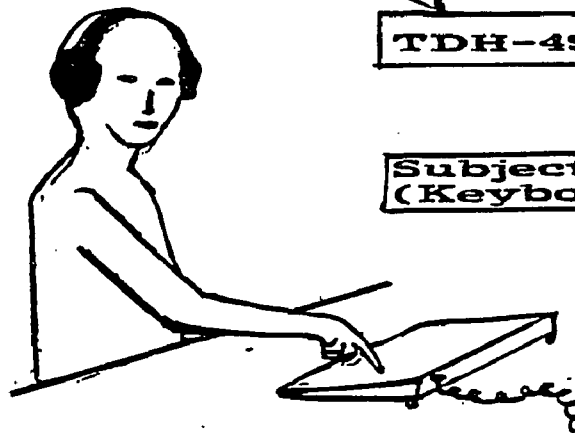


Figure 34. Schematic of the operation of the testing program.

the last four reversals for each set of interleaved trials for each stimulus in a file. A message on the screen of the computer prompted the subject to wait while the test stimulus was being copied to the virtual disk, and then to hit the enter key to start the next set of trials. When all the stimuli on the diskette had been tested, the program ended.

7.3.2 Calibration of testing system

Subjects were tested using the line output from the audio card and an external amplifier (Sony WM6-DC) as shown in figure 30. The gain was adjusted by measuring the voltage across the headphones when playing the 800 Hz calibration tone. The determination of the relation between the voltage and the actual playback levels was described in section 6.2.1. The gain was checked at regular intervals throughout the test session and was found to be stable within 0.6 dB.

The performance of the two-alternative forced-choice (2AFC) adaptive testing program was checked by debugging routines and by measuring the levels of the test and reference stimuli with a digital voltmeter during a loudness balance between the steady, white noise reference stimulus and the calibration tone. Then, a more thorough test was conducted with the set of white steady, white noise calibration stimuli that was discussed in section 5.2.2. These stimuli were identical to the reference stimuli except that, when they ranged in level from 12 dB below the reference stimulus level, to 12 dB above, in 3 dB steps. The exact levels of these stimuli were determined on the NE-830 analyzer (see section 6.2 for details). Since the stimuli were identical except for level, subjective factors should not have played a role in the loudness matching, i.e. the stimulus that was 6 dB higher in level than the reference should have had a playback level 6 dB below that of the reference stimulus at the point of subjective equality (PSE). Therefore, the subjects' responses to these trials provided a check on the linearity of the system, the sequence effect (the tendency for the loudness of the stimulus that is presented last to be enhanced in loudness), and the presence of any problems with either hardware or software. The results

of these trials, which were randomly mixed in the main experiment, are discussed in Chapters 8 and 9.

7.3.3 Testing Procedures

The design of the experiments was outlined in chapter 5. The way in which the stimuli were randomized and the testing was performed is discussed below. The test stimuli for each experiment were randomly divided into groups of 10 or 11 and stored on diskettes. Experiment 1 consisted of four diskettes, and experiment 2 required three. One or two of the steady white noise calibration stimuli was placed on each diskette to ensure that the system was working properly. A separate diskette with all of the calibration stimuli was also prepared for use during subject orientation.

Within each experiment, the different diskettes were presented in a random order to each subject. Moreover, the order in which noises on any given diskette were presented was also randomized. Since the testing program read the names of the files to be tested from a separate list file, this was easily done by creating several versions of the list file for each diskette and varying the order on each list. There were six forms of each list for experiments 1 and 2, and they randomly assigned to the subjects.

Subjects were initially given a brief orientation during which they read and signed the release form, had their right ear screened as described in section 7.2, and answered questions about their otologic history. All testing was conducted in a quiet, ordinary room with a background level 26 dB L_{Aeq} . Subjects were seated in a moderately comfortable chair and were given the following written instructions:

"You will be listening to pairs of sounds. After each pair, you will be asked which sound seemed louder to you. If the first sound seemed louder, hit the '1', and if the second seemed louder, hit the '2'. You will not need to hit the enter key.

"After a group of about 20 pairs, the computer will stop to copy some files and record the results. When you are ready to start again, just hit 'enter' at the computer's prompt. If you have any questions, please let me know."

The subjects' questions were answered to ensure that they understood the procedure, but information as to the intent of the study or the testing method was not divulged. It was emphasized that they simply needed to choose the noise that sounded louder to them, and to choose one even when they sounded equal. Generally there were very few questions. Several subjects asked why there was not a third category in the test procedure (i.e. that the sounds seem equally loud) and were told just to do their best with the two options. One subject, when performing a loudness balance on a stimulus with a low peak-to-background ratio, asked whether he was to attend to the "whoosh" part of the noise (the background) or the interrupted part, and was told to consider both at once.

Before starting on the first experiment, each subject had a short practice session using the white noise reference and the steady white noise calibration stimuli. The results of this session were checked to ensure that the subject had mastered the task. Subjects required anywhere from 15 to 35 minutes to complete 12 loudness balances. Several subjects speeded up with practice and commented that the program wasn't giving them as many pairs of noises as it had formerly (they were unaware of their role in controlling this factor). Typically, two to four diskettes were tested in each session.

All of the testing was carried out by the 2AFC program INOISE.EXE

(see Appendix D) with five reversals using the steady white noise reference stimulus. Each subject's results were stored in separate files that were generated by the testing program. The file contained the individual reversal levels and also the mean of the last four reversals, which was taken stimulus level at the PSE for that trial. Averaging was not performed over replications or over interleaved trials, so that these effects could be tested for significance in the data analysis. The data from the two main experiments and the white noise calibration data and steady background noise data were collated and entered into ASCII files on the computer. The data were read into APL2 in numerical form and converted to L_{eq} levels using the calibration factors that had been determined for each stimulus (see section 6.3 for a discussion of the conversion procedure). Procedures that were specific to the two main experiments are as follows:

Experiment 1. A complete series of the 12 rate-duration conditions with a background of white noise with three different peak-to-background noise ratios was studied at a reference level of 60 dB L_{eq} . This portion of the experiment required the synthesis of 36 stimuli. The stimuli were randomly grouped on four diskettes. Each diskette also contained one of the white noise calibration signals, and one of the steady background noises. Since each section was to be run twice to improve the reliability of the data, the experiment consisted of eight diskettes (80 sets of interleaved trials). As was mentioned above, the order of the diskettes and the order of the noises on each diskette were randomized differently for each subject, with the proviso that each subject was tested on all stimuli once before repeating any of them.

Experiment 2. The stimuli used for experiment 2 consisted of white noise impulses, as in experiment 1, but with four different steady background noises: white, low-pass filtered, band-pass filtered, and high-pass filtered; at peak-to-background ratios of 10 and 20 dB. (The 30-dB condition corresponded essentially to a "no background noise" situation, and hence was not useful in studying the effects of the spectral shape of the background noise.) The repetition rate-duration conditions that were studied were:

100 Hz	1.5 msec
50 Hz	3.5 msec
20 Hz	5.0 msec
10 Hz	10.0 msec

These stimuli plus the steady background noise stimuli and several of the white noise calibration stimuli were randomized on three diskettes.

Testing was conducted in the same manner as experiment 1 in all ten subjects.

CHAPTER 8

RESULTS

8.1 Overview

The data from the two experiments, as well as the calibration data and the steady background noise data, were analyzed in the same manner. First, the means of the last four reversals of each pair of interleaved trials for each test condition in all of the subjects that had been stored during the testing were read into the APL2 environment. The raw data were converted into L_{eq} levels using the procedures that were outlined in Chapter 6.

Conventionally, the difference between the L_{eq} level of a given test stimulus and the L_{eq} level of the reference stimulus at the point of subjective equality (PSE) is referred to as the PSE for that stimulus. A test stimulus with a negative PSE (i.e. an L_{eq} level below that of the reference stimulus at the point of subjective equality) was louder than the reference stimulus. Test stimuli that were less loud than the reference stimulus had to be increased in level in order to reach the point of subjective equality, and these stimuli therefore had positive PSEs.

The converted data were transformed back into text files for the statistical analyses. All of the data were analyzed using a standard analysis of variance (ANOVA) with repeated measures (Winer 1966). Post hoc testing was performed with the Tukey HSD method (Winer 1966).

8.2 Steady White Noise Calibration

In order to check the linearity of the testing system, the subjects performed loudness balances between the steady white noise reference stimulus and a set of steady white noise calibration stimuli of varying levels that were interspersed throughout the two main experiments. The calibration stimuli were identical to the reference stimulus except that their amplitude was varied during the synthesis so that they would be at -12, -9, -6, -3, 0, +3, +6, +9, and +12 dB relative to the reference stimulus when presented at the same playback level. (These stimuli were also used to train the subjects before beginning the experiments, but those initial results were not included in the calibration analysis). The change in playback level of the test stimuli (in decibels) in order to reach the point of subjective equality (PSE) with the reference stimulus, which was presented at 60 dB Leq, is shown in figure 35. The means of the last four reversals from each of two pairs of interleaved trials by each of ten subjects are shown in the figure. The vertical error bars represent plus and minus one half of one standard deviation of the data for all measurements on all ten subjects.

An analysis of variance was conducted in which the differences between the actual sound pressure levels of the different noises at the PSE were compared. The factors were: noise level, L, (nine levels), the sequence effect, R, (two levels; test stimulus followed by reference, and reference stimulus followed by test stimulus), the order effect, O, (two levels, first and second administration of the interleaved trials) and subjects, S, (ten levels). None of these main effects were significant. The results of the analysis are shown in table 5.

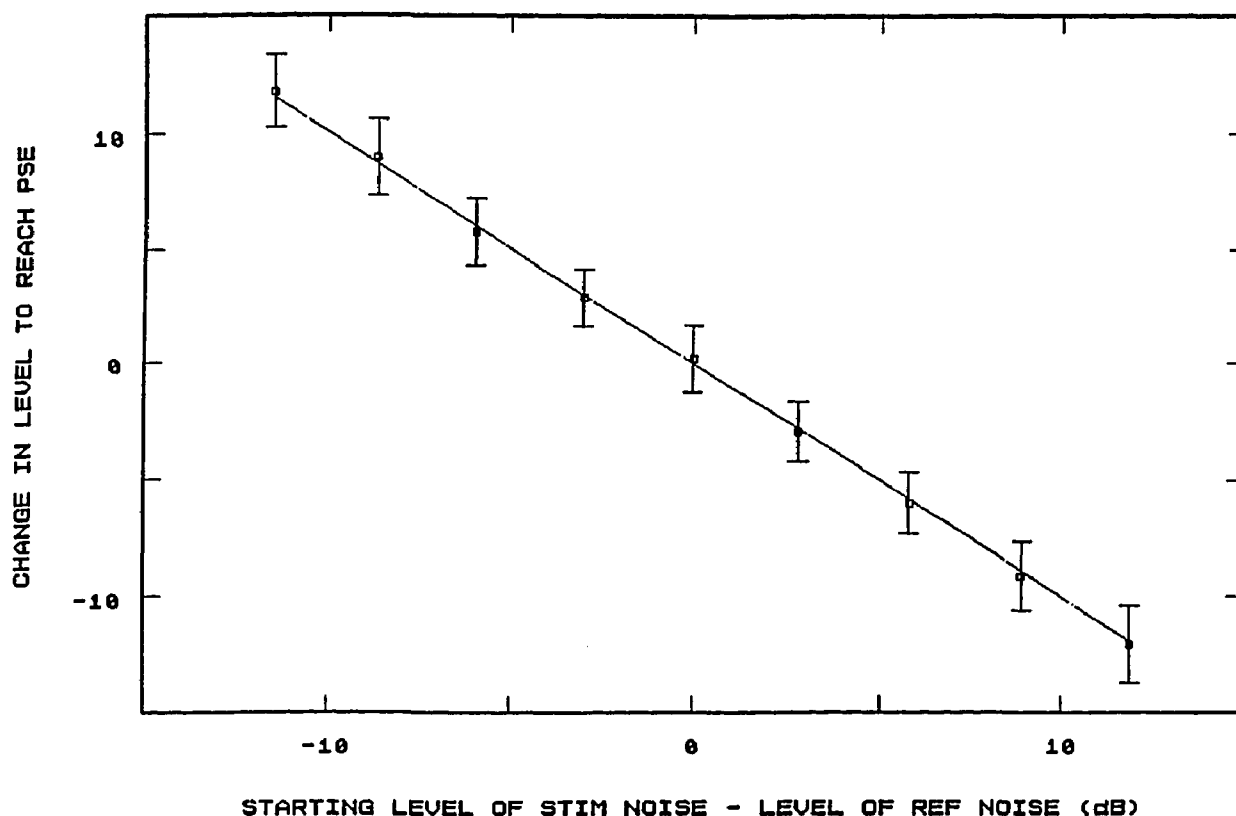


Figure 35. Results of the steady white noise calibration measurements.

TABLE 5
ANALYSIS OF VARIANCE OF THE STEADY
WHITE NOISE CALIBRATION STIMULI

Source of Variation	Sums of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Signif.
N (Noise Level)	15.632	8	1.954	1.840	0.0830
R (Sequence)	26.136	1	26.136	0.890	0.6273
NR	28.723	8	3.590	2.015	0.0562
O (Order)	0.201	1	0.201	0.268	0.6212
NO	8.452	8	1.057	1.273	0.2707
RO	4.011	1	4.011	3.120	0.1087
NRO	16.261	8	2.033	1.423	0.2011
S (Subjects)	19.965	9	2.218	1.553	0.1458
NS	76.451	72	1.062	0.744	0.8943
RS	264.246	9	29.361	20.561	0.0010
NRS	128.301	72	1.782	1.248	0.1749
OS	6.730	9	0.748	0.524	0.8532
NOS	59.773	72	0.830	0.581	0.9887
ROS	11.572	9	1.286	0.900	0.5301
NROS	102.812	72	1.428		
Total	769.26	359			

8.3 Steady Background Noise Stimuli

The ten subjects also performed loudness balances between the four steady background noise stimuli and the steady white reference stimulus. The frequency ranges of the steady background noises were shown in table 2. The results of the measurements, averaged over the two sets of interleaved trials and over subjects, are shown in figure 36. The error bars indicate plus and minus one-half standard deviation.

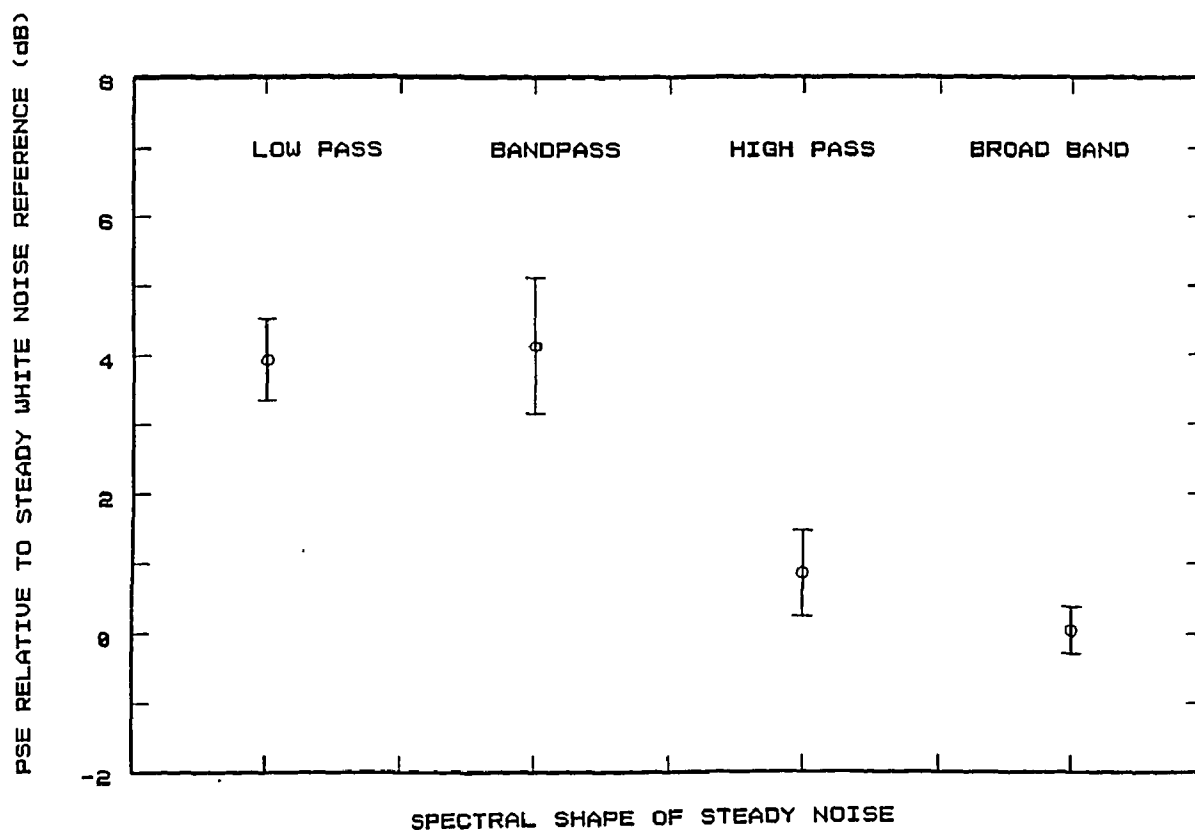


Figure 36. Point of subjective equality of the four steady background noise stimuli relative to the steady white reference stimulus.

The results of the analysis of variance of these data are shown in table 6. The factors were: spectral shape of the steady background noise, B, (four levels; white, low-pass filtered, band-pass filtered, and high-pass filtered), the sequence effect R (two levels; test stimulus followed by reference stimulus, and reference stimulus followed by test stimulus), the order effect O (two levels, first and second administration of the interleaved trials) and subjects S (ten levels).

TABLE 6
ANALYSIS OF VARIANCE OF THE STEADY
BACKGROUND NOISE STIMULI

Source of Variation	Sums of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Signif.
B (Spectrum)	656.373	3	218.79	16.504	0.0010
R (Sequence)	75.282	1	75.28	9.540	0.0126
BR	9.211	3	3.07	1.680	0.1938
O (Order)	0.010	1	0.01	0.003	0.9573
BO	14.170	3	4.72	2.122	0.1197
RO	1.182	1	1.18	0.946	0.6417
BRO	0.929	3	0.31	0.209	0.8895
S (Subjects)	411.197	9	45.69	30.788	0.0010
BS	357.926	27	13.26	8.933	0.0010
RS	71.019	9	7.89	5.318	0.0010
BRS	49.348	27	1.83	1.232	0.2956
OS	30.463	9	3.38	2.281	0.0470
BOS	60.092	27	2.23	1.500	0.1493
ROS	11.244	9	1.25	0.842	0.5858
BROS	40.067	27	1.48		
Total	1788.512	159			

It can be seen in table 6 that, as in the case of the calibration data, the order effect was not significant ($p=0.9573$). However, the sequence effect was significant ($p=0.0126$). The results of post hoc testing on this interaction are shown in figure 37. In this figure, the means that were computed in the ANOVA for the sequence effect are depicted in rank order along the abscissa. The fact that both means were higher than the

reference level at PSE is a reflection of the fact that the steady background noise stimuli (with the exception of the white noise stimulus) were less loud than the reference stimulus, as was shown in figure 36. However, the difference between the two means in figure 37 is due to the sequence effect. The mean obtained when the reference stimulus was presented prior to the test stimulus was approximately 1.37 dB lower than the mean obtained when the reference stimulus was presented after the test stimulus, a difference that was significant at the 0.01 level. The effect was nearly three times as large in this case as it was in the calibration measurements, which had a mean sequence effect of 0.55 dB.

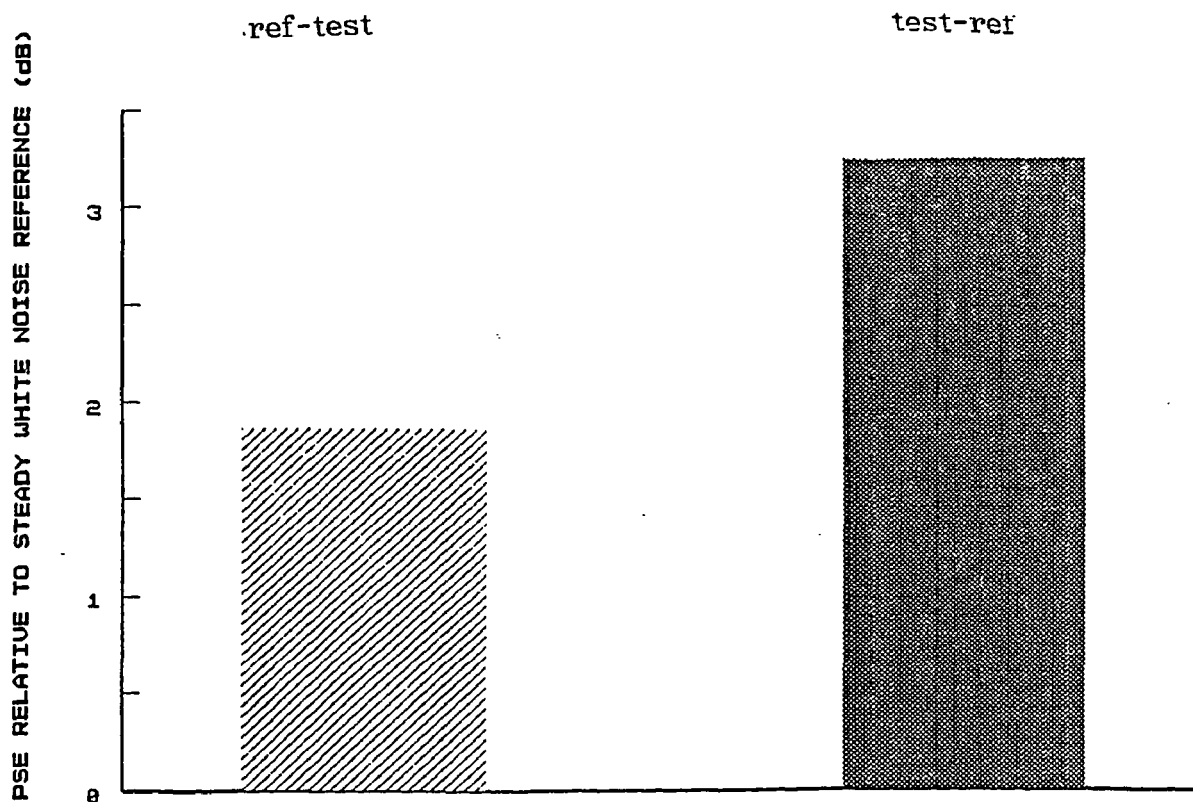


Figure 37. Results of post hoc testing on the sequence effect, R, in the steady background noise data.

There was also a significant main effect due to the spectral shape of the steady background noise stimulus ($p < 0.001$). The results of post hoc testing on this main effect are shown in figure 38. The PSE of the white background noise test stimulus was quite close to that of the white noise reference stimulus because they were essentially identical, as was explained in chapter 6. The horizontal lines underneath the bars indicate groups whose means did not differ significantly at the 0.01 level upon post hoc testing. Thus, the mean PSEs of the white and the high-pass filtered background noise stimuli were significantly lower than those of the band-pass and low-pass filtered noise stimuli (i.e. the low-pass and band-pass filtered noise stimuli were less loud).

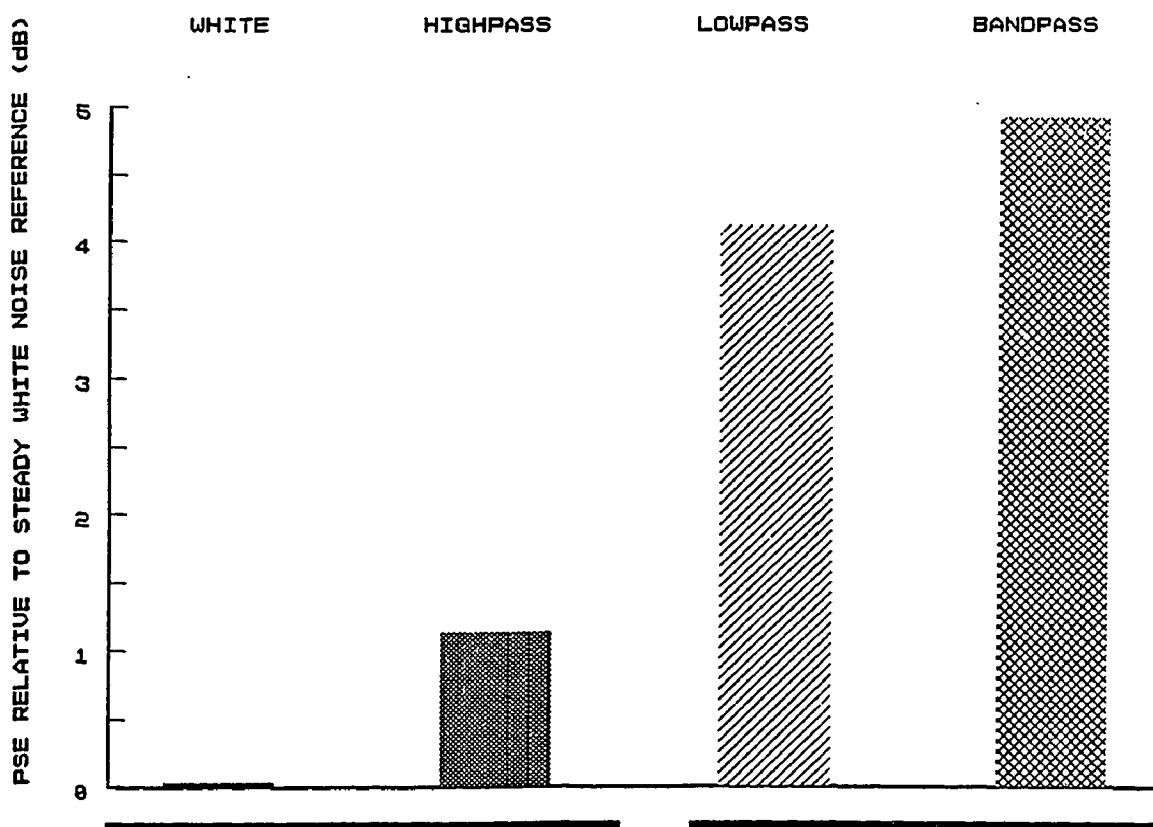


Figure 38. Results of post hoc testing on the effect of spectral shape, B, of the steady background noise stimuli.

8.4 Experiment 1

The purpose of experiment 1 was to measure the loudness of impulse noise stimuli relative to that of a steady reference stimulus with a comparable time-averaged spectrum as a function of impulse repetition rate and duration, and the relative level of added steady white background noise. The combinations of repetition rate and duration that were studied were shown in Table 1. The steady white background noise was added at peak-to-background ratios of 10, 20, and 30 dB.

The first ANOVA that was performed on the results of experiment 1 treated the combinations of repetition rate and duration as a single variable, noise type, (N), with 12 levels, as shown in table 1. The other variables in the analysis were: the peak-to-background ratio, P with three levels; (10, 20, and 30 dB), the sequence effect, R, (two levels; test stimulus followed by reference stimulus, and reference stimulus followed by test stimulus), the order effect, O, (two levels, first and second administration of the interleaved trials) and subjects, S, (ten levels).

The results of the repeated measures ANOVA are shown in table 7. The noise type, N, was significant ($p < 0.001$), as was the interaction between noise type and peak-to-background ratio, NP, ($p < 0.001$). Neither the peak to background ratio, P, nor the order, O, were significant. The main effect for sequence, R, was significant ($p = .0052$), and it had a significant interaction with the peak-to-background ratio, P ($p = 0.0024$). Also significant at the $p < 0.001$ level were the main effect due to the subjects, S, and several two and three way interactions between subjects and other variables, as may be seen in table 7.

TABLE 7
ANALYSIS OF VARIANCE OF EXPERIMENT 1
Treating Repetition Rate and Duration
as a Single Combined Factor

Source of Variation	Sums of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Signif.
N (Noise Type)	1038.713	11	94.428	7.559	0.0010
P (Peak/Backgr.)	246.499	2	123.250	0.991	0.6076
NP	569.328	22	25.879	2.604	0.0010
R (Sequence)	845.940	1	845.940	13.586	0.0052
NR	39.588	11	3.599	0.928	0.5178
PR	77.182	2	38.591	8.844	0.0024
NPR	35.551	22	1.616	0.668	0.8677
O (Order)	0.079	1	0.080	0.004	0.9502
NO	70.047	11	6.368	0.874	0.5691
PO	22.411	2	11.205	2.103	0.1497
NPO	178.161	22	8.098	1.296	0.1772
RO	0.915	1	0.915	0.147	0.7103
NRO	29.956	11	2.723	1.138	0.3400
PRO	0.730	2	0.365	0.280	0.7625
NPRO	31.211	22	1.419	0.674	0.8617
S (Subjects)	12696.808	9	1410.756	670.425	0.0010
NS	1236.799	99	12.493	5.937	0.0010
PS	2238.042	18	124.336	59.087	0.0010
NPS	1967.392	198	9.936	4.722	0.0010
RS	560.383	9	62.265	29.590	0.0010
NRS	384.119	99	3.880	1.844	0.0010
PRS	78.547	18	4.364	2.074	0.0082
NPRS	479.288	198	2.421	1.150	0.1628
OS	183.141	9	20.349	9.670	0.0010
NOS	721.720	99	7.290	3.464	0.0010
POS	95.922	18	5.329	2.532	0.0011
NPOS	1237.441	198	6.250	2.970	0.0010
ROS	56.044	9	6.227	2.959	0.0028
NROS	236.840	99	2.392	1.137	0.2236
PROS	23.492	18	1.305	0.620	0.8815
NPROS	416.646	198	2.104		
Total	25798.936	1439			

The results of post hoc testing on the sequence effect and its interaction with peak-to-background ratio are shown in figure 39. The magnitude of the sequence effect (the difference between the levels of the 2 bars in figure 39a) was 1.533 dB, which is comparable to the value

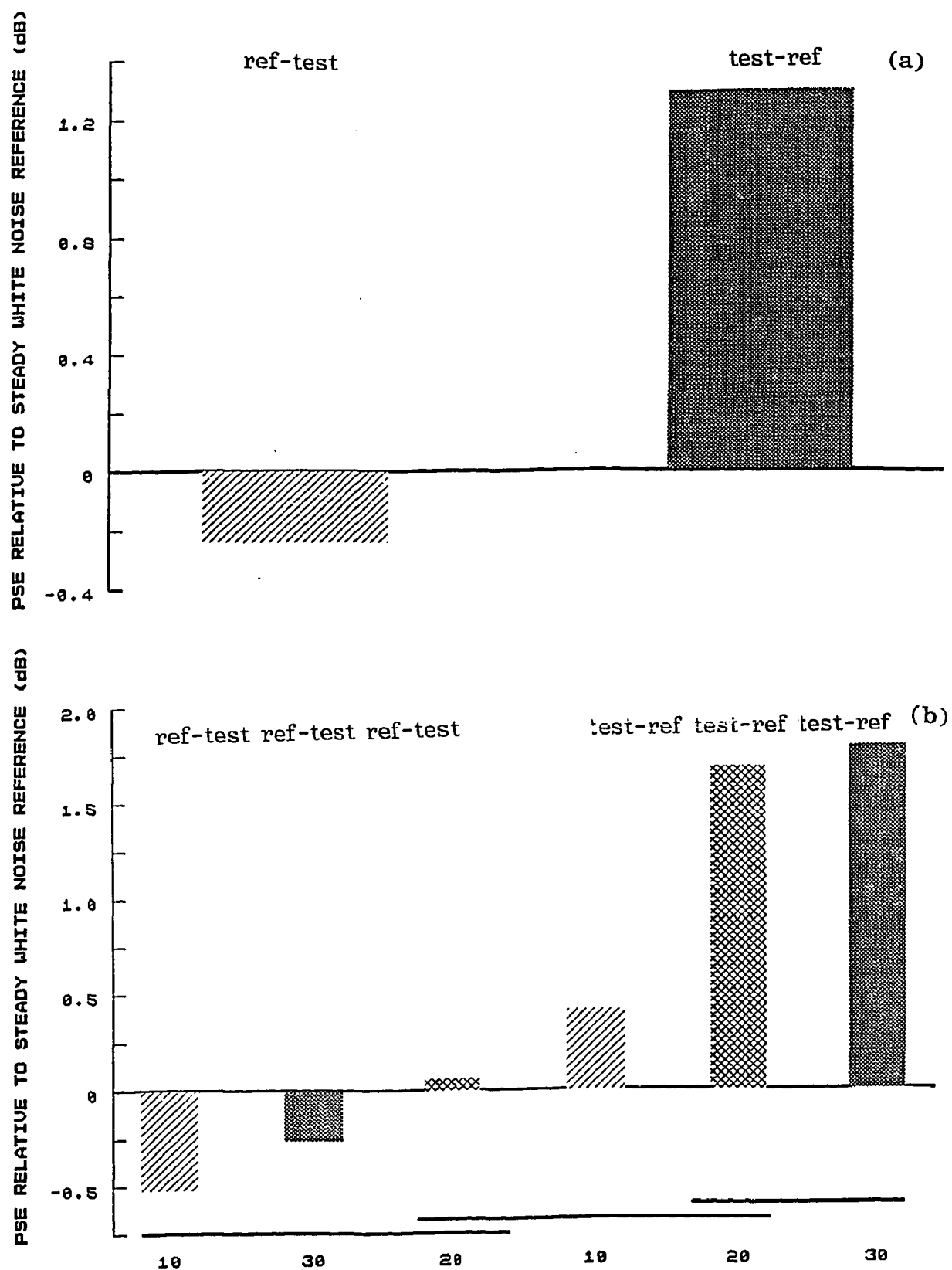


Figure 39. Results of post hoc testing on the sequence effect, R, in experiment 1. a, sequence main effect. b, interaction between sequence, R, and peak-to-background ratio, P.

of 1.37 obtained in the measurements on the steady background noise stimuli. Figure 39b shows how the sequence effect depended on the peak-to-background noise ratio. The sequence effect for the 10-dB condition (highest amount of background noise) was 0.93 db, at 20 dB it was 1.62 dB, and at 30-dB it was 2.05 dB.

The main effect of the noise type, N, which is the combination of repetition rate and duration into a single factor, was also analyzed by post hoc testing. Figure 40 shows the results of post hoc testing by the Tukey HSD method on the different noise types, averaged over peak-to-background ratio. The numbers at the top of the figure indicate the

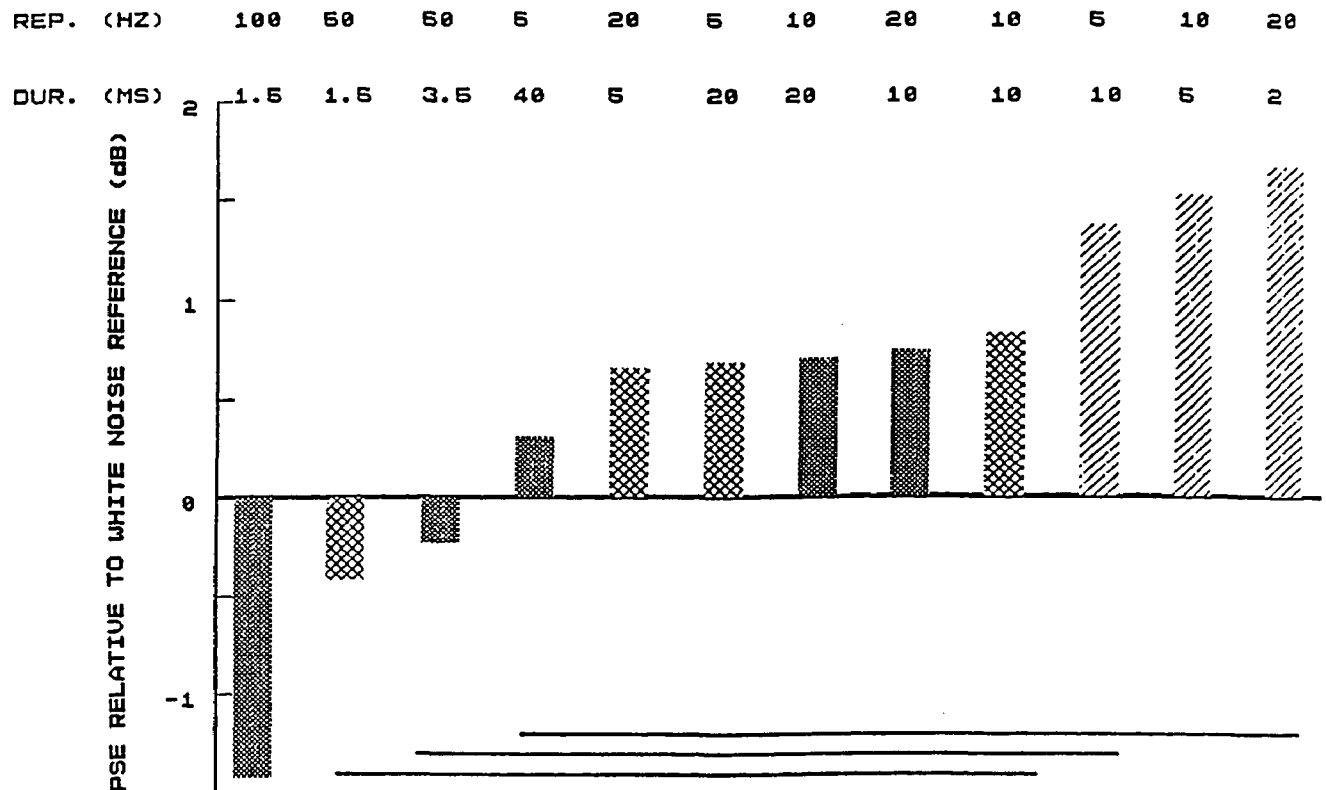


Figure 40. Results of post-hoc testing on the main effect of noise type, N, in the results of experiment 1.

repetition rates and durations. The shading of the bars indicates the duty factor, (i.e. the product of the repetition rate and effective duration of the impulse), which was indicated for each noise type in table 1. As was discussed in Chapter 5, the decay times of the impulses were selected to yield 3 different duty factors of approximately 0.025, 0.05, and 0.1. For example, at a 10-Hz repetition rate, the 5-msec impulse had the lowest of the three duty factors (0.025) and is indicated by diagonal shading, while the 10-Hz, 20-msec condition had the highest duty factor (0.1) and is indicated by dark cross hatching.

The horizontal lines below the bar chart in figure 40 indicate groups whose means did not differ significantly at the $p=0.01$ level upon post hoc testing. It can be seen from the post hoc testing results that the test stimuli can be divided into three groups; (a) those with impulses at the 50 and 100 Hz repetition rates, which tended to be louder than the reference, (b) those with the shortest duration impulses (lowest duty factor) at the lower repetition rates (5, 10, and 20 Hz), which were rated 1-2 dB softer than the reference, and (c), those with the longer duration impulses (medium and highest duty factors) at the lower repetition rates, which fell somewhere in between.

In addition to being a significant main effect, the noise type, N also had a significant interaction with the peak-to background ratio. Post hoc testing on this interaction was not feasible, since there were a total of 36 combinations (12 noise types times three peak-to-background ratios), which would yield too high an error term in the Tukey HSD method. The bar chart in figure 41 shows the means for these 36 groups. The rank ordering of figure 40 has been preserved in order to illustrate how each bar breaks down into its components at the 10, 20 and 30-dB peak-to-

background ratios.

The left-most bar in each group of three in figure 41 is the 10-dB condition (lightest shading) and the right-most bar is the 30-dB condition (heaviest shading). It can be seen that the higher PSE of the shortest impulses (lowest duty factor) at 5, 10, and 20 Hz is due mostly to the high PSE of these stimuli at the 30-dB peak-to-background ratio condition

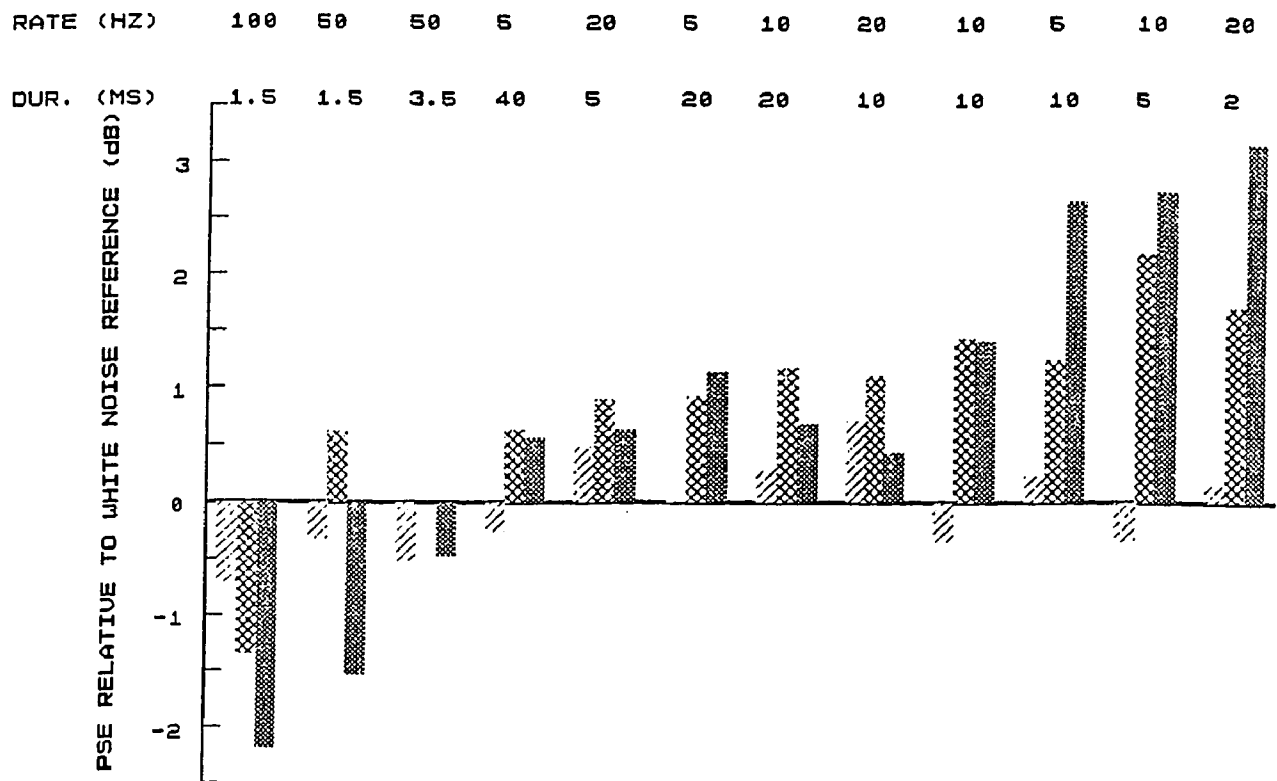


Figure 41. The dependence of the means PSEs in experiment 1 on the noise type and the peak-to-background ratio. Each group of three bars represents one noise type (combination of repetition rate and duration), following the order of the post hoc test results in figure 38. The repetition rates and durations are shown at the top of the figure. The left-most bar in each group is the means PSE at 10 dB; the center bar, at 20 dB; and the right-most bar, 30 dB.

and also, to a lesser extent, at the 20-dB condition.

Similarly, at the 100-Hz repetition rate, deviations from the loudness level of the reference stimulus (zero) increase with increasing peak-to-background ratio, but the change is in the opposite sense. The fact that the PSEs at 100 Hz are negative indicates that these impulse noise stimuli were louder than the reference stimulus.

Because the effect of noise type, N, depended strongly on peak-to-background ratio (as seen in both in the ANOVA (table 7) and in figure 41, each peak-to-background ratio condition was treated separately in the next phase of the analysis. Separate ANOVAs were performed on the data at peak-to-background ratios of 10, 20, and 30 dB. The variables were identical to those of the first ANOVA except that the peak-to-background ratio parameter, P, was omitted. The results are shown in tables 8 to 10. The noise type, N, was significant at the 20 and 30-dB peak-to-background ratios ($p < 0.001$) but was not significant at 10 dB ($p = 0.059$). The other significant effects in the three analyses were the sequence effect, R, and the subject main effect and interactions.

TABLE 8
ANALYSIS OF VARIANCE OF EXPERIMENT 1
AT 10 dB PEAK-TO-BACKGROUND RATIO

Source of Variation	Sums of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Signif.
N (Noise)	80.720	11	7.338	1.826	0.0590
R (Sequence)	103.138	1	103.138	6.460	0.0304
NR	6.803	11	0.618	0.385	0.9589
O (Order)	0.013	1	0.013	0.003	0.9590
NO	36.740	11	3.340	1.432	0.1705
RO	1.302	1	1.302	0.760	0.5900
NRO	16.801	11	1.527	0.928	0.5176
S (Subjects)	1118.955	9	124.328	75.524	0.0010
NS	397.854	99	4.019	2.441	0.0010
RS	143.701	9	15.967	9.699	0.0010
NRS	158.984	99	1.606	0.976	0.5487
OS	44.201	9	4.911	2.983	0.0038
NOS	230.984	99	2.333	1.417	0.0419
ROS	15.422	9	1.714	1.041	0.4137
NROS	162.975	99	1.646		
Total	2518.592	479			

TABLE 9
ANALYSIS OF VARIANCE OF EXPERIMENT 1
AT 20 dB PEAK-TO-BACKGROUND RATIO

Source of Variation	Sums of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Signif.
N (Noise)	352.863	11	32.078	3.412	0.0010
R (Sequence)	315.171	1	315.171	12.051	0.0071
NR	19.513	11	1.774	0.651	0.7814
O (Order)	9.227	1	9.227	0.998	0.6546
NO	113.426	11	10.311	1.401	0.1841
RO	0.004	1	0.004	0.001	0.9714
NRO	17.157	11	1.560	0.601	0.8249
S (Subjects)	4834.961	9	537.218	206.832	0.0010
NS	930.767	99	9.402	3.620	0.0010
RS	235.374	9	26.153	10.069	0.0010
NRS	269.649	99	2.724	1.049	0.4069
OS	83.185	9	9.243	3.559	0.0010
NOS	728.694	99	7.361	2.834	0.0010
ROS	31.644	9	3.516	1.354	0.2191
NROS	257.139	99	2.597		
Total	8198.774	479			

TABLE 10
ANALYSIS OF VARIANCE OF EXPERIMENT 1
AT 30 dB PEAK-TO-BACKGROUND RATIO

Source of Variation	Sums of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Signif.
N (Noise)	1174.459	11	106.769	5.636	0.0010
R (Sequence)	504.813	1	504.813	17.484	0.0027
NR	48.823	11	4.438	1.011	0.4432
O (Order)	13.250	1	13.250	0.786	0.5980
NO	98.042	11	8.913	0.883	0.5601
RO	0.339	1	0.339	0.094	0.7628
NRO	27.210	11	2.474	1.049	0.4102
S (Subject)	8980.929	9	997.881	423.315	0.0010
NS	1875.570	99	18.945	8.037	0.0010
RS	259.855	9	28.873	12.248	0.0010
NRS	434.774	99	4.392	1.863	0.0013
OS	151.678	9	16.853	7.149	0.0010
NOS	999.483	99	10.096	4.283	0.0010
ROS	32.470	9	3.608	1.530	0.1473
NROS	233.373	99	2.357		
Total	14835.069	479			

Figure 42 displays the results of post hoc testing for noise type, N, of the analyses at 20 and 30 dB peak-to-background ratios. The horizontal lines below the bars show the groups whose means were not significantly different (at the $p=0.01$ level) upon post-hoc testing. The basic pattern of results was already illustrated in figure 41. Increasing the peak-to-background ratio from 20 to 30 dB increased the loudness of the noises at the 100 and 50-Hz repetition rates, but decreased the loudness of the noises with the lowest duty factor at the 5, 10, and 20-Hz repetition rates. As in figure 40, the shading of the bars in figure 42 indicates the duty factor condition.

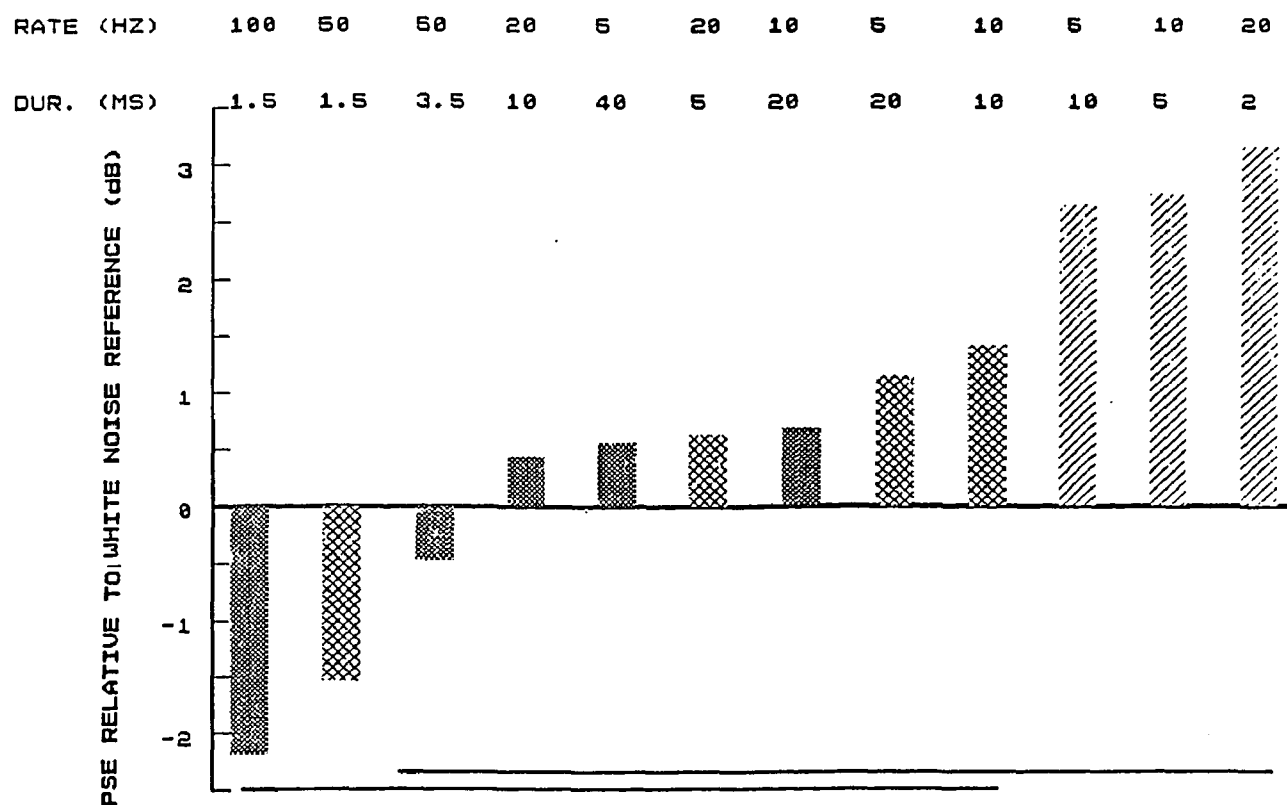
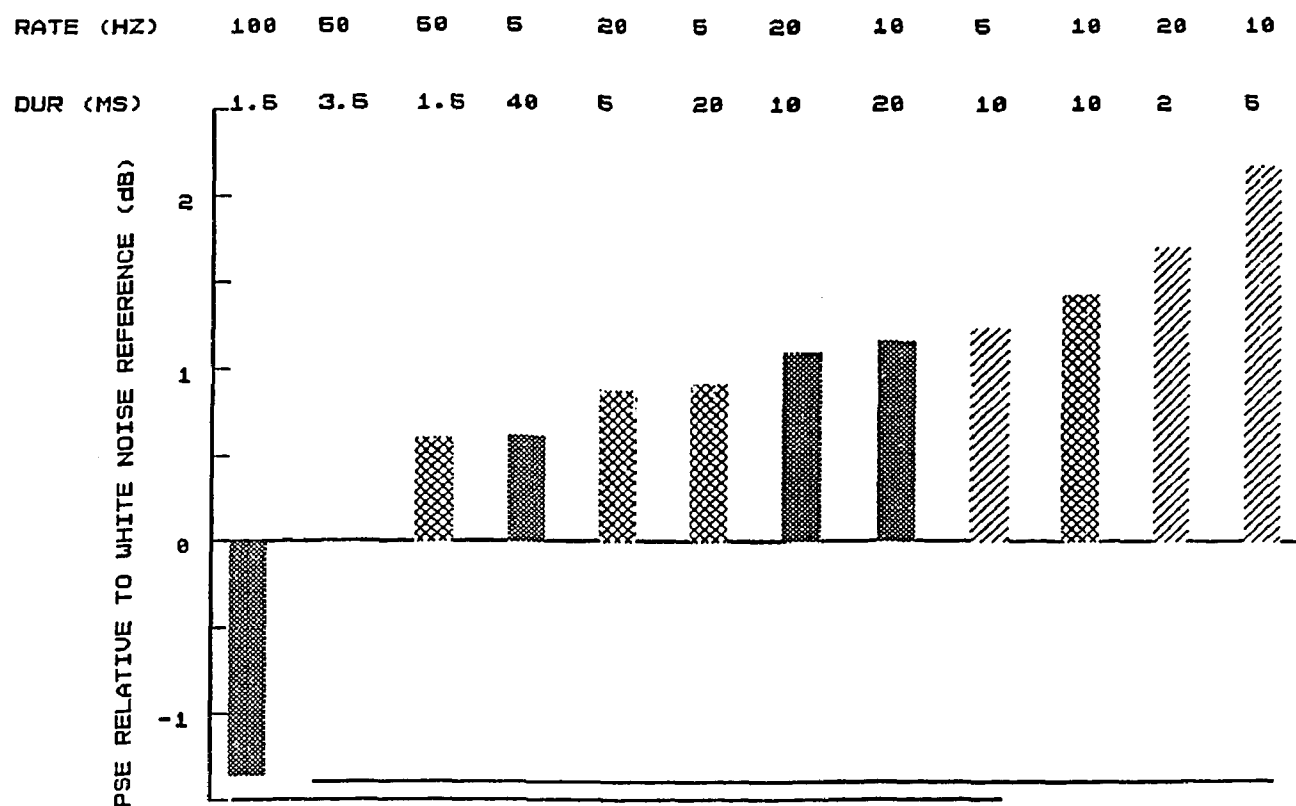


Figure 42. Results of Post hoc testing on the main effect of Noise type, N, in experiment 1 at peak-to-background ratios of a, 20 dB, and b, 30 dB.

The parameters of the impulse noise test stimuli were selected based on the assumption that the duty factor might prove to be a useful way of analyzing the data. In figures 43 to 45, the data of experiment 1 are plotted as a function of duty factor with repetition rate as a parameter at each peak-to-background ratio condition. As was shown in table 2, there were three values of duty factor at 5, 10, and 20 Hz, two values at 50 Hz, and one value at 100 Hz, because of the constraints discussed in Chapter 5.

At the 10-dB peak-to-background ratio (figure 41), it is unclear whether plotting the data as a function of duty factor is meaningful because the main effect due to noise type was not significant. However,

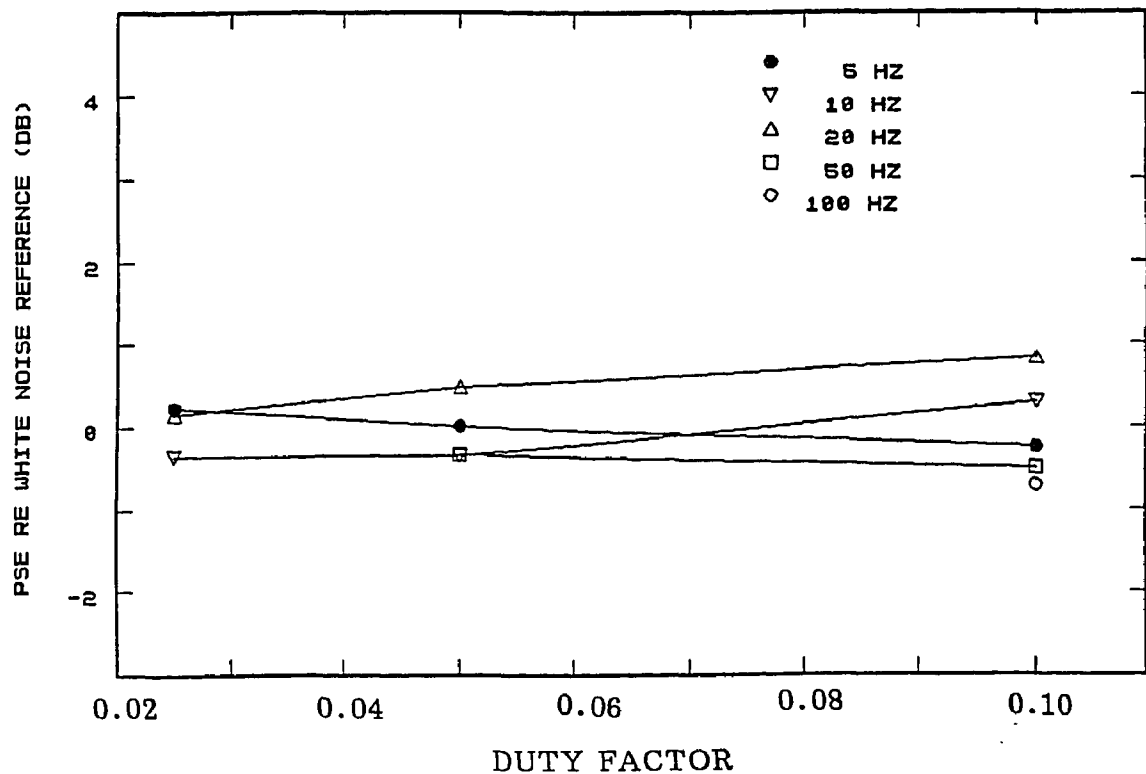


Figure 43. Mean PSEs of the impulse noise test stimuli of experiment 1 at a peak-to-background ratio of 10 dB as a function of duty factor.

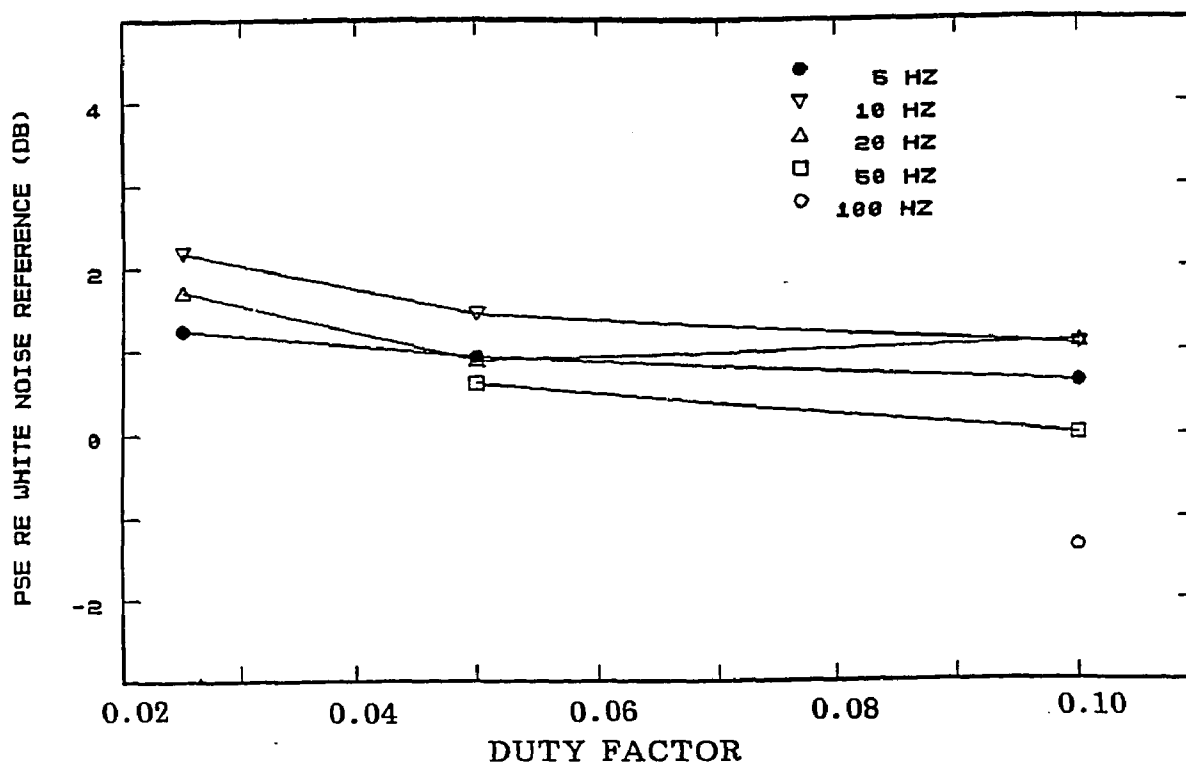


Figure 44. Mean PSEs of the impulse noise test stimuli of experiment 1 at a peak-to-background ratio of 20 dB as a function of duty factor.

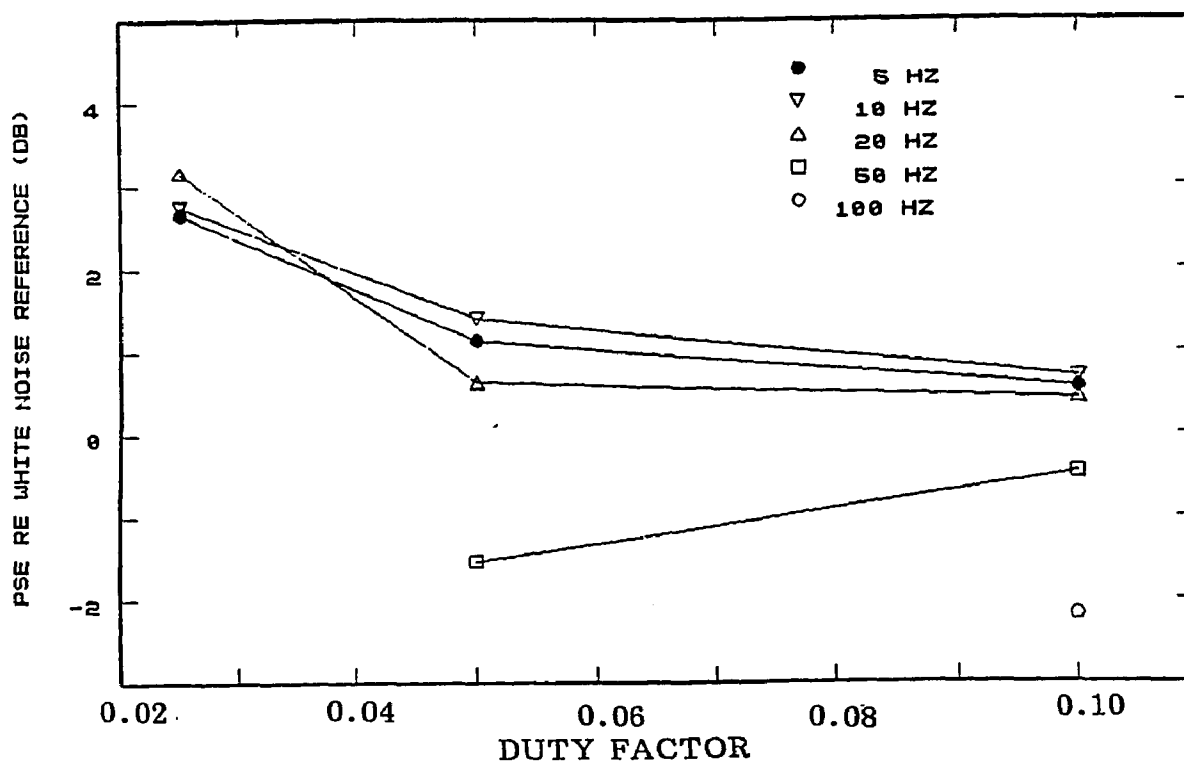


Figure 45. Mean PSEs of the impulse noise test stimuli of experiment 1 at a peak-to-background ratio of 30-dB as a function of duty factor.

in figures 44 and 45, which represent the 20 and 30 dB peak-to-background ratio conditions, it is clear that plotting on the basis of duty factor causes the data at the 5, 10, and 20-Hz repetition rates to overlap.

To confirm the validity of treating the data on the basis of the duty factor of the test stimuli, a separate ANOVA was performed on the data at the 5, 10, and 20-Hz repetition rates. Since all three duty factor conditions were tested at these repetition rates, it was possible to treat the duty factor as an a separate variable rather than combining it with the repetition rate to in a "noise type" parameter. Therefore, the factors in the analysis were: duty factor, D, (three levels; 0.025, 0.05, 0.1), repetition rate, F, (three levels; 5, 10, and 20 Hz), peak-to-background ratio, P, (three levels; 10, 20, and 30 dB), and the sequence, R, order, O, and subject, S, factors as in the other analyses. The results of this ANOVA are shown in Table 11.

TABLE 11
ANALYSIS OF VARIANCE OF EXPERIMENT 1
AT 5, 10, AND 20-Hz REPETITION RATES

Source of Variation	Sums of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Signif.
P (Peak/Backgr.)	102.936	2	51.468	2.820	0.0847
D (Duty Factor)	58.981	2	29.491	1.544	0.2397
PD	72.336	4	18.084	1.809	0.1476
F (Rep. Rate)	310.044	2	155.022	2.556	0.1040
PF	253.866	4	63.467	4.673	0.0041
DF	684.015	4	171.004	8.697	0.0010
PDF	125.179	8	15.647	1.123	0.3580
R (Sequence)	791.304	1	791.304	14.866	0.0041
PR	9.489	2	4.745	0.994	0.6084
DR	3.008	2	1.504	0.531	0.6017
PDR	5.124	4	1.281	0.697	0.6017
FR	20.323	2	10.161	3.170	0.0649
PFR	20.783	4	5.196	1.389	0.2566
DFR	32.083	4	8.021	1.366	0.2644
PDFR	24.145	8	3.018	1.244	0.2862

cont. on next page.

TABLE 11, cont.

Source of Variation	Sums of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Signif.
O (Order)	0.975	1	0.975	0.046	0.8294
PO	23.831	2	11.916	1.595	0.2293
DO	81.647	2	40.824	3.409	0.0544
PDO	55.284	4	13.821	2.336	0.0732
FO	13.721	2	6.860	1.848	0.1850
PFO	14.927	4	3.732	0.507	0.7339
DFO	31.344	4	7.836	0.962	0.5583
PDFO	26.380	8	3.298	0.370	0.9330
RO	0.009	1	0.009	0.002	0.9681
PRO	10.755	2	5.377	2.511	0.1077
DRO	0.212	2	0.106	0.052	0.9498
PDRO	14.815	4	3.704	1.643	0.1838
FRO	0.267	2	0.134	0.048	0.9530
PFRO	7.434	4	1.859	0.808	0.5302
DFRO	7.254	4	1.813	0.930	0.5411
PDFRO	6.336	8	0.792	0.330	0.9512
S (Subjects)	12499.244	9	1388.805	579.430	0.0010
PS	328.538	18	18.252	7.615	0.0010
DS	343.899	18	19.106	7.971	0.0010
PDS	359.822	36	9.995	4.170	0.0010
FS	1091.502	18	60.639	25.299	0.0010
PFS	488.915	36	13.581	5.666	0.0010
DFS	707.847	36	19.662	8.203	0.0010
PDFS	1002.980	72	13.930	5.812	0.0010
RS	479.053	9	53.228	22.208	0.0010
PRS	85.951	18	4.775	1.992	0.0209
DRS	50.966	18	2.831	1.181	0.2990
PDRS	66.185	36	1.838	0.767	0.8072
FRS	57.694	18	3.205	1.337	0.1916
PFRS	134.683	36	3.741	1.561	0.0546
DFRS	211.447	36	5.874	2.451	0.0010
PDFRS	174.719	72	2.427	1.012	0.4793
OS	192.260	9	21.362	8.913	0.0010
POS	134.448	18	7.469	3.116	0.0010
DOS	215.561	18	11.976	4.996	0.0010
PDOS	212.982	36	5.916	2.468	0.0010
FOS	66.830	18	3.713	1.549	0.0983
PFOS	265.229	36	7.367	3.074	0.0010
DFOS	293.328	36	8.148	3.399	0.0010
PDFOS	641.973	72	8.916	3.720	0.0010
ROS	48.944	9	5.438	2.269	0.0265
PROS	38.541	18	2.141	0.893	0.5882
DROS	36.892	18	2.050	0.855	0.6320
PDROS	81.133	36	2.254	0.940	0.5711
FROS	49.728	18	2.763	1.153	0.3229
PFROS	82.814	36	2.300	0.960	0.5433
DFROS	70.176	36	1.949	0.813	0.7494
PDFROS	172.573	72	2.397		
TOTAL	23495.664	1079			

As in the first ANOVA, the sequence effect was significant ($p=0.0078$) and it interacted with the peak-to-background ratio ($p=0.0021$). The repetition rate, F , was not significant ($p=0.5594$). However, the duty factor, D , was significant ($p=0.0011$) and it interacted with the peak-to-background ratio ($p=0.0326$).

The results of post hoc testing on the main effect of the duty factor, D , are shown in figure 46. The horizontal line below the bars indicates that the overall means of the 0.1 and 0.05 duty factor conditions were equivalent. Decreasing the factor to 0.025 increased the PSE by about one dB, a difference which was significant at the $p=0.01$ level on post hoc testing.

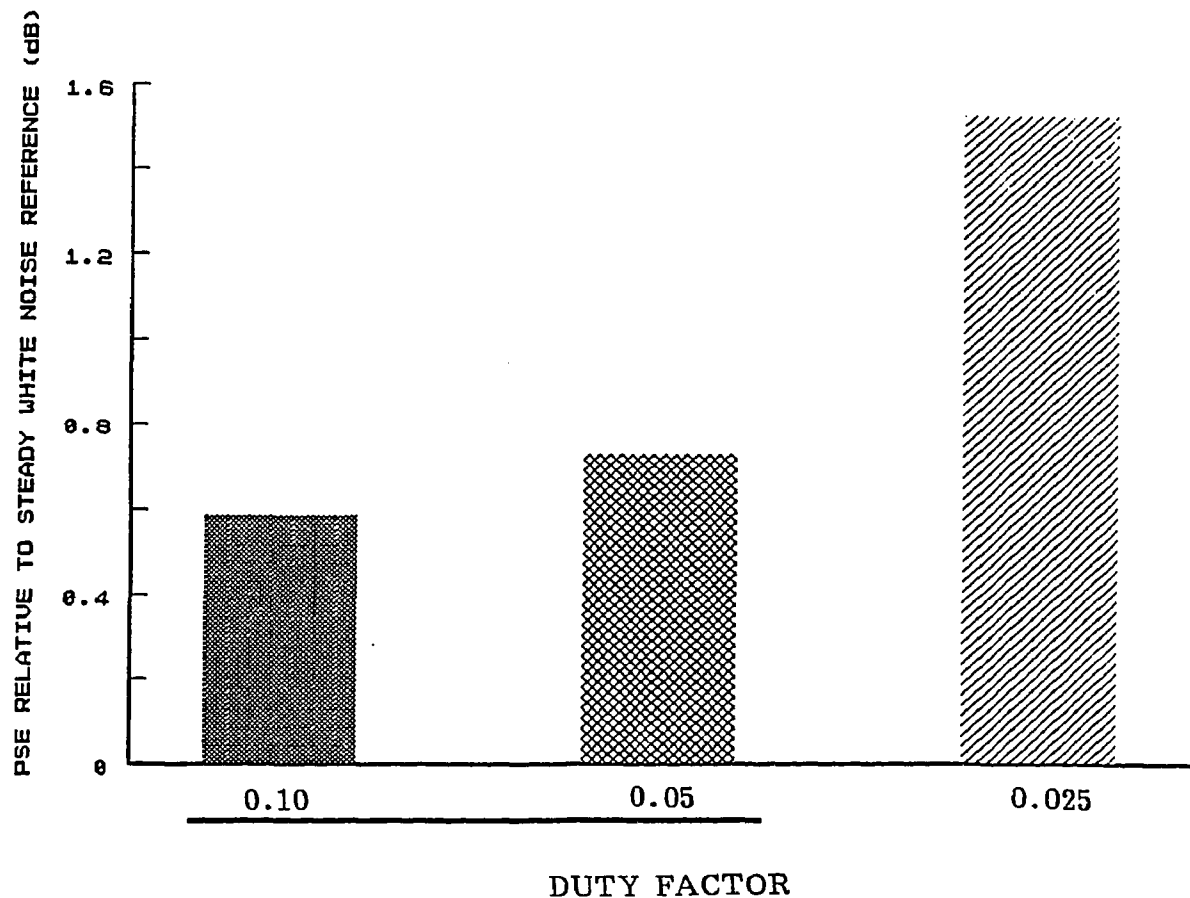


Figure 46. Results of post-hoc testing on the main effect of the duty factor, D , in the data of experiment 1 at 5, 10, and 20 Hz.

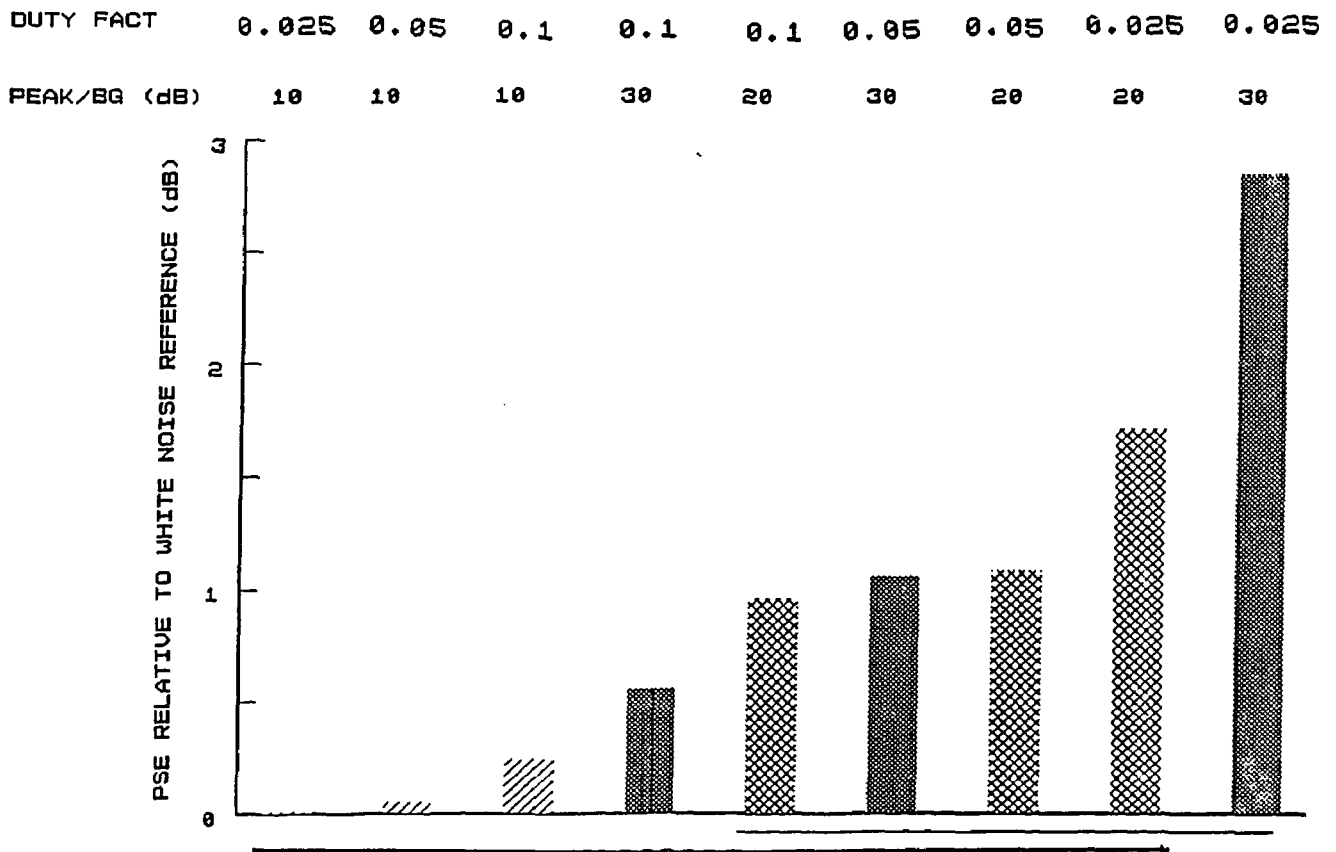


Figure 47. Results of post-hoc testing on the interaction between the duty factor, D , and the peak-to-background ratio, P , in the data of experiment 1 at 5, 10, and 20 Hz. The duty factors and peak-to-background ratios are indicated at the top of the figure. The shading of the bars indicates the peak-to-background ratio condition: light diagonal shading, 10 dB; light cross-hatching, 20 dB; dark cross-hatching, 30 dB.

Figure 47 shows how the duty factor, D , interacted with peak-to-background ratio, P . The shading of the bars indicates the peak-to-background ratio, and the duty factors and peak-to-background ratios are indicated at the top of the bar chart. At the 10 dB peak-to-background ratio, the three duty factor conditions were equivalent on post hoc testing. The duty factor conditions at 20 dB peak-to-background ratio were significantly different from the 10-dB conditions, but not from each other. However, at 30 dB peak-to-background ratio, all three duty factor conditions differed significantly. The PSE at the

lowest duty factor exceeded that at the medium duty factor by about two dB, and it, in turn was about 0.5 dB higher than that of the highest duty factor.

All of the foregoing analyses have shown strong variability between subjects. Although individual subjects were quite consistent in their results, as evidenced by the small magnitude of the order effect (the difference between replications of the measurements), there were significant subject effects and interactions ($p < 0.0010$) in the data on the steady background noise stimuli and in experiment 1. As can be seen in

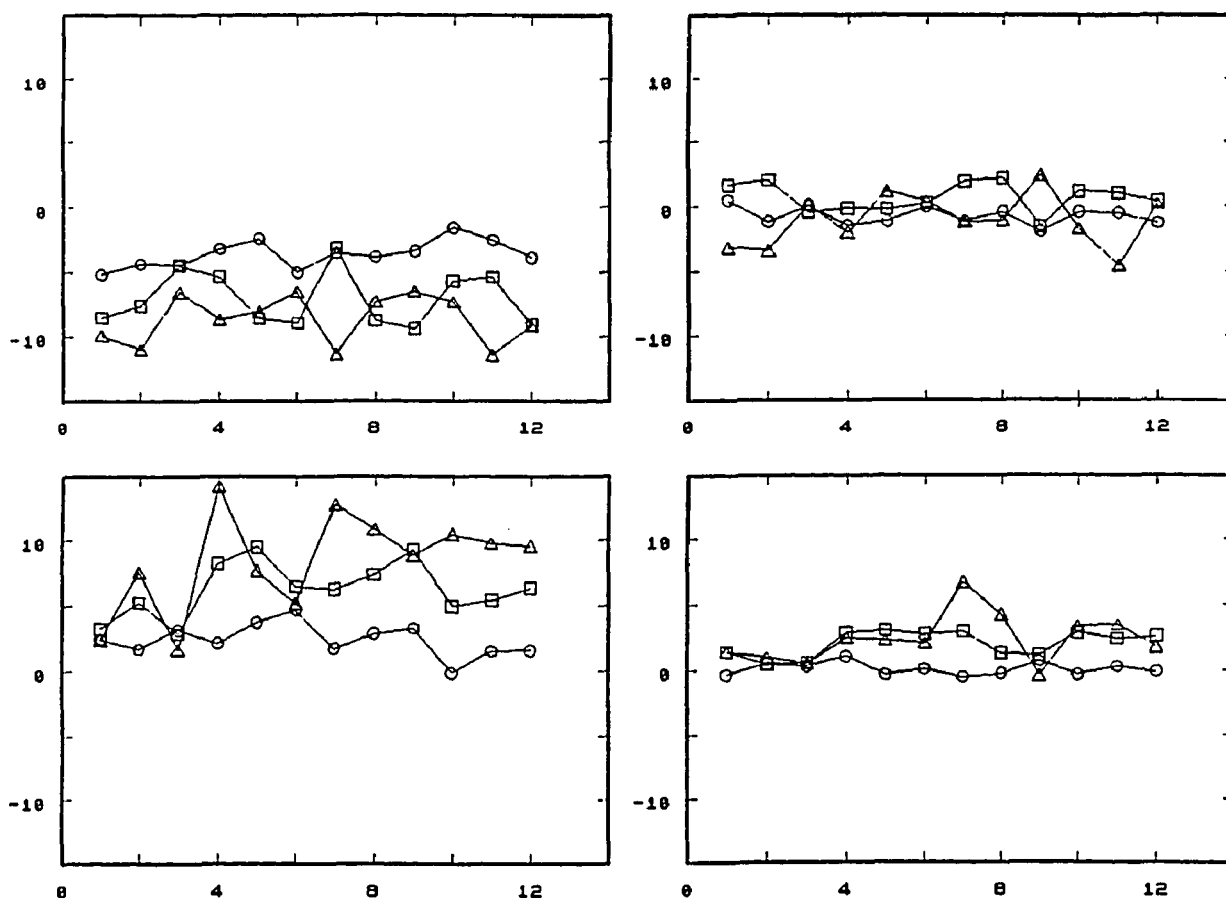


Figure 48. Individual data profiles of four subjects in experiment 1. The abscissa in each plot is the mean PSE relative to the steady white noise reference. The 12 different noise types are represented from left to right along the abscissa in the order of Table 1. The three lines in each profile represent the 3 peak-to-background ratio conditions: circles, 10 dB; squares, 20 dB; triangles, 30 dB.

figure 48, the mean PSEs of the different subjects in experiment 1 seemed to follow several patterns. This figure shows examples of the profiles of four individual subjects. The numbers along the abscissa of each profile represent the twelve different noise types (combinations of repetition rate and duration) in the order of table 1; The ordinate is the subject's point of subjective equality (PSE) relative to the steady white noise reference. The subjects whose profiles are shown in figure 48a and b were extreme outliers, while the two profiles in parts c and d of the figure were more typical of the remainder of the subjects. The three lines in each profile represent the three peak-to-background ratio conditions.

The subject whose profile is shown in figure 48a was the only subject who perceived all of the impulse noise stimuli as louder than the steady white noise reference stimulus (i.e. had PSEs less than zero), even at the 10-dB peak-to-background ratio. He consistently had the lowest PSEs at the 30 dB peak-to-background ratio, and the highest PSEs at the 10-dB peak-to-background ratio. The stimuli at the lowest duty factor (numbers 4, 7, and 10) had higher PSEs than all of the other noises at the 20-dB peak-to-background ratio, i.e. the loudness increased with increasing duty factor. However, the converse was true at the 30-dB peak-to-background ratio.

The data of the subject in figure 48b is practically a mirror image of the first subject's. All but one of the impulse noise stimuli were perceived as softer than the reference (i.e. had relative PSEs greater than zero). He consistently had the highest PSEs at the 30-dB peak-to-background ratio, and the lowest PSEs at the 10-dB peak-to-background ratio. The stimuli with the lowest duty factor (numbers 4, 7, and 10) had higher

PSEs than all of the other stimuli at 30-dB peak-to-background ratio, while those at the highest duty factor (6, 9, and 12) had lower PSEs than all of the other stimuli. Thus, the loudness increased with increasing duty factor at the 30 dB peak-to-background ratio. At the 20 and 10-dB peak-to-background ratios, however, the loudness decreased with increasing duty factor in a consistent pattern.

This type of consistency is not seen in the profile shown in figure 48c, and overall the PSE for this subject was much closer to the reference stimulus level. The negative PSE of the 100-Hz stimulus at the 30-dB peak-to background ratio (noise number 1) was observed in the profiles of most of the subjects. The profile in figure 48d is somewhat similar to the profile in figure 48b, but again there was a much narrower range of PSEs for the different conditions. The data at the 10-dB peak-to-background ratio were consistently within one dB of the reference level for all 12 noise types. The data at the 30-dB peak-to-background ratio, and also, to some extent, at 20 dB, followed the pattern of subject of figure 48b at 30 dB in that the loudness increased with increasing duty factor. This is especially marked in noises 7, 8 and 9, which are at the 10-Hz repetition rate with duration of 5, 10 and 20 msec.

In the course of analyzing the data, it was noted that those subjects who tended to have high PSEs for the impulse noise test stimuli also had high PSEs for some of the steady background noise stimuli, particularly the band-pass filtered noise. Therefore, an attempt was made to fit the mean PSEs of the individual subjects that were measured in experiment 1 to the mean PSEs for the steady band-pass filtered background noise stimulus using a linear least squares fitting procedure. Initially, the procedure was applied to the means for all of the noise conditions of

experiment 1, i.e. after averaging each subject's measured PSEs over the 12 noise types and over the three peak-to-background ratios. The result of this procedure is shown in figure 49. The abscissa is the PSE for the steady band-pass filtered noise stimulus, while the ordinate is the mean PSE for all of the impulse noise stimuli of experiment 1.

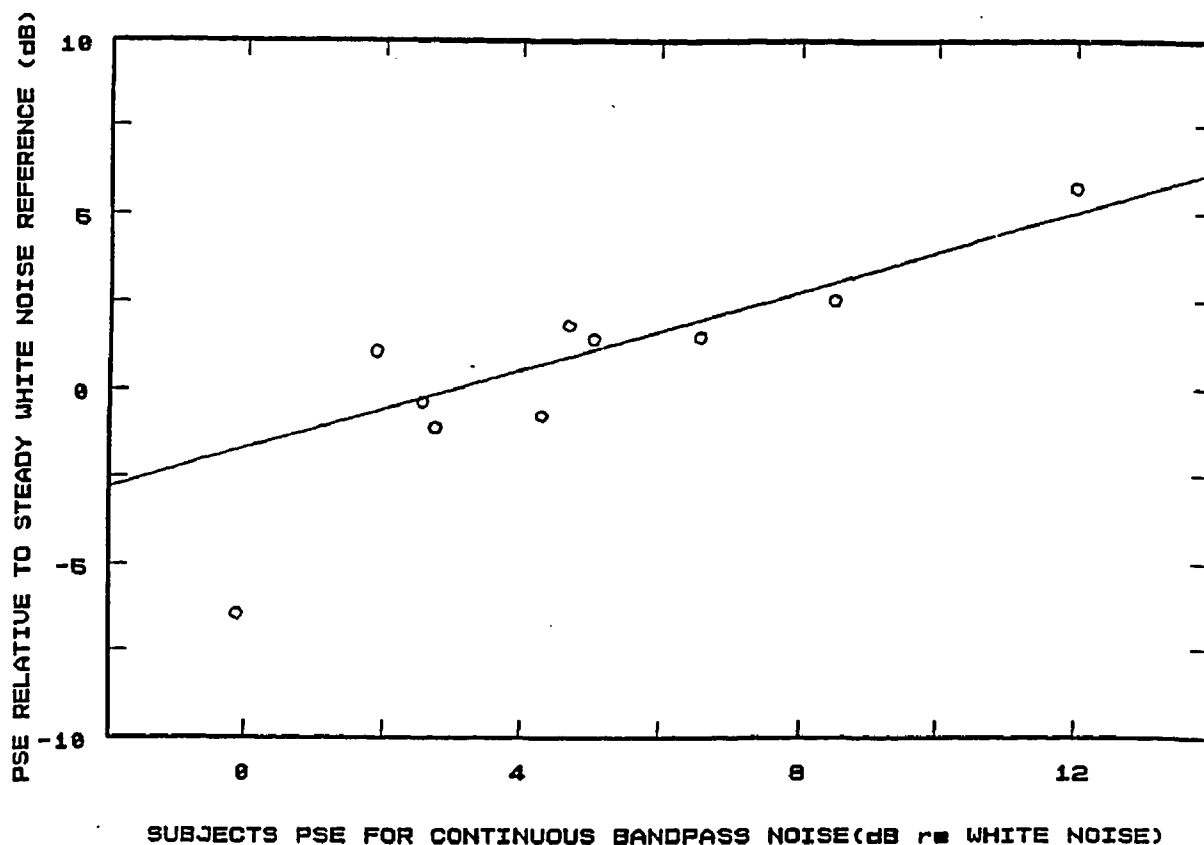


Figure 49. Mean PSEs of individual subjects (averaged over all impulse noise test stimuli of experiment 1) plotted as a function of the subjects' mean PSEs for the steady, band-pass filtered background noise stimulus. The straight line was determined by a least squares fitting procedure and is given by equation 8.1.

The equation for the least squares fit shown in figure 49 was:

$$(8.1) \quad \text{PSE}_{\text{imp}} = 0.56 \times \text{PSE}_{\text{bn}} - 1.7 \text{ dB}$$

where PSE_{IMP} is a subject's mean PSE for all of the impulse noise stimuli of experiment 1, and PSE_{BN} is that same subject's mean PSE for the steady, band-pass filtered background noise stimulus. The mean PSE of the subject whose profile was shown in shown in Figure 48a is plotted but was not included in the least squares fitting routine (this is the outlier point at a mean PSE of approximately -6 dB). However, the mean PSE of approximately +5 dB of the other "outlier" subject, (whose profile was shown in figure 48b), was included in the fitting procedure because it agrees rather well with the rest of the data. The mean squared error, sigma, of the this line compared to the data was 1.06.

Next, the subjects' mean PSEs were averaged over the 12 noise types, but not over peak-to-background ratio, and a separate least squares fitting procedure was conducted at each peak-to-background ratio. The data of the outlier subject whose profile was shown in figure 48a was excluded from the fitting procedure. The equation for the least squares fit at the 10 and 20-dB peak-to-background ratios was

$$(8.2) \quad PSE_{IMP} = M_{PB} \times PSE_{BN} - 1.2 \text{ dB}$$

where PSE_{IMP} is a subject's mean PSE for all of the impulse noise stimuli of experiment 1 at the given peak-to-background ratio, PSE_{BN} is that same subject's mean PSE for the steady, band-pass filtered background noise stimulus, and M_{PB} is a slope that depended on the peak-to-background ratio. At the 10-dB peak-to-background ratio, the slope was 0.29, while at 20 dB, it was 0.55. At peak-to-background ratios of 10 and 20 dB, the mean squared error, sigma, of the least squares fitting procedure was 0.61 and 0.87, respectively. However, at the 30-dB peak-

to-background ratio, the best agreement obtainable with the least squares procedure was much higher ($\sigma = 2.02$). The best fit line for this condition was given by

$$(8.3) \quad PSE_{IMP} = 0.84 \times PSE_{BN} - 2.7 \text{ dB}$$

where PSE_{IMP} is a subject's mean PSE for all of the impulse noise stimuli at the 30 dB peak-to-background ratio in experiment 1, and PSE_{BN} is that same subject's mean PSE for the steady, band-pass filtered background noise stimulus.

Figure 50 shows the results of separate least squares fitting at each of the three peak-to-background ratios. The abscissa is the PSE for the band-pass filtered noise stimulus, while the ordinate is the mean PSE for all 12 of the impulse noise test stimuli at each peak-to-background ratio. From the pattern of the symbols on this plot, it can be seen that the subjects may be divided into three groups: (a) those subjects (six in number) who had higher PSEs for the impulse noise stimuli at the 30- dB peak-to-background ratio (triangles) than at 20 dB (squares), and lower PSEs at 10 dB than at 20 dB. (With one exception, these subjects had the highest PSEs for the band-pass filtered steady noise), (b) Those subjects (three in number) who had the highest mean PSE for the impulse noise stimuli at the 20 dB peak-to-background ratio; and (c), the single, outlier subject, who had the lowest PSE for the band-pass filtered steady noise and ranked the different peak-to-background ratio conditions in the opposite order from the first group.

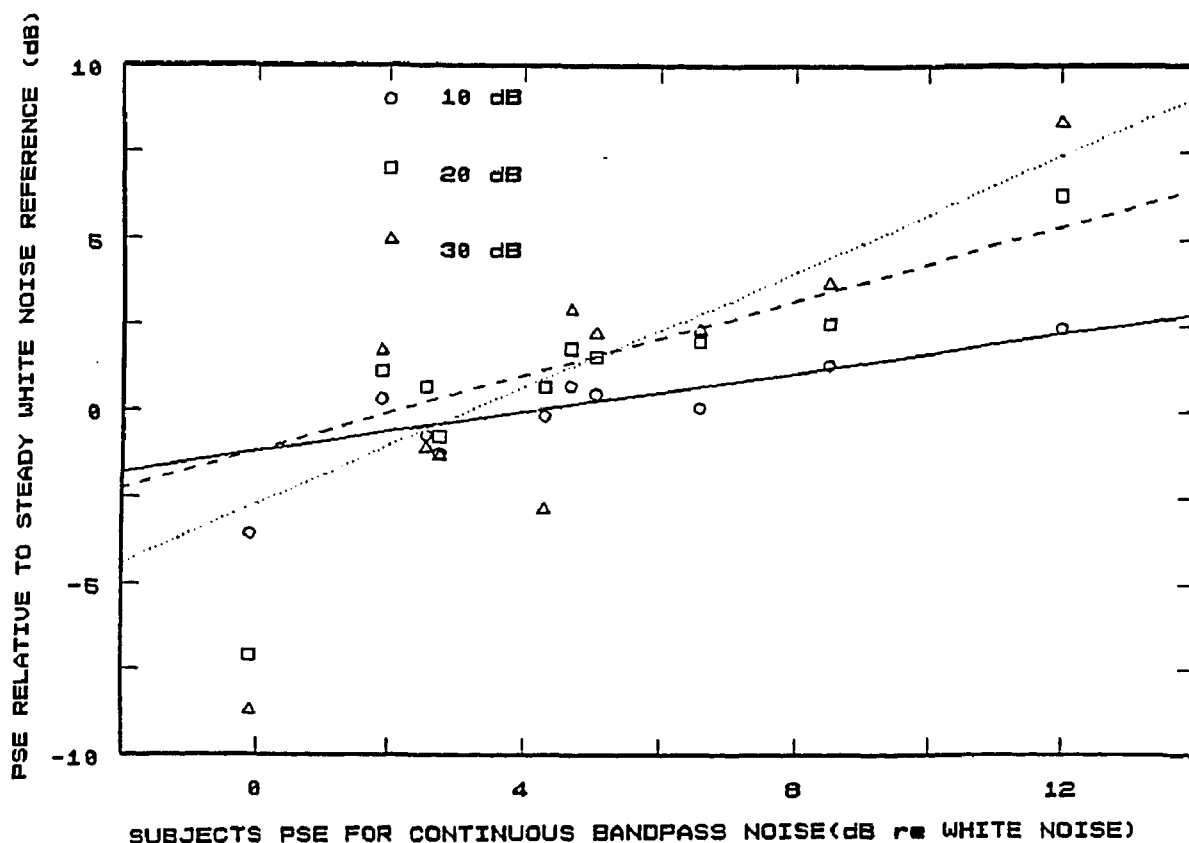


Figure 50. Mean PSEs of individual subjects (averaged over the impulse noise stimuli at each peak-to background ratio in experiment 1) plotted as a function of the subjects' mean PSEs for the steady, band-pass filtered background noise stimulus: circles, mean PSEs at 10 dB peak-to-background ratio; squares, mean PSEs at 20 dB; triangles, mean PSEs at 30 dB. The straight lines are the results of fitting these data by a linear least squares procedure at each peak-to-background ratio: solid line, 10 dB; dashed line, 20 dB; dotted line, 30 dB.

8.5 Experiment 2

In experiment 2, the steady background of four different spectral shapes was added to the white noise impulses at peak-to-background ratios of 10 and 20 dB. The parameters of the background noises were given in Table 2. The repetition rates and durations of the stimuli were outlined in chapter 5. The reference presentation level was 60.5 dB L_{eq} .

The results of the repeated measures ANOVA on the data of experiment 2 are shown in table 12. The factors in this analysis were: background noise shape, B, (four levels; white, low-pass filtered, band-pass filtered, and high-pass filtered), noise type, F, (four levels; 100 Hz-1.5 msec, 50 Hz-3.5 msec, 20 Hz-5 msec, and 10 Hz-10 msec), peak-to-background ratio, P, (two levels, 10 and 20 dB), and the sequence (R), order (O), and subject (S) factors as in experiment 1.

TABLE 12
ANALYSIS OF VARIANCE OF EXPERIMENT 2

Source of Variation	Sums of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Signif.
B (Spectrum)	66.373	3	22.124	1.391	0.2662
P (Peak/Backgr.)	0.043	1	0.043	0.000	0.9805
BP	44.392	3	14.797	3.997	0.0175
F (Noise Type)	602.846	3	200.949	13.476	0.0010
BF	53.686	9	5.965	1.173	0.3230
PF	33.654	3	11.218	1.895	0.1533
BPF	149.393	9	16.599	3.339	0.0019
R (Sequence)	35833.922	1	35833.922	668.089	0.0010
BR	6.284	3	2.095	0.730	0.5458
PR	6.764	1	6.764	1.584	0.2387
BPR	7.543	3	2.514	1.568	0.2192
FR	2.067	3	0.689	0.737	0.5419
BFR	12.135	9	1.348	0.760	0.6546
PFR	5.897	3	1.966	1.228	0.3187
BPFR	39.139	9	4.349	2.229	0.0278
O (Order)	25709.373	1	25709.373	1539.000	0.0010
BO	116.186	3	38.729	5.794	0.0037
PO	19.515	1	19.515	2.406	0.1529
BPO	27.965	3	9.322	1.721	0.1852
FO	26.587	3	8.862	2.769	0.0601
BFO	93.262	9	10.363	2.116	0.0370
PO	19.515	1	19.515	2.406	0.1529
BPO	27.965	3	9.322	1.721	0.1852
FO	26.587	3	8.862	2.769	0.0601
BFO	93.262	9	10.363	2.116	0.0370
PFO	19.077	3	6.359	1.293	0.2965
BPFO	77.456	9	8.606	2.173	0.0321
RO	26191.143	1	26191.143	9100.482	0.0010
BRO	4.664	3	1.555	1.135	0.3530
PRO	1.102	1	1.102	0.699	0.5708
BPRO	4.510	3	1.503	0.532	0.6681

cont. on next page.

TABLE 12, cont.

Source of Variation	Sums of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Signif.
FRO	8.006	3	2.669	1.139	0.3514
BFRO	11.796	9	1.311	0.794	0.6235
PYRO	6.574	3	2.191	0.865	0.5265
BPYRO	8.958	9	0.995	0.821	0.5993
S (Subjects)	10961.767	9	1217.974	1004.883	0.0010
BS	429.437	27	15.905	13.122	0.0010
PS	765.823	9	85.091	70.204	0.0010
BPS	99.960	27	3.702	3.054	0.0010
FS	402.614	27	14.912	12.303	0.0010
BFS	411.959	81	5.086	4.196	0.0010
PFS	159.867	27	5.921	4.885	0.0010
BPFS	402.662	81	4.971	4.101	0.0010
RS	482.728	9	53.636	44.252	0.0010
BRS	77.455	27	2.869	2.367	0.0018
PRS	38.423	9	4.269	3.522	0.0013
BPRS	43.303	27	1.604	1.323	0.1688
FRS	25.244	27	0.935	0.771	0.7739
BFRS	143.707	81	1.774	1.464	0.0440
PFRS	43.232	27	1.601	1.321	0.1702
BPFRS	158.009	81	1.951	1.609	0.0167
OS	150.347	9	16.705	13.783	0.0010
BOS	180.481	27	6.684	5.515	0.0010
POS	72.991	9	8.110	6.691	0.0010
BPOS	146.216	27	5.415	4.468	0.0010
FOS	86.420	27	3.201	2.641	0.0010
BFOS	396.744	81	4.898	4.041	0.0010
PFOS	132.777	27	4.918	4.057	0.0010
BPPOS	320.868	81	3.961	3.268	0.0010
ROS	25.902	9	2.878	2.374	0.0193
BROS	36.984	27	1.370	1.130	0.3283
PROS	14.176	9	1.575	1.300	0.2496
BPROS	76.299	27	2.826	2.331	0.0021
FROS	63.265	27	2.343	1.933	0.0124
BFROS	133.649	81	1.650	1.361	0.0836
PFRS	68.384	27	2.533	2.090	0.0061
BPFRS	98.176	81	1.212		
TOTAL	105840.188	1279			

As may be seen in table 12, there were no significant main effects due to either background noise shape, B, peak-to-background ratio, P, or order, O. The noise type, F, was significant ($p < 0.010$), as was the sequence effect, R, ($p = 0.0047$). There was a significant interaction

between background noise shape, B, and peak-to-background ratio, P. The results of post hoc testing on this interaction are shown in Figure 51. The horizontal lines beneath the bars show groups whose means did not differ significantly upon post-hoc testing. The shading of the bars indicates the peak-to-background ratio.

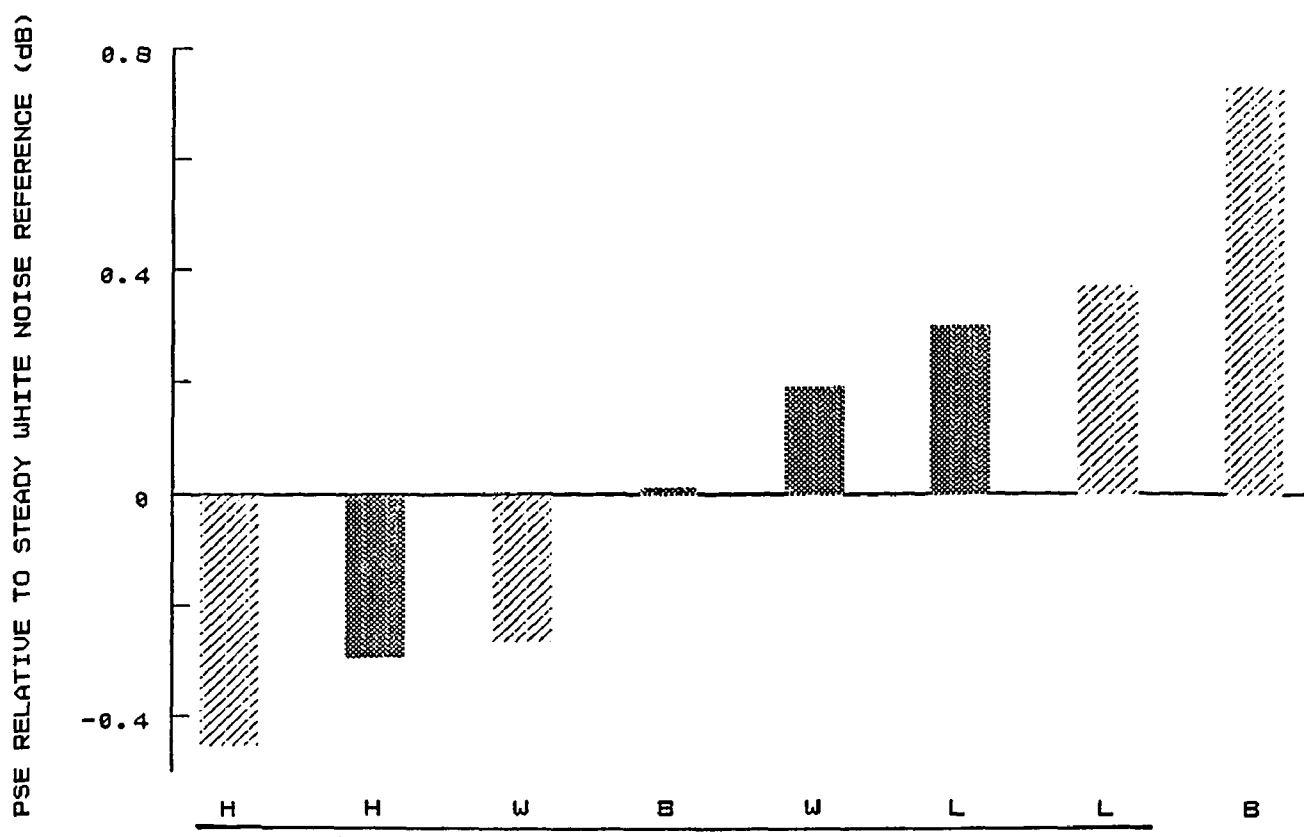


Figure 51. Results of post hoc testing on the interaction between the spectral shape of the background noise, B, and the peak-to-background ratio, P. The shading of the bars indicates the peak-to-background ratio condition: light diagonal shading, 10 dB; dark cross-hatching, 20 dB.

CHAPTER 9

DISCUSSION

9.1 White Noise Calibration

The results of the calibration analysis are a measure of the linearity of the testing system. In principle, it was possible to perform exact loudness balances between the test stimuli and the reference stimulus because they were identical in all respects except for their amplitude. If the testing system was linear, the test stimulus that was initially at -12 dB relative to the reference stimulus should have had a playback level of 12 dB above the reference stimulus playback level at the point of subjective equality (PSE); the test stimulus that was initially at +6 dB should have a playback level of 6 dB below the reference stimulus volume at PSE, and so on. In each case, the mean L_{eq} level of each test stimulus level should, on average, be equal to the reference stimulus level (60.5 dB L_{eq}) at the point of subjective equality (PSE).

The first of the former points is illustrated in figure 35, which shows the relation between the amount by which each test stimulus level differed from that of the reference stimulus (at equal playback level) and the change in level needed to compensate for this difference in order to reach the PSE. This change should correspond exactly to the physical level differences, yielding a linear relation between starting level and the PSE with a slope of -1 and an intercept of 0, indicated by the straight

line in the figure. Clearly, the line agrees with the data and falls well within the vertical error bars which indicate plus and minus one-half standard deviation.

The second of the above points, namely that the level of the calibration stimuli should, on average, have been the same as the presentation level of the reference noise (60.5 dB) is demonstrated by statistical analysis. The results of the statistical analysis displayed in Table 5 show that the noise level was not significant ($p=0.083$). This confirms that the testing system was linear and free of systematic biases.

The mean order effect in the calibration experiment was less than 0.05 dB ($p=0.6212$). The order effect is a comparison between the means obtained on the first and second set of interleaved trials. Thus the analysis shows that there was no learning effect for the steady state sounds. The mean sequence effect of 0.55 dB was not significant ($p=0.6273$). However, there was a significant interaction ($p<0.01$) between the sequence and subject factors. One would expect the point of subjective equality to be higher in the set of trials in which the test stimulus precedes the reference; since the reference is last it should be louder, and the subject would have to increase the level of the test stimulus to compensate. However, only four of the ten subjects followed this prediction. Moreover, the magnitude of the effect was as high as 4 dB in one subject, while values of order 0.5 dB were more typical.

9.2 Steady Background Noise Stimuli

The PSE of the four steady background noises stimuli was measured for two reasons. First, the measurements provided a baseline for the data

of experiment 2, in which combinations of these steady noises with impulses were studied. Second, the measurements allowed for comparison between the accuracy of the Zwicker loudness computation procedure for predicting the loudness of impulse noises and its accuracy in predicting the loudness of steady noise in the same subject population.

The results of the ANOVA (table 6) and the post hoc testing (figures 37 and 38) on the steady background noise stimuli show that the band-pass and low-pass filtered stimuli had a significantly higher PSE than the white and the high-pass filtered stimuli. The fact that the order effect was not significant indicates that, as in the case of the calibration data, there was no learning effect. However, the mean sequence effect of 1.37 dB was nearly three times as high as that observed in the white noise calibration, suggesting that the subjects found it more difficult to retain the subjective impression due to the stimuli when there was a difference in noise spectrum between the test and reference stimuli.

In order to compare the data with the predictions of the Zwicker procedure, the loudness of each of the steady noises at the mean PSE was computed. The waveforms and one-third octave band spectra of these noises are shown in figures 60 to 63 of Appendix C. The loudness computations, according to ISO 532B (1975) that were performed using these one-third-octave-band spectra are shown in figure 60 of Appendix C. Since the computations were performed on the background noise stimuli at the levels which corresponded to the mean PSE for the subjects, this method should have predicted equal loudness values in sones for the four stimuli.

As can be seen in the figure, the values that were obtained ranged from a low of 12.9 sones for the high-pass filtered noise to 17.3

sones for the low-pass filtered noise. The predicted loudness for the white and the band-pass filtered noises were 14.5 and 16.8 sones, respectively. The subjects perceived the high-pass filtered noise as louder than would be predicted by the Zwicker method, and the low-pass and band-pass filtered noises were less loud than the Zwicker prediction. Thus, the Zwicker procedure does not appear to account for the differences in PSE that were observed for these subjects any more successfully than did the measured equivalent continuous sound pressure level.

9.3 Experiment 1

9.3.1 Discussion

The results the experiment 1 are summarized in figures 52 to 55 which show the effects of varying the duration and the peak-to-background ratio at each repetition rate. Several effects may be seen in the figures. First, the magnitude of the difference in L_{eq} between the test stimuli and the reference stimulus at PSE was less than three dB in all cases. Thus, to within plus or minus three dB, equal L_{eq} implied equal loudness for the stimuli used in this study. Second, the loudness depended on the peak-to-background ratio, and deviations from the equal L_{eq} rule were larger at higher peak-to-background ratios. Third, both repetition rate and duration were important parameters. At the 50 and 100-Hz repetition rates, most of the impulse noise test stimuli were louder than the reference stimulus (negative PSE). At the lower repetition rates the opposite was generally true. Increasing the duration tended to increase loudness at the low repetition rates, especially at the 30-dB peak-to-background ratio.

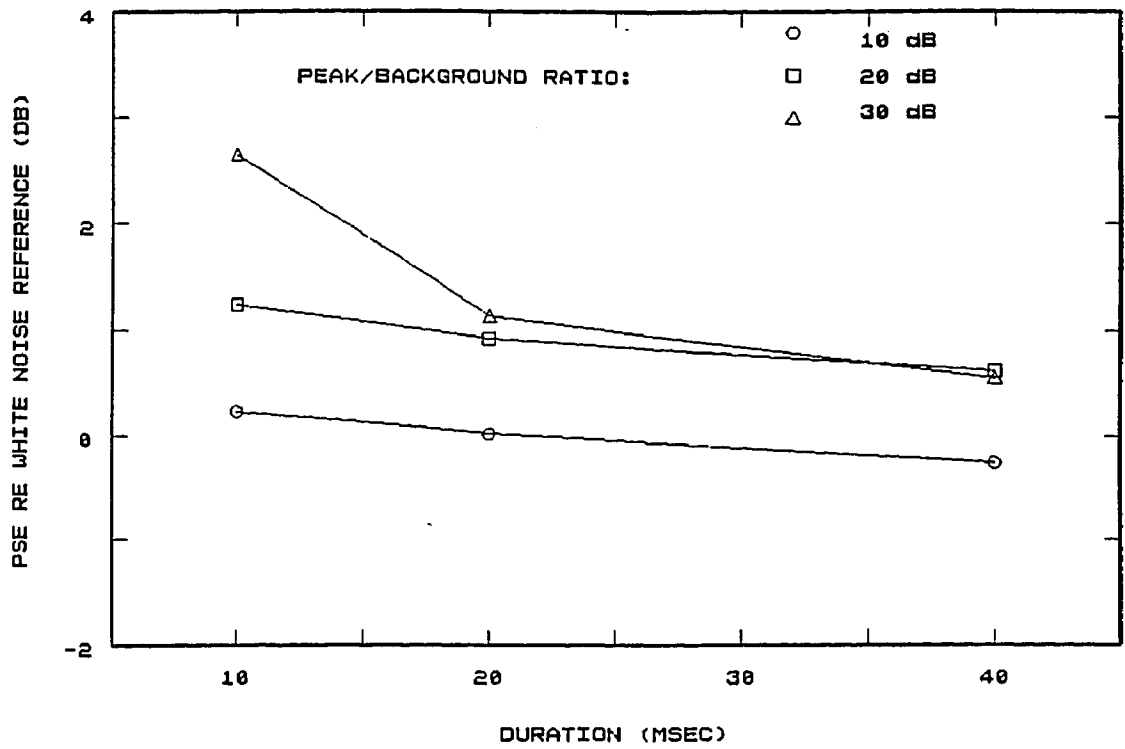


Figure 52. PSE as a function of duration, with peak-to-background ratio as a parameter, at a 5-Hz repetition rate.

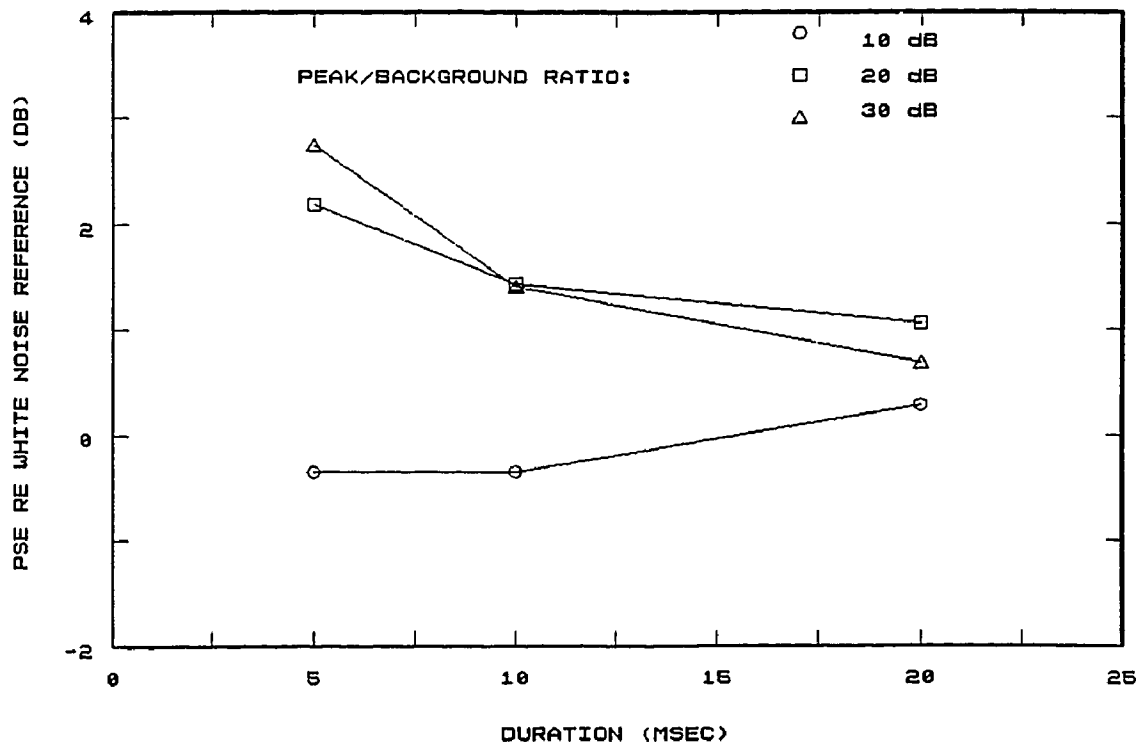


Figure 53. PSE as a function of duration, with peak-to-background ratio as a parameter, at a 10-Hz repetition rate.

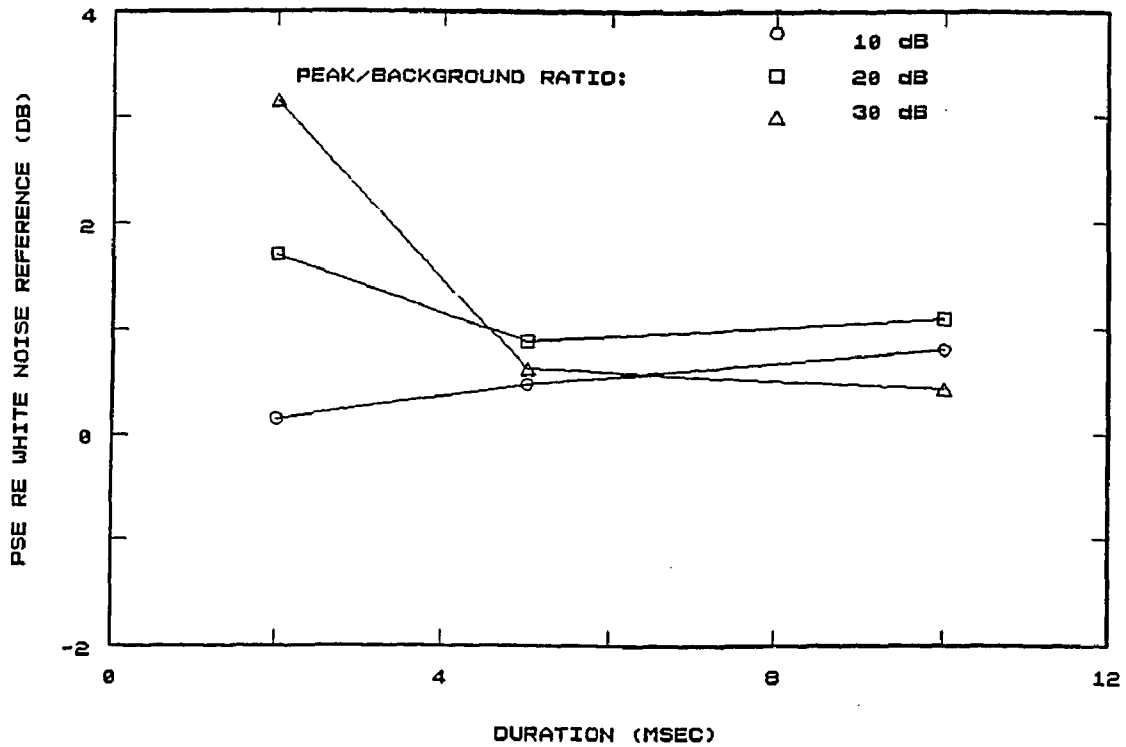


Figure 54. PSE as a function of duration, with peak-to-background ratio as a parameter, at a 20-Hz repetition rate.

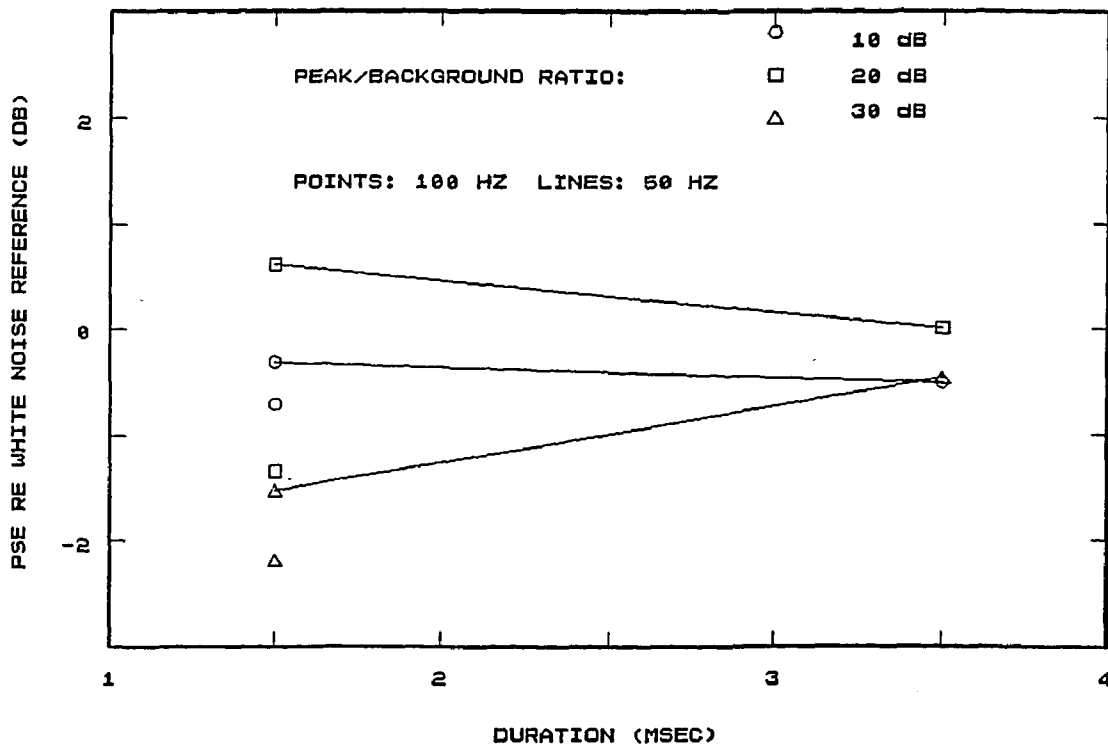


Figure 55. PSE as a function of duration, with peak-to-background ratio as a parameter, at the 50 and 100-Hz repetition rates.

The PSEs of the stimuli also were affected differently by changes in the peak-to-background ratio. At 100 Hz, increasing the peak to background ratio monotonically increased the loudness, while at the low repetition rates, the opposite was true. The results at 50 Hz data were an intermediate case; both the 30-dB and the 10-dB conditions were louder than the 20-dB condition.

The above observations on the data are reflected by the results of the statistical analyses that were described in Chapter 8. The first ANOVA that was performed (table 7) demonstrated that noise type (combination of repetition rate and duration) has a significant effect on loudness. As was discussed in chapter 8, the results of post hoc testing on this effect (figure 40) indicate that the 12 noise types may be divided into three groups. The loudness levels of the impulse noise stimuli with the longest durations at the 5, 10, and 20-Hz repetition rates were not significantly different from that of the reference stimulus. Thus, within experimental error, equal L_{eq} corresponded to equal loudness for these stimuli. The fact that the stimuli at 50 and 100 Hz were louder than the reference stimulus may have been due to the roughness effect (Pollack 1969; Terhardt 1974). The fact that the shortest impulses at 5, 10, and 20 Hz were less loud than the reference stimulus may be due to auditory temporal integration behavior at short durations. Both of these possibilities will be considered in more detail below.

The order effect was not significant in the first experiment, which suggests that, as in the case of the steady calibration and background noise stimuli, there was no learning effect. The mean sequence effect of 1.53 dB was comparable to that obtained with the steady background noise stimuli. However, as can be seen in figure 39, the magnitude of the

effect depended on the peak-to-background ratio. The shading in the figure indicates the peak-to-background ratio. The magnitude of the sequence effect is the difference between the levels of the test-stimulus-first condition and the reference-stimulus-first conditions. It can be seen that the sequence effect was highest at the 30-dB peak-to-background ratio condition (2.05 dB). At the 20-dB peak-to-background ratio, the sequence effect was 1.62 dB, and it dropped to 0.93 dB at the 10-dB peak to background ratio. Thus, the ease with which the subjects retained the subjective impression due to the stimuli appears to be related to how similar those noises were to steady noise.

The results of the separate ANOVAs at the different peak-to-background ratios (tables 8-10) elucidated the effects of varying the peak-to-background ratio. The absence of a significant main effect due to noise type in the first of these analyses demonstrates that, at a peak-to-background ratio of 10 dB, the loudness was fully predicted by the equivalent continuous sound pressure level, L_{eq} .

At the 20-dB peak-to-background ratio, the only impulse noise stimulus that was significantly louder than the reference noise was the 100-Hz condition, as may be seen from the results of the post hoc testing in figure 42a. The tendency of the PSE to increase with decreasing duration is evident in this figure, but it is not nearly so marked as at the 30-dB peak-to-background ratio, as shown in figure 42b. This figure also shows that, at the 30-dB peak-to-background ratio, the stimuli with the 100-Hz and 50-Hz repetition rates and 1.5-msec duration were significantly louder than the reference stimulus. Overall, in going from 20 to 30 dB, the PSE of the 100 Hz impulses drops by about 1 dB in PSE, and that of the shortest impulses at 5, 10, and 20 Hz

increases by about 1 dB. The other notable change is the increase in the loudness of the 50 Hz, 1.5 msec condition by almost 2 dB as the peak-to-background ratio increases from 20 to 30 dB.

The results of experiment 1 may be qualitatively explained as a combination of three effects; (a) the roughness effect, (b) temporal integration, and (c) a monotonic transition between the PSE for background noise alone at high background noise levels (10-dB peak-to-background ratio) to the PSE for the impulses alone at low background levels (30-dB peak-to-background ratio). The roughness effect appears to increase the loudness level of the impulses at the 50 and 100-Hz repetition rates. The fact that the shortest impulses at the lower repetition rates were perceived as softer than the reference noise is most probably a manifestation of the temporal integration process. The dependence of both of these effects on the peak-to-background ratio is suggestive of a simple masking process.

There are several reasons to pinpoint the roughness effect as the source of the lower PSE of the impulses at 50 and 100 Hz. The roughness effect is due to periodic amplitude modulation of noise (i.e. either noise bursts or noise with a fluctuating level) when the modulation rate is high enough that the bursts or impulses fuse psychoacoustically. The resulting harsh, tonal buzzing has a pitch that corresponds to the modulation or repetition rate. Terhardt (1974) has stated that the onset of roughness occurs at a repetition rate of about 20 Hz. Pollack (1969) found that subjects were able to perform pitch matches between interrupted white noise and sine waves down to interruption rates of 10-100 Hz. The lower limit of 10 Hz occurred at higher presentation levels. (This level dependence could be explained by assuming that the

roughness effect consists of a harmonic series, with a fundamental frequency at the repetition rate, and decreasing amplitude with increasing frequency. At rates so low that the fundamental is not perceived, the level would have to be increased so that the higher harmonics would be audible).

In the data of experiment 1, the lowering of the PSE below that of the reference is more marked at 100 Hz than at 50 Hz, in agreement with the data of Pollack (1969). Moreover, there were clearly audible differences between the stimuli at 50 and 100 Hz and those at the lower repetition rates. At the higher repetition rates, the impulses were not individually distinguishable, and the tonal buzzing was audible. Thus, it is plausible that the roughness effect played a significant role in determining the loudness of the impulses in experiment 1 at the higher repetition rates (50 and 100 Hz).

The magnitude of the roughness effect, i.e. the degree to which it increases the loudness of repeated impulses (or amplitude modulated noise) has not received extensive study. Reichardt and Niese (1970) have indicated that the roughness effect may confound the results of psychoacoustical studies on impulse noise. Certainly, one may argue that, in a study on the effects of isolated impulses, repeating the stimuli at too high a rate would lead to a roughness component that would have little relevance to the loudness of isolated impulses. However, it seems clear that the roughness effect may constitute a legitimate contribution to the psychoacoustical impact of repeated impulses.

Temporal integration effects may be evident in the fact that the PSE for the shortest impulses (lowest duty factor) at 5, 10, and 20 Hz is higher than what would be predicted from an equal energy basis, while at

longer durations, the data follow an equal energy rule. This behavior may be explained using one of the two-time-constant "duration models" such as those of Green et al. (1957) or of Poulsen (1978), which were discussed in Section 4.5. It was shown in chapter 4 that the models predict approximate equal energy behavior over for durations that are between the two auditory integration times. At durations that exceed the longer integration time, T_2 , auditory temporal integration is complete, and further increases in duration yield no further increase in loudness level. At durations shorter than the short integration time, T_1 , loudness decreases with decreasing duration at a rate that exceeds the predictions of the equal energy rule.

The deviation from the equal energy relation in the vicinity of the short integration time T_1 (usually of order 10-20 msec) is evident in the data of experiment 1. Equal energy behavior manifests as a PSE of 0 dB because the data are plotted in terms of the difference in the L_{eq} of the test stimulus and the reference stimulus at the PSE, and the overall stimulus durations are equal. The elevated PSE at short durations means that loudness decreased with decreasing duration at a rate higher than that predicted by the equal energy relation.

However, direct application of the duration model for isolated impulses to these data would not account for the fact that the deviation from the equal energy relation with decreasing duration occurred at different durations depending upon the repetition rate. For example, the loudness levels of the 10-msec impulses at 10 and 20 Hz were not significantly different from that of the reference stimulus. However, at 5 Hz, the 10-msec impulse was perceived to be significantly less loud than the reference stimulus, despite the fact that its peak level was higher at

the 5-Hz repetition rate than at the 10 and 20 Hz rates. The implication of this result is that, in applying the two-time-constant model, the short time constant would have to depend on the repetition rate.

An alternative approach would be to incorporate the duty factor, rather than the impulse duration, into the model. It was shown in chapter 8 that, when analyzed on the basis of duty factor rather than duration, the data of experiment 1 at 5, 10, and 20 Hz follow a consistent pattern. In the analysis, neither duration nor repetition rate were significant, but there was a significant main effect due to duty factor. As will be seen below, this finding has allowed the application of Poulsen's model of auditory temporal integration to the data.

The observed dependence of the PSE on the peak-to-background ratio suggests that, as the peak-to-background noise ratio is decreased (background noise level is increased) the background noise simply masks the impulses. In the case of physiological damage due to hazardous levels of impulse noise, there is evidence that a synergistic interaction between continuous and impulse noise leads to more damage than would be obtained from comparable levels of either component by itself (Henderson and Hamernick 1986). In contrast, the psychoacoustical data do not show a synergistic interaction of this type. Rather, there was a fairly smooth transition in the loudness levels of each noise type as the peak-to-background noise ratio was decreased from 30 dB to 10 dB. The largest deviations from the equal energy rule were generally observed at 30-dB peak-to-background ratio, while at 10 dB, the loudness levels of the impulse noise test stimuli at the PSE were not significantly different from that of the reference stimulus.

The fact that adding background noise to the impulse noise test

stimuli at 50 and 100 Hz decreased their loudness suggests that the background noise reduced the roughness effect. Terhardt (1974) has shown that, for amplitude modulated noise (rather than discrete impulse trains) the roughness decreases with decreasing modulation depth. It also seems plausible that the addition of background noise to impulses that are short compared to the shorter time constant of temporal integration would increase the amount of energy that would be integrated, and thus increase the loudness level. An interaction between these two counteracting effects that depends on the peak-to-background ratio may be able to explain some of the results of experiment 1. For example, it may be seen in figure 41 that, at the 50-Hz repetition rate, the impulses had a higher PSE at 20-dB peak-to-background ratio than at either 10 or 30 dB. One explanation for this is that the higher PSE at 20 dB is due to temporal integration, but that the roughness effect, which is rather weaker than at 100 Hz, is masked by the background noise. However, at the 30-dB peak-to-background ratio, the drop in PSE due to the roughness effect may be strong enough to counteract the increase due to temporal integration. Similarly, the decrease in the loudness level of the impulses with the longest durations at 10 and 20 Hz in going from a peak-to-background ratio of 20 to 30 dB may be due to the onset of the roughness effect.

9.3.2 Model for the Results of Experiment 1

An empirical model was applied to the results of experiment 1 at the lower repetition rates of 5, 10, and 20 Hz. This model is an adaptation of the model of Poulsen (1978) which was discussed in Chapter 4. Poulsen's model was developed for isolated, rectangular tone bursts in the absence of background noise. In order to be applied to the present data, the

model had to be modified to account for: (a) the exponential envelopes of the impulse noise test stimuli, (b) the fact that the impulses were repeated, and (c) the effect of adding steady background noise.

Poulsen's model is expressed in terms of the ratio between the intensity (mean squared pressure) of a rectangular impulse of duration t and one of duration $2t$ at the PSE. However, as was shown in section 4.5.2.2, this expression was derived by Poulsen from a more general equation that is analogous to the exponential integration model of Plomp and Bouman (1959) but with two time constants:

$$(9.1) \quad S(t) = kI(1 - \exp\{-t/T_1\})(1 - \exp\{-t/T_2\})$$

where S is the sensation produced by a rectangular impulse of intensity (mean-squared pressure) I , T_1 and T_2 are auditory integration times (with $T_1 < T_2$), and k is a constant. As was discussed in Chapter 4, this model divides the range of impulse durations into three separate sections. At durations exceeding the long integration time T_2 , each bracketed term approaches unity and the sensation stays constant with increasing duration (i.e. loudness integration is complete). For impulse durations shorter than T_2 but much longer than T_1 , the expression predicts equal energy behavior (three dB increase in loudness level per doubling of duration). As the duration is decreased below T_1 , the model predicts that the loudness level will decrease more rapidly than the equal-energy prediction, with an asymptotic value of 6 decrease in loudness level per halving of the duration at the shortest durations.

Poulsen (1978) expressed this model in terms of the ratio of the intensities of impulses of duration t and $2t$ at the PSE for loudness (see equation 4.16, page 115). However, a more general expression may be

derived from the double exponential integration model of eq. 9.1 by taking the ratio of the sensation due to an impulse of effectively infinite duration and that due to an impulse of duration t , in analogy with the derivation for the single-time-constant model in chapter 4 (page 110). According to eq. 9.1, the sensation due to an impulse of effectively infinite duration, and intensity I_{∞} , asymptotically approaches the value $S_{\infty} = kI_{\infty}$. Thus the ratio between the sensation due to an impulse of duration t and intensity I_t and that of an impulse of effectively infinite duration and level I_{∞} is:

$$(9.2) \quad \frac{S_t}{S_{\infty}} = \frac{kI_t(1-\exp\{-t/T_1\})(1-\exp\{-t/T_2\})}{kI_{\infty}}$$

Setting the left side of the equation to unity (at PSE) yields:

$$(9.3) \quad \frac{I_t}{I_{\infty}} = \frac{1}{(1-\exp\{-t/T_1\})(1-\exp\{-t/T_2\})}$$

in analogy with eq. 4.9. This expression gives the intensity (mean-squared pressure) of a rectangular impulse of duration t compared to the intensity of an impulse of level I_{∞} and effectively infinite duration ($t \gg T_2$) at the PSE.

In order to apply this model to repeated impulses with exponential envelopes and added background noise, several modifications and assumptions were made. The first step was to address the fact that the stimuli in the present experiment had double-sided exponential envelopes rather than the rectangular envelopes used by Poulsen. Thus, in order to apply the Poulsen model, it was assumed that an isolated impulse with

arbitrary envelope shape can be approximated as a rectangular impulse with the same energy and the same peak level. As was shown in chapter 5, the "effective duration" of this equivalent rectangular impulse is given by:

$$(9.4) \quad t_{eff} = \frac{1}{I_p} \int_0^{\infty} p(t)^2 dt$$

where I_p is the peak level of the impulse.

The effective duration of an individual impulse in an impulse train is obtained from eq. 9.4 by replacing the upper integration limit with the repetition period, τ :

$$(9.5) \quad t_{eff} = \frac{1}{I_p} \int_0^{\tau} p(t)^2 dt$$

Next, it was assumed that the effective duration of a train of repeated impulses with arbitrary, but constant envelope shape, and constant repetition rate and peak level may be estimated from the integral of the mean-squared pressure waveform over the auditory integration time window, divided by the peak level, in analogy with the expression for a single impulse. In other words, if N impulses, each of equal effective duration t_{err} , and of constant level I_a , occur during the integration time window, the effective duration for the impulse train is Nt_{err} . Thus, the effective duration, d , for a train of these impulses is equal to the product of the number of impulses occurring in the

integration time window T_2 and the effective duration of a single impulse.

Because the duration of the impulse train may or may not consist of an integral number of repetition periods, a more accurate estimate of the effective duration is obtained first determining the effective duration for the entire impulse train, and then multiplying the result by the ratio between the integration time window and the overall duration of the impulse train. In other words, if the overall duration is T_o , the number of impulses in the train is given by $T_o/\gamma = T_o \times F$, where γ is the period of the impulse train, and F is the repetition rate. Therefore the effective duration, d_o , for the entire train of impulses is:

$$(9.6) \quad d_o = \frac{(FxT_o)}{I_a} \int_0^{\gamma} p(t)^2 dt$$

However, the assumption of this model is that the above effective duration of the entire impulse train, d_o , is not the quantity to which the Poulsen model should be applied. Rather, as was stated above, the salient quantity is the effective duration in the integration time T_2 . Therefore, the effective duration, d , is

$$(9.7) \quad d = \frac{T_2}{T_o} \times d_o$$

Substituting eq. 9.6 into this expression yields:

$$(9.8) \quad \begin{aligned} d_o &= \frac{T_2}{T_o} \frac{(FxT_o)}{I_a} \int_0^{\gamma} p(t)^2 dt \\ &= \frac{(FxT_2)}{I_a} \int_0^{\gamma} p(t)^2 dt \end{aligned}$$

It was shown in chapter 5 that the duty factor of a train of repeated impulses is

$$(9.9) \quad DF = \frac{F}{I_a} \int_0^{\tau} p(t)^2 dt$$

thus, the effective duration d of the impulse train is simply

$$(9.10) \quad d = DF \times T_2$$

Substituting this expression for the effective duration d into the Poulsen model yields:

$$(9.11) \quad \frac{I_a}{I_\infty} = \frac{1}{(1 - \exp\{-(DF \times T_2)/T_1\})(1 - \exp\{-DF\})}$$

However, the levels in this expression are intensities, i.e. the mean-squared levels of individual rectangular impulses, while the experimental data are reported in equivalent continuous sound pressure levels, L_{eq} . The L_{eq} of the impulse of effectively infinite duration is simply $10 \log I_\infty$, and is equivalent to the L_{eq} of the steady reference stimulus. The L_{eq} level of the impulse of effective duration d is $10 \log (d \times I_a)/T_0$, which, from eq. 9.7 is equal to $10 \log (d \times I_a)/T_2$. Thus, the difference between the L_{eq} of a train of repeated impulses of effective duration d and a steady reference stimulus at the PSE is given by:

$$(9.12) \quad PSE = 10 \log \frac{d \times I_a}{T_2 \times I}$$

Substituting the duty factor DF for d/T_2 (from eq. 9.10) and the

expression from I_a/I_∞ from equation 9.11 yields:

$$(9.13) \quad \text{PSE} = 10 \log \frac{1}{DFx(1-\exp\{-(DFxT_2)/T_1\})(1-\exp\{-DF\})}$$

Thus, this expression predicts the L_{eq} at PSE of a train of repeated impulses of arbitrary envelope shape, but constant repetition rate and peak level, and in the absence of steady background noise, compared to the L_{eq} of a steady reference stimulus with a duration that is long compared to the temporal integration time, T_2 .

The effect of varying the peak-to-background ratio of the steady background noise was accounted for by assuming that the loudness level is linearly dependent on the difference, ΔL_{eq} , between the L_{eq} of the impulses and the L_{eq} of the background noise. At low values of the L_{eq} difference (e.g., -10 dB) the PSE relative to the steady reference stimulus is 0 dB because the steady background noise component of the stimulus masks the impulsive component. As the L_{eq} difference is increased above some value ΔL_{eq0} , the PSE increases linearly. Once

ΔL_{eq} reaches a high enough level that the stimulus is effectively background-free, the PSE reaches a plateau, PSE_{Max} , at an L_{eq} difference $\Delta L_{eq\text{Max}}$, and further increases in ΔL_{eq} will have no effect on the PSE. Thus, the PSE of the impulse noise stimuli with steady background noise is assumed to behave according to:

$$(9.14) \quad \text{PSE} = \frac{(\Delta L_{eq} - \Delta L_{eq0})}{(\Delta L_{eq\text{Max}} - \Delta L_{eq0})} \text{PSE}_{\text{Max}}$$

Where the value of PSE_{max} is dependent on the duty factor and is determined from the modified Poulsen model of eq. 9.13, and ΔL_{eq} is the difference between the L_{eq} of the impulsive component of the stimulus and the L_{eq} of the steady background noise component.

The values of ΔL_{eq0} and ΔL_{eqMax} were determined empirically. First, the L_{eq} differences for each of the stimulus noise-types (rate-duration combinations) of experiment 1 were determined from the synthesis parameters and from the duty factors in Table 2. The duty factor was divided by the square of the background noise level parameter, b . (This parameter was the factor by which the pressure-time waveform of the steady background noise was multiplied before adding it to the impulse pressure-time waveform to obtain the desired peak-to-background ratio). Ten times the log of this ratio was used as the ΔL_{eq} for each stimulus. Next, the data were plotted as a function of ΔL_{eq} , with duty factor as a parameter. The value of ΔL_{eq0} was obtained from this plot by estimating the L_{eq} difference at which the PSE dropped to zero. A value of ΔL_{eq0} of -5 dB appeared to be the best estimate at all three duty factors. The value of ΔL_{eqMax} (the L_{eq} difference at which the stimulus was effectively background-free was estimated to be between 20 and 25 dB.

The next step in applying the model was to set the time-constant T_2 . The fact that the data at the 5, 10, and 20-Hz repetition rates did not differ significantly when compared on the basis of duty factor suggests that T_2 should be at least 200 msec (the repetition period corresponding to 5 Hz), so that the effective durations for all three repetition rates were the same at a given duty factor. On the other hand, the results of the auditory temporal integration experiments discussed in chapter 4

suggest that T_2 should not be significantly longer than 200 msec. Accordingly, T_2 was set to 200 msec. Next, the values of T_1 and ΔL_{eqMax} were adjusted to obtain the best qualitative agreement with the data. The values that were determined were $T_1=10$ msec and $\Delta L_{eqMax}=25$ dB.

The predictions of the model using these values are shown in figures 56 and 57. In figure 56, the predictions are plotted as a function of duty factor, with the L_{eq} difference between impulses and background noise, ΔL_{eq} , as a parameter. The model predicts that, for high background levels (e.g., $\Delta L_{eq} = 0$ dB), the PSE will be that of the reference stimulus except at an extremely low duty factor. This makes sense because, if the duty factor is decreased sufficiently, the peak levels will become so high relative to the background noise that the impulses will begin to have some effect on the loudness. The sharp increase in the PSE at duty factors below 0.05 occurs because the effective duration of the impulse train is less than the short integration time constant T_1 . At the other extreme, as the duty factor approaches unity, the PSE approaches that of the reference stimulus, as it should, because the impulses overlap extensively at high duty factors. The fact that the lines are parallel at the intermediate durations is due to the assumption that the PSE varies linearly with ΔL_{eq} (the difference between the L_{eq} of the impulsive component and the L_{eq} of the steady background component).

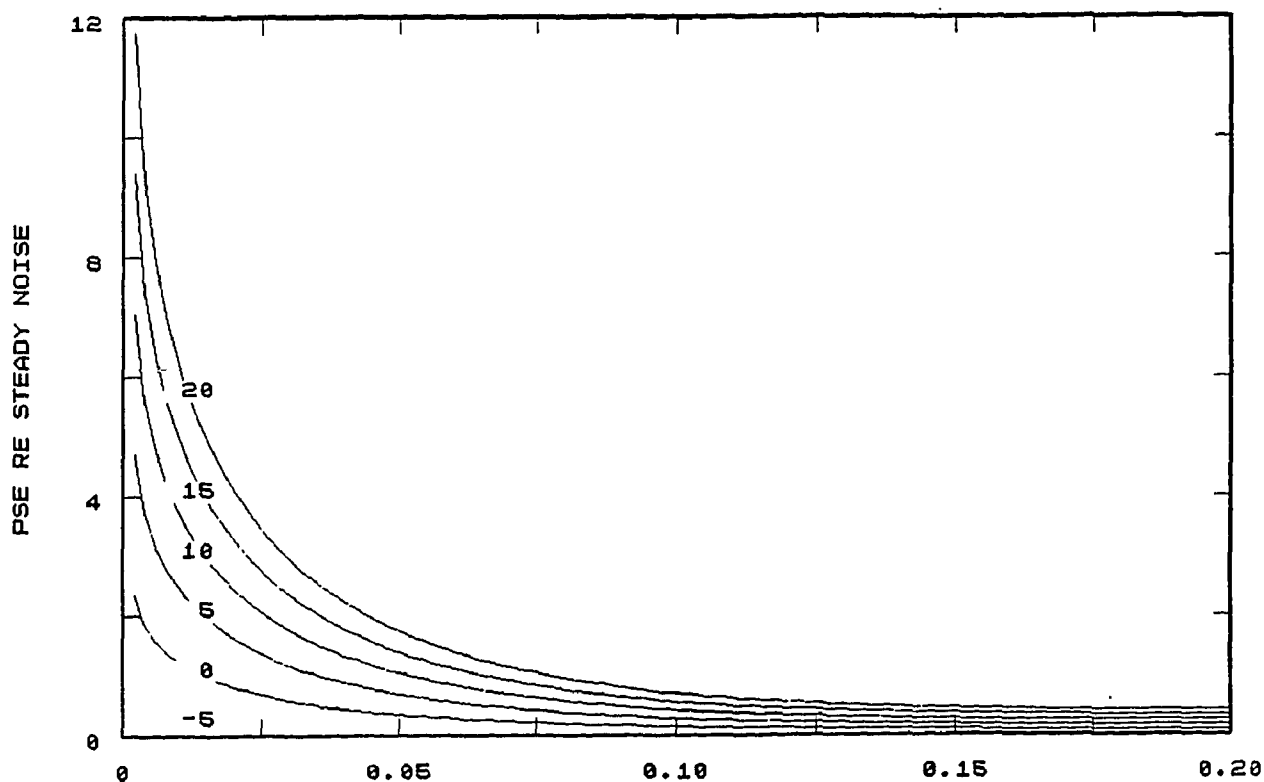


Figure 56. Predictions of the model for the results of experiment 1.

In figure 57, the predictions of the model are plotted as a function of ΔL_{ea} , with duty factor as a parameter, in order to allow comparison with the data from experiment 1 at the 5, 10, and 20-Hz repetition rates. The three lines show the predictions at the three duty factors, and the symbols are the data. The qualitative agreement between theory and experiment is evident.

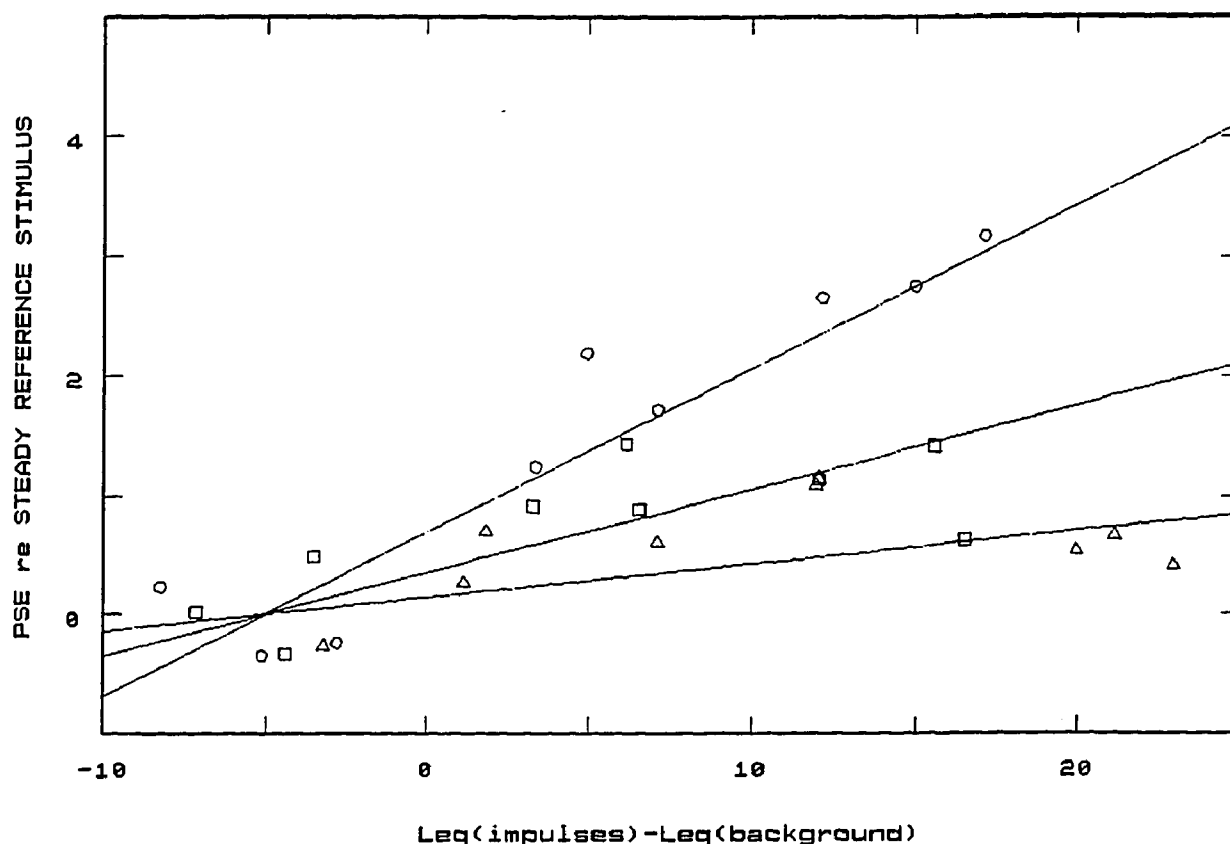


Figure 57. Agreement between the predictions of the model and the data of experiment 1 at 5, 10, and 20-Hz repetition rates at duty factors of 0.05 (circles), 0.1 (squares), and 0.2 (triangles).

However, there are several aspects of the agreement that are less than ideal. First, the use of the Leq difference rather does not cause the data to fall on perfectly straight lines, although the situation is far better than if peak-to-background ratio had been used. In particular, the data at the duty factor of 0.025 and at 20 Hz tended to have a higher PSE than at 5 and 10 Hz, despite the higher peak levels at 20 Hz. Second, the PSEs for the impulses at the higher duty factors tended to

drop rather than increase with increasing L_{oa} difference. As was mentioned earlier, this may have been a manifestation of the roughness effect. Third, because the experiment was designed for equal peak-to-background ratios, rather than equal L_{oa} differences, the net effect was that the range of L_{oa} differences that was tested was not identical for the different duty factors. It is unclear, for example, whether or not the data at a duty factor of 0.025 would have begun to level off, as is seen in the data at higher duty factors, if higher values of the L_{oa} difference had been tested.

9.4 Experiment 2

The analysis of variance on the data of experiment 2 (table 12) demonstrated that the spectral shape of the steady background noise was not a significant main effect at peak-to-background ratios of 10 and 20 dB. However, there was a significant interaction between background noise spectrum and peak-to-background ratio. Figure 51 shows the results of post hoc testing on this interaction. There was a significant elevation of the PSE of the impulses at 10 dB peak-to-background ratio when the background noise was band-pass filtered (500 Hz to 3.15 kHz). The PSE for the low-pass filtered case at 10 dB was also elevated, albeit to a lesser degree. As was shown in figure 38, both of these steady background noise stimuli had significantly higher PSEs than the white reference stimulus. Clearly, the elevation in PSE of the combined noises is reflective of the higher PSEs of the steady noises in isolation. As the peak-to-background ratio was increased to 20 dB, the PSE of the low-pass filtered condition was essentially unchanged, but that of the band-pass filtered condition dropped to a level close to that of the

reference stimulus. The data for the high-pass filtered noise condition showed a PSE below that of the reference stimulus at peak-to-background ratios of both 10 and 20 dB, in keeping with the lower PSE of the high-pass steady filtered noise in isolation.

However, the means that were compared in this analysis were obtained from data at four different repetition rates (100, 50, 20, and 10 Hz), and it is clear from the foregoing discussion that the effects of roughness and temporal integration are highly dependent on repetition rate. In figure 58, the data at 10 and 20 Hz are shown in comparison to the predictions of the model that was developed for experiment 1. The straight line is the prediction of the model for a duty factor of 0.05, which is the duty factor that was studied in experiment 2 at the 10 and 20 Hz repetition rates. The ordinate is the PSE relative to that of continuous white noise, while the abscissa is the difference between the L_{eq} of the impulses and that of the background noise. It can be seen that, at these repetition rates, the low pass filtered background noise conditions and white seemed to be equivalent. The PSE for the high pass filtered case was much lower than that predicted by the model at a peak-to-background ratio of 20 dB (L_{eq} difference of approximately 0). The elevation of the PSE at 10 dB peak to background ratio (L_{eq} difference of approximately -5) for the band-pass filtered condition is also evident.

One possible explanation for the drop in PSE for the high-pass filtered case is that the roughness effect is higher in this case. This would imply that the presence of background noise with spectral energy below 2 kHz masks the roughness effect. The dependence of the PSE for the band-pass filtered condition on the peak-to-background ratio suggests that the overall response to the combination of impulses and

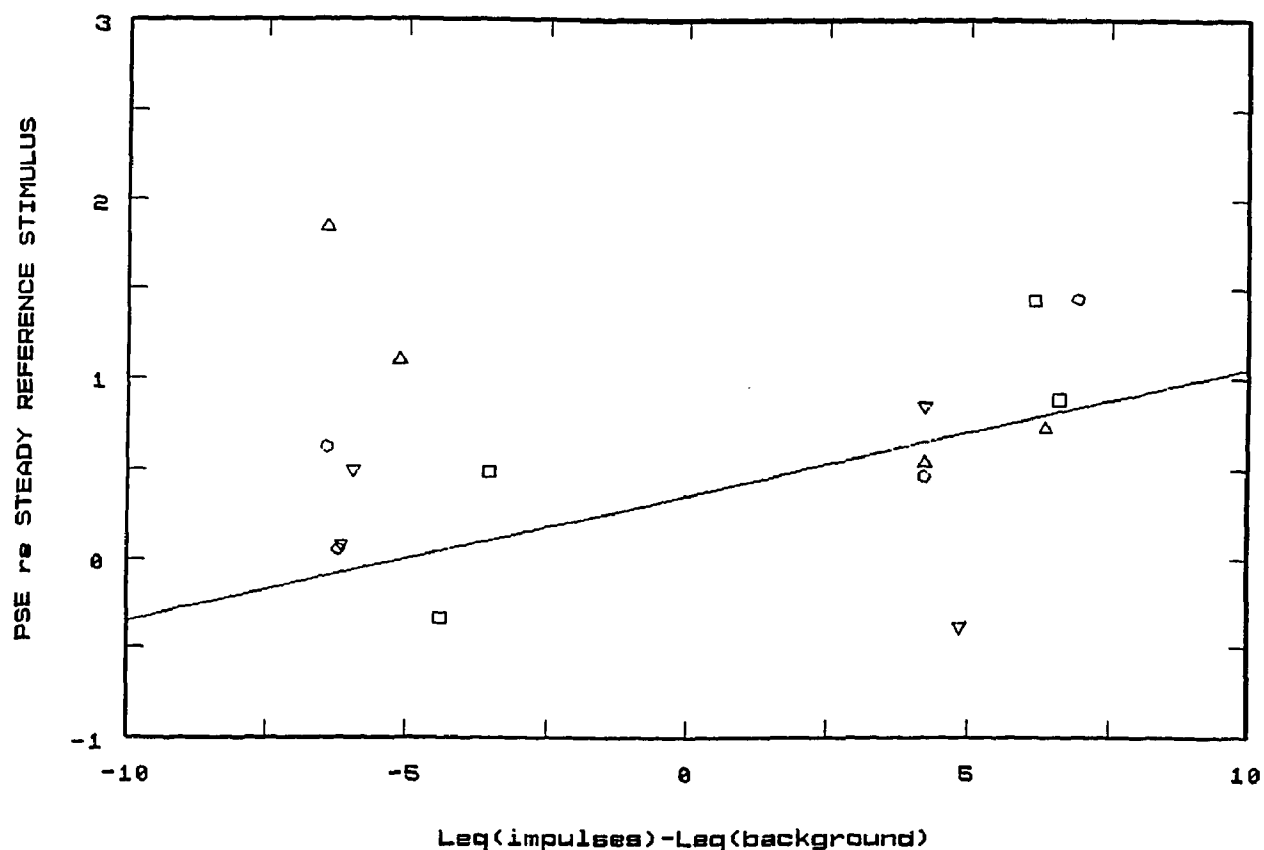


Figure 58. Agreement between the predictions of the model and the data of experiment 2 at 5, 10, and 20-Hz repetition rate. The spectral shapes of the steady background noises that were mixed with the impulses were: squares, white; circles, band-pass filtered; inverted triangles, high-pass filtered; triangles, low-pass filtered.

continuous noise is largely influenced by the spectral content of the noise in the range of 1-3 kHz. Thus, at 10-dB peak-to-background ratio, the higher PSE of the background noises compared to the impulses elevates the PSE. This concept is supported by the fact that the PSEs of the individual subjects in experiment 1 were correlated with the PSE for the

steady band-pass filtered noise. As was shown in figure 50, the correlation was quite high at the 10 and 20-dB peak-to-background ratios, and rather poorer at 30 dB.

Overall, the results of experiment 2 suggest that there are some interesting interactions between the spectral shape of the impulse noise and the continuous background noise, but that these interactions are rather weak. The results of the experiment are not well predicted by the loudness computations using the Zwicker procedure (table 4). The variations between the results of these computations are somewhat smaller than was obtained for the steady background noises. However, this is a reflection of the fact that the spectra of the combined impulse and steady noises are more similar to each other than they are to the spectra of the steady noises.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

To a first approximation, the loudness of the quasi continuous impulse noise in this study was predicted by the equivalent sound pressure level L_{eq} measured over a one-second time interval. The results suggest that L_{eq} may be used as an indicator of the loudness of quasi continuous impulse noise compared to a steady noise of comparable spectrum at moderate levels (50-70 dB).

Deviations from the predictions based on L_{eq} were found to occur under two conditions; at high repetition rates (above 20 Hz) and at low repetition rates when the duty factor was low. Both of these effects increased with increasing peak-to-background ratio. The deviation at high repetition rates was an increase in loudness level (relative to the L_{eq} prediction) of approximately 1 to 3 dB and was most probably due to the roughness effect. The deviation at low duty factors was a decrease in loudness level (relative to the L_{eq} prediction) of approximately 1 to 3 dB. This deviation appeared to be due to temporal integration phenomena at short stimulus durations.

The results at the lower repetition rates (5-20 Hz), including the deviation from the L_{eq} prediction at low duty factors, were found to depend on the duty factor and on the difference between the L_{eq} of the impulses and the L_{eq} of the background noise. Poulsen's (1978) two-time-

constant model of temporal integration was successfully extended to the case of repeated impulses with steady background noise. Excellent qualitative agreement was obtained with the data using integration time constants of 10 and 200 msec.

One of the goals of this study was to explore the psychoacoustical transition between isolated impulses and quasi continuous impulse noise. The results of the study suggest that impulse noise should be divided into three categories rather than two: (a) isolated impulses (repetition rates below about 2 Hz), (b) quasi continuous impulse noise (repetition rates from about 2 Hz to about 20 Hz), and (c) "continuous impulse noise", with repetition rates above 20 Hz, i.e. such that the roughness effect occurs). The latter category is aptly named because the roughness effect commences when the impulses fuse into a psychoacoustical continuum.

The other boundary that was explored in this study is the transition between impulses that are effectively free of background noise, and impulses with a psychoacoustically significant amount of background noise. The results suggest that this transition is adequately described in terms of the difference between the L_{eq} of the impulses and the L_{eq} of the background noise. At an L_{eq} difference of about -5 dB, the background noise was dominant. The background-free condition corresponded to an L_{eq} difference of 20 to 25 dB.

Thus, it appears reasonable to define impulse noise on the basis of the difference between the peak level of an impulse and an effective ambient level as in the proposed definition in section 2.5. The effective ambient is an estimate of the L_{eq} of the background noise. The proposed impulsivity criterion of 10 dB difference between the peak level and the

effective ambient corresponds to an L_{eq} difference of about 0 dB.

In the second experiment, the spectral shape of the background noise was found to interact with the peak to background noise ratio. The results suggest that the band-pass filtered noise masked the impulses at the 10-dB peak-to-background ratio, while the white and high-pass filtered background noise added to the overall loudness of the complex.

Several of the questions that have been raised by this study merit further investigation. For example, in the current study, the roughness effect was not studied in enough detail to allow the extension of the model to the repetition rates above 20 Hz. Future experiments could include the study of intermediate repetition rates (between 20 and 50 Hz) as well as higher repetition rates (50 Hz and up).

In order to test the model more fully, a study involving a greater range of duty factors could be performed. Ideally, the stimuli used in this study would be set at constant values of the L_{eq} difference rather than constant peak-to-background ratios.

The results might have been more informative if lower duty factors had been studied. For example, useful information might be gained about the temporal integration process in order to determine the physiological basis for the deviation from the equal energy relation at short durations.

Another possible direction for future study would be to test and improve the definition of impulse noise that has been proposed.

APPENDIX A

PILOT STUDY

A brief pilot study was conducted to determine whether the loudness of quasi continuous impulse noise (relative to the steady reference stimulus) was dependent on the presentation level. The experiment was performed using white noise impulses with steady white background noise at a subset of the rate-duration combinations of experiment 1:

100 Hz	1.5 msec
50 Hz	3.5 msec
20 Hz	5.0 msec
10 Hz	10.0 msec
5 Hz	20.0 msec

The reference stimulus levels were 42, 48, 54, 60, and 66 dB L_{eq} . The highest level, 66 dB, was the highest reference level that could be used without causing the subjects to raise the impulse stimuli above 70 dB L_{eq} . At levels below 42 dB L_{eq} , the background noise due to the audio card became noticeable. Six subjects participated in the pilot study. Testing was conducted in the same manner as the main experiments except that the test stimuli were all on one diskette. The subjects tested each stimulus twice at each level. The order of levels and the order in which

the stimuli were presented each time were randomized as described in chapter 7, with the proviso that each stimulus was tested once at each level before any were tested for the second time.

The results of the repeated measures ANOVA on the data of the pilot study are shown in Table 13. The factors were: Presentation Level L of the reference stimulus (five levels; 42, 48, 54, 60, and 66 dB), Noise type, F, (five levels, as outlined above), peak-to-background ratio, P, (two levels, 10 and 20 dB), the sequence, R, and order, O, factors as in experiment 1, and subjects, S, (six levels).

TABLE 13
ANALYSIS OF VARIANCE OF EXPERIMENT 3

Source of Variation	Sums of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Signif.
L (Level)	442.690	4	110.672	8.109	0.0010
P (Peak/Backgr.)	139.265	1	139.265	0.667	0.5446
LP	72.776	4	18.194	2.046	0.1258
F (Noise Type)	294.591	4	73.648	4.579	0.0088
LF	124.560	16	7.785	1.420	0.1537
PF	17.021	4	4.255	0.738	0.5791
LPF	88.670	16	5.542	1.353	0.1874
R (Sequence)	603.075	1	603.075	15.115	0.0120
LR	81.272	4	20.318	6.645	0.0017
PR	28.737	1	28.737	1.309	0.3049
LPR	20.292	4	5.073	4.415	0.0102
FR	6.762	4	1.691	0.573	0.6878
LFR	37.567	16	2.348	1.412	0.1576
PFR	9.389	4	2.347	1.668	0.1962
LPFR	17.560	16	1.097	0.650	0.8331
O (Order)	1.009	1	1.009	0.048	0.8286
LO	19.102	4	4.776	0.800	0.5412
PO	8.807	1	8.807	3.156	0.1345
LPO	7.597	4	1.899	0.525	0.7212
FO	4.923	4	1.231	0.621	0.6554
LFO	24.771	16	1.548	0.366	0.9864
PFO	17.100	4	4.275	0.883	0.5066
LPFO	85.103	16	5.319	1.293	0.2221
RO	0.072	1	0.072	0.029	0.8657
LRO	11.660	4	2.915	1.312	0.2991
PRO	0.134	1	0.134	0.164	0.7015
LPRO	8.075	4	2.019	1.885	0.1519
FRO	9.048	4	2.262	0.895	0.5134

cont. on next page.

TABLE 13, cont.

Source of Variation	Sums of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Signif.
LFRO	21.199	16	1.325	0.698	0.7881
Pfro	6.266	4	1.567	1.221	0.3333
LPfro	14.578	16	0.911	0.654	0.8295
S (Subjects)	11926.408	5	2385.282	1712.427	0.0010
LS	272.956	20	13.648	9.798	0.0010
PS	1044.446	5	208.889	149.964	0.0010
LPS	177.825	20	8.891	6.383	0.0010
FS	321.645	20	16.082	11.546	0.0010
LFS	438.561	80	5.482	3.936	0.0010
PFS	115.338	20	5.76	4.140	0.0010
LPFS	327.740	80	4.097	2.941	0.0010
RS	199.501	5	39.900	28.645	0.0010
LRS	61.157	20	3.058	2.195	0.0074
PRS	109.782	5	21.956	15.763	0.0010
LPRS	22.979	20	1.149	0.825	0.6778
FRS	58.984	20	2.949	2.117	0.0100
LFRS	133.063	80	1.663	1.194	0.2147
PFRS	28.145	20	1.407	1.010	0.4606
LPFRS	135.064	80	1.688	1.212	0.1959
OS	105.233	5	21.047	15.110	0.0010
LOS	119.421	20	5.971	4.287	0.0010
POS	13.954	5	2.791	2.004	0.0863
LPOS	72.376	20	3.619	2.598	0.0016
FOS	39.634	20	1.982	1.423	0.1365
LFOS	338.862	80	4.236	3.041	0.0010
PFOS	96.814	20	4.841	3.475	0.0010
LPFOS	329.060	80	4.113	2.953	0.0010
ROS	12.523	5	2.505	1.798	0.1219
LROS	44.435	20	2.222	1.595	0.0744
PROS	4.097	5	0.819	0.588	0.7115
LPROS	21.417	20	1.071	0.769	0.7423
FROS	50.527	20	2.526	1.814	0.0326
LFROS	151.810	80	1.898	1.362	0.0845
PFROS	25.666	20	1.283	0.921	0.5626
LPFROS	111.434	80	1.393		
TOTAL	19134.529	1199			

As is shown in table 13, there was a significant main effect for reference stimulus presentation level, L ($p = 0.0015$). The results of post hoc testing on this main effect are shown in figure 59.

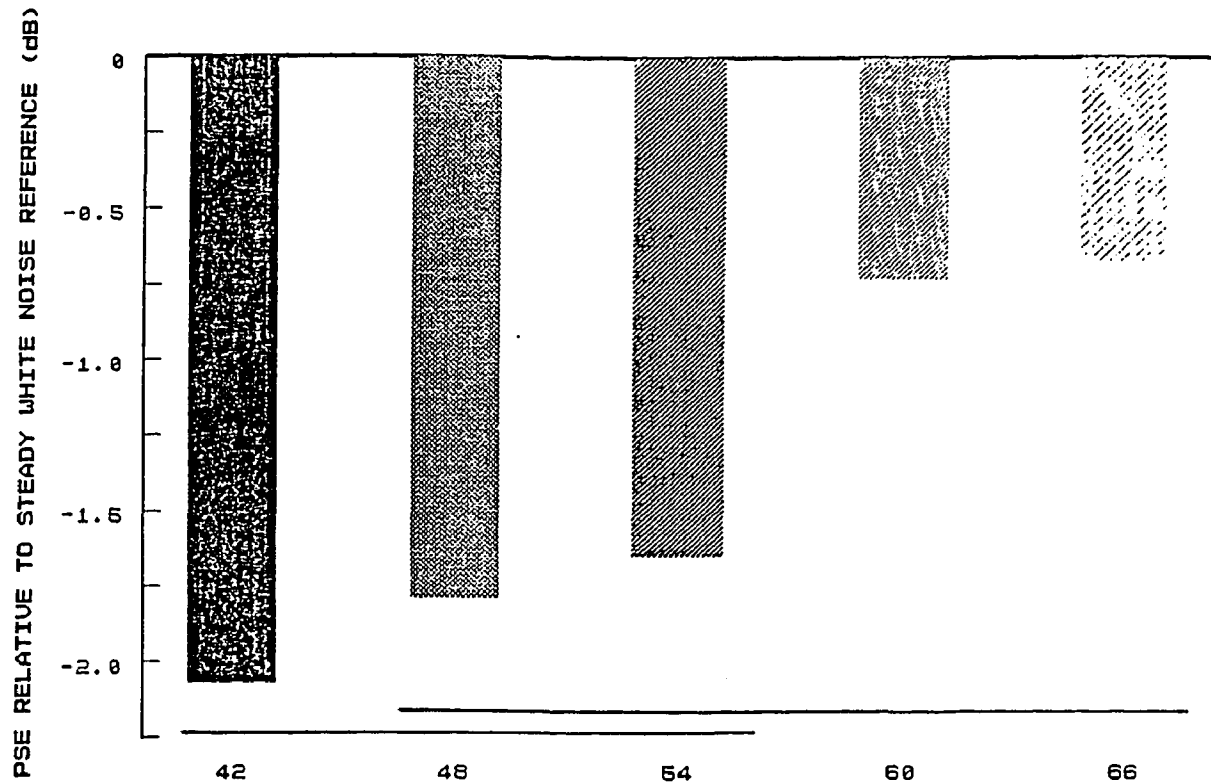


Figure 59. Results of post hoc testing on the main effect of presentation level in the pilot study.

It can be seen in figure 59 that the data showed a dependence on the presentation level in that there was a slight but significant increase in the mean PSE with increasing presentation level. However, this conclusion is substantially weakened by the fact that only six subjects participated in the experiment. An additional concern was the presence of internal background noise in the testing system, which may have interfered with the results at the lowest presentation level. Therefore, these data would need to be reconfirmed before any firm conclusions may be drawn.

APPENDIX B APL2 PROGRAMS

```

Z←DCB BIN;N;INDS;TMP;TMP1
N←(÷16)×ρBIN
TMP1←(N,16)ρBIN
TMP←(N,16)ρ0
TMP[;8]←TMP1[;8+8]
TMP[;8+8]←TMP1[;8]
INDS←(TMP[;1]=1)/N
TMP[INDS;(1+15)]←~TMP[INDS;(1+15)]
TMP[INDS;16]←1+TMP[INDS;16]
TMP[;15]←2×TMP[;15]
TMP[;14]←4×TMP[;14]
TMP[;13]←8×TMP[;13]
TMP[;12]←16×TMP[;12]
TMP[;11]←32×TMP[;11]
TMP[;10]←64×TMP[;10]
TMP[;9]←128×TMP[;9]
TMP[;8]←256×TMP[;8]
TMP[;7]←512×TMP[;7]
TMP[;6]←1024×TMP[;6]
TMP[;5]←2048×TMP[;5]
TMP[;4]←4096×TMP[;4]
TMP[;3]←8192×TMP[;3]
TMP[;2]←16384×TMP[;2]
TMP←+/TMP[;(1+15)]
TMP[INDS]←-TMP[INDS]
Z←,TMP

```

```

Z←ECB NIM;TMP;TMP0;INDS;INDS0
N←ρNIM
INDS0←(NIM<0)/N
TMP0←TMP←(N,16)ρ0
TMP[INDS0;1]←II←1
NIM[INDS0]←NIM[INDS0]+1
NIM←|NIM
LOOP:INDS←(NIM≠2*16-II+II+1)/N
TMP[INDS;II]←1
NIM[INDS]←NIM[INDS]-2*16-II
→(II<16)/LOOP
TMP[INDS0;(1+15)]←~TMP[INDS0;1+15]
TMP0[;8]←TMP[;8+8]
TMP0[;8+8]←TMP[;8]
Z←,TMP0

```

```

FIVEIO;ENVEL;ENVEL1;DAT;LDAT
SN←SNO
STATMAT←((SNF+1),6)ρ0
ENVEL1←TOS SINTH5 T+DT×4408
ENVEL←(÷NORM)×TOS SINTH5 T
ENVEL1←ENVEL1÷NORM
LOOP:BS←1186+1128×-1+(SN×8)+18+JJ←0
LDAT←0×EO←2|SN
LOOP1:RN←BS[JJ+1]
DAT←DCB READD FNR RN 1102
DAT←DAT×(EO×ENVEL[(551×JJ)+1551])+(~EO)×ENVEL1[(551×JJ)+1551]
LDAT←LDAT,DAT←FACT×DAT+BBASE×DCB READD FNRB RN 1102
DAT←ECB DAT
FNW RN 1102 WRITED DAT
→((JJ←JJ+1)<8)/LOOP1
NEWSTAT 1↓LDAT
→((SN←SN+1)<SNF)/LOOP

```

```

IMPIO;ENVEL;DAT;LDAT
SN←SNO
STAMAT←((SN+1),6)ρ0
LDAT←0
ENVEL←FACT×TOS SINTH T
LOOP:BS←1186+1128×-1+(SN×8)+18+JJ←0
LDAT←0
LOOP1:RN←BS[JJ+1]
DAT←DCB READD FNR(RN+FN0)1102
LDAT←LDAT,DAT←DAT×ENVEL[(551×JJ)+1551]
FNW RN 1102 WRITED DAT←ECB DAT
→((JJ←JJ+1)<8)/LOOP1
NEWSTAT 1↓LDAT
→((SN←SN+1)<SNF)/LOOP

```

```

MIXIO;ENVEL;DAT
SN←SNO
ENVEL←TOS SINTH T
LOOP:BS←1186+1128×-1+(SN×8)+18+JJ←0
LOOP1:RN←BS[JJ+1]
DAT←DCB READD FNR RN 1102
DAT←DAT×ENVEL[(551×JJ)+1551]
DAT←ECB FACT×DAT+BBASE×DCB READD FNRB RN 1102
FNW RN 1102 WRITED DAT
→((JJ←JJ+1)<8)/LOOP1
→((SN←SN+1)<SNF)/LOOP

```

```

NEWSTAT X;N;M1;M2;MC2;MC3;MAX;MIN;K;CF;PEAK;PINDS
R MAX, MIN, PRMS2, PEAK, K, CF
N←ρX
M1←(+/X)÷N
M2←(+/X*2)÷N
PINDS←((LTOS[1]÷DT)-3)+144
PEAK←(÷44)×+/X[PINDS]*2
MC2←(÷N)×+/(X-M1)*2
MC3←(÷N)×+/(X-M1)*3
MC4←(÷N)×+/(X-M1)*4
(⊘'KURTOSIS = '),⊘K←MC4÷MC2*2
(⊘'CREST FACTOR (DB)= '),⊘CF←20×100(↑/X)÷M2*0.5
(⊘'MAX = '),⊘MAX←↑/X
(⊘'MIN = '),⊘MIN←↓/X
STATMAT[SN+1;]←MAX,MIN,M2,PEAK,K,CF

```

```

NEWBIO;ENVEL;DAT;LDAT;KDAT;BG;LDAT1
SN←SNO
STATMAT←((SNF+1),6)ρ0
STATMAT1←((SNF+1),6)ρ0
ENVEL←TOS SINTH T
LOOP:BS←1186+1128×-1+(SN×8)+-18+JJ←0
LDAT1←LDAT←0
LOOP1:RN←BS[JJ+1]
KDAT←DCB READD FNR RN 1102
KDAT←KDAT×ENVEL[(551×JJ)+-1551]
LDAT←LDAT,DAT←FACT×KDAT+BBASE×BG←DCB READD FNRB RN 1102
DAT←ECB DAT
FNW RN 1102 WRITED DAT
LDAT1←LDAT1,DAT←FACT1×KDAT+BBASE1×BG
DAT←ECB DAT
FNW1 RN 1102 WRITED DAT
→((JJ←JJ+1)<8)/LOOP1
NEWSTAT 1↓LDAT
NEWSTAT1 1↓LDAT1
→((SN←SN+1)<SNF)/LOOP

Z←START MAX TRY
Z←10×109(POW TRY[1097+-144])÷POW TRY[START+-144]

Z←TRY1 MAX5 TRY
Z←10×109(POW TRY[1097+-144])÷POW TRY1[4000+-144]

FACT←TRY1 SETFACT TRY
FACT←2500000÷0.5×(POW TRY)+(POW TRY1)
FACT←FACT×0.5

FACT←SEFACT TRY
FACT←2500000÷(POW TRY)
FACT←FACT×0.5

Z←TOS SINTH5 T;EXP;EXP0
EXP0←EXP←(ρT)ρ0×KK←1
JUMP←4408×DT
QZ:ADD←*(((T-TOS[KK])<0)/T)-TOS[KK])÷WR
ADD←ADD,*-(((T-TOS[KK])≥0)/T)-TOS[KK])÷WW
EXP←EXP+ADD
→((KK←KK+1)≤ρTOS)/QZ
NORM←-11↑EXP[↑EXP]
Z←BASE+(1-BASE)×EXP

Z←TOS SINTH T;ADD;EXP
EXP←(ρT)ρ0×KK←1
QZ:ADD←*(((T-TOS[KK])<0)/T)-TOS[KK])÷WR
ADD←ADD,*-(((T-TOS[KK])≥0)/T)-TOS[KK])÷WW
EXP←EXP+ADD
→((KK←KK+1)≤ρTOS)/QZ
EXP←EXP÷-11↑EXP[↑EXP]
Z←BASE+(1-BASE)×EXP

```

APPENDIX C TIME-WAVEFORMS, SPECTRA, AND LOUDNESS COMPUTATIONS

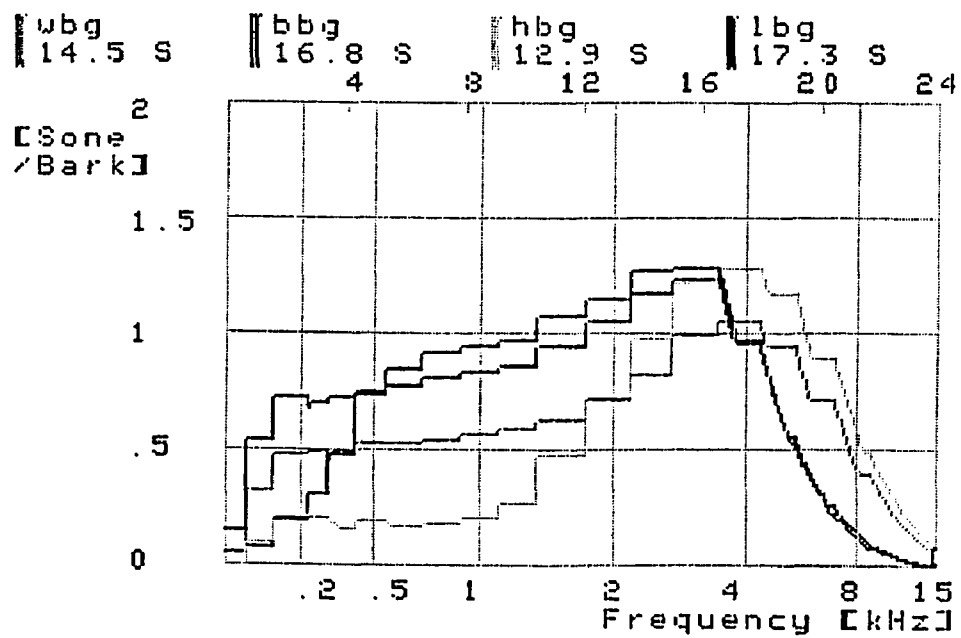


Figure 60. Loudness computations on the four steady background noise stimuli by the method of ISO532B (1975).

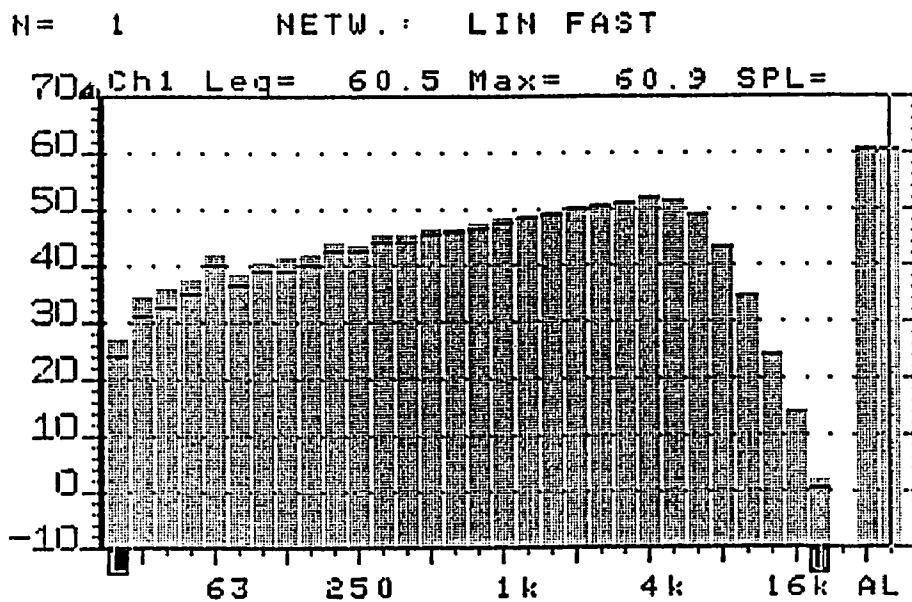
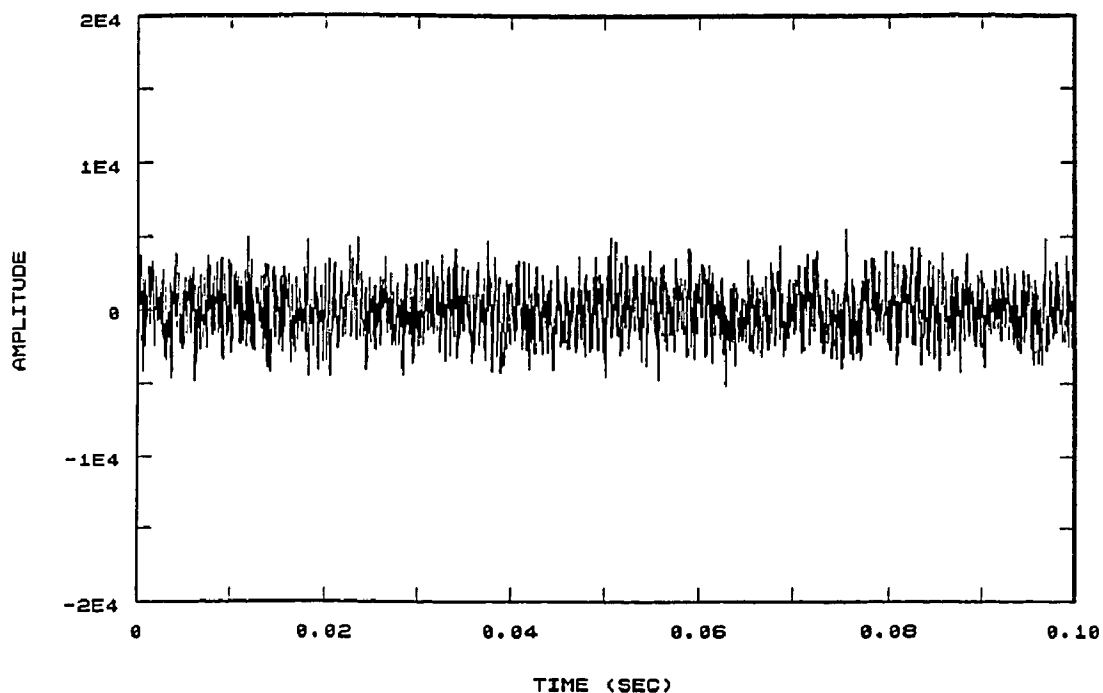


Figure 61. a, Time-waveform of the steady, white background noise stimulus; b, One-third octave-band spectrum of the steady, white background noise stimulus.

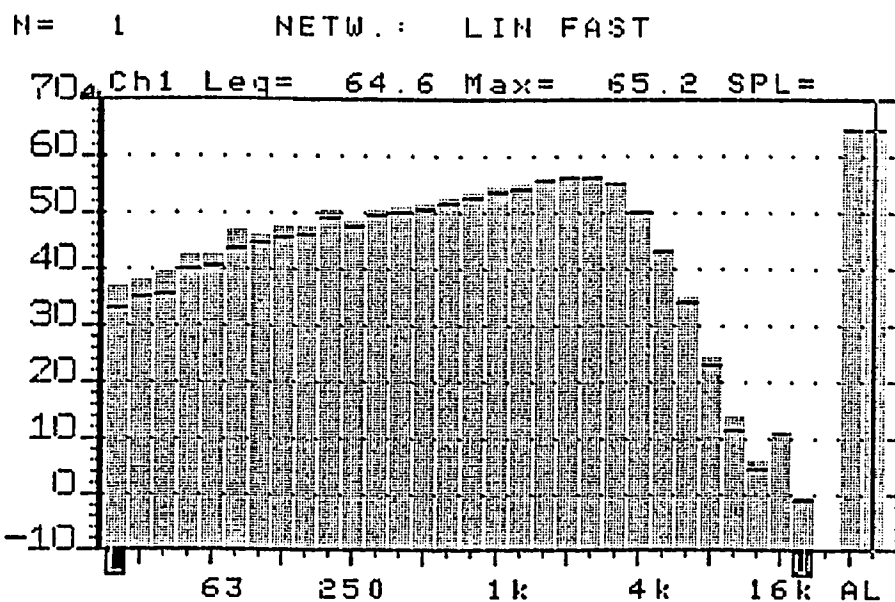
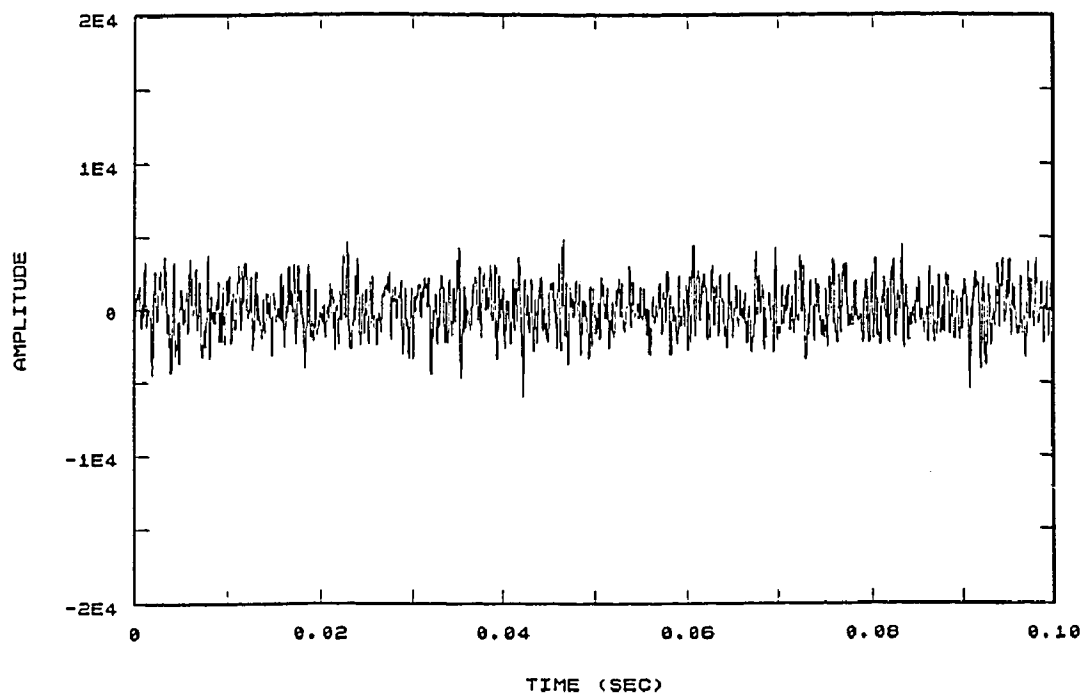


Figure 62. **a**, Time-waveform of the steady, low-pass filtered background noise stimulus; **b**, One-third octave-band spectrum of the steady, low-pass filtered background noise stimulus.

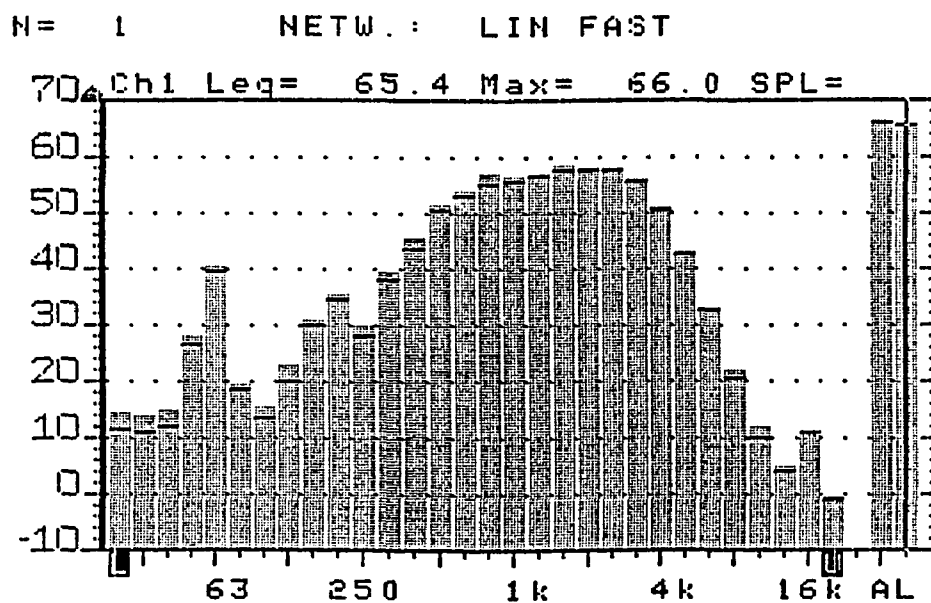
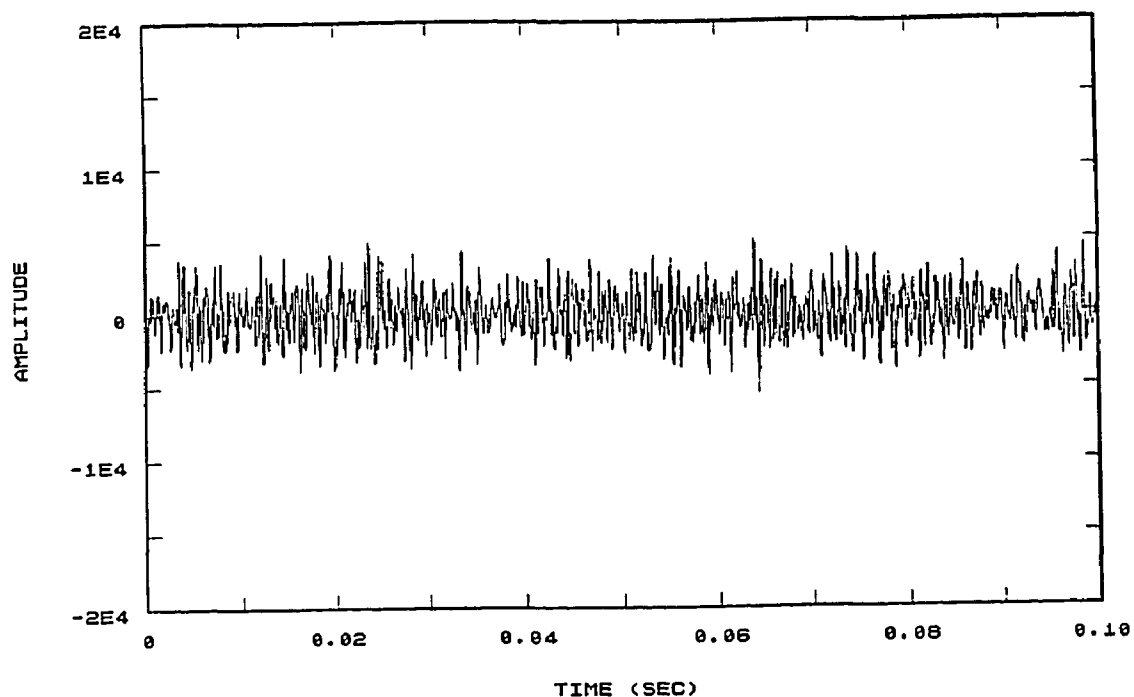
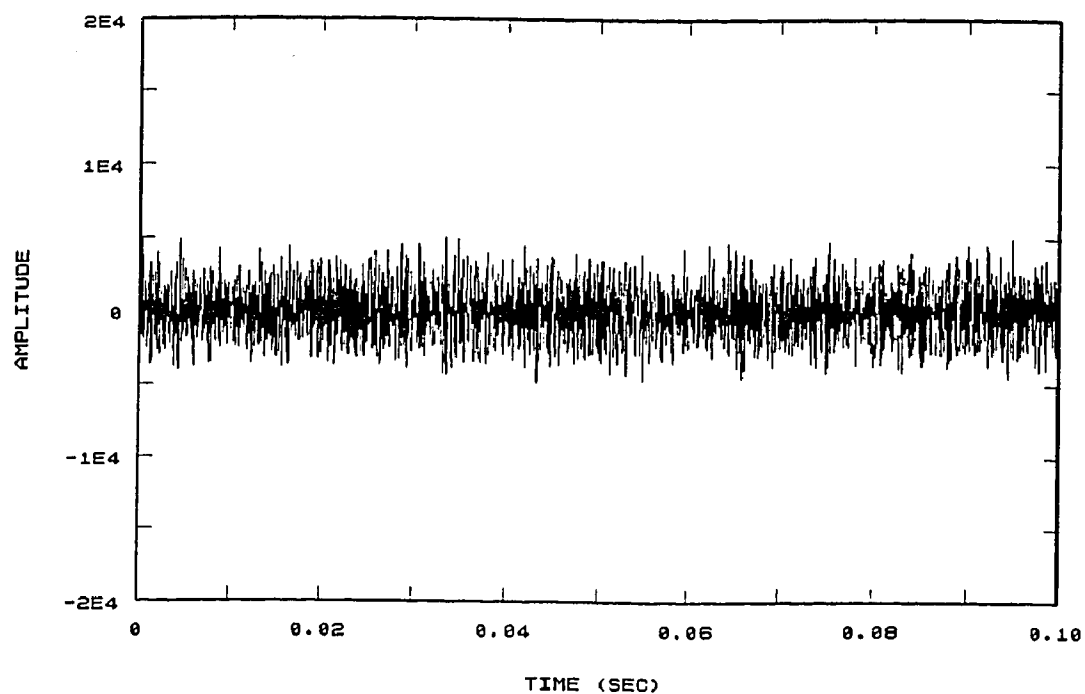


Figure 63. a, Time-waveform of the steady, band-pass filtered background noise stimulus; b, One-third octave-band spectrum of the steady, band-pass filtered background noise stimulus.



N= 1 NETW.: LIN FAST

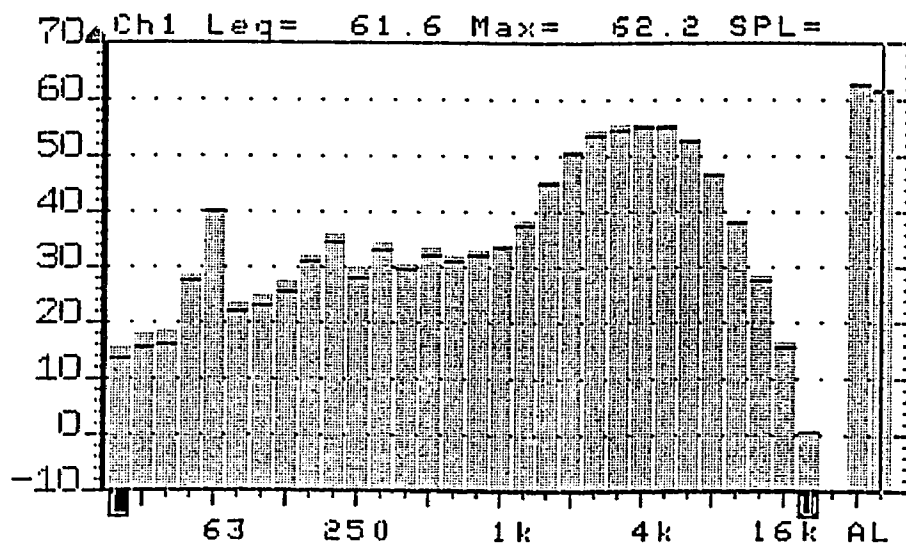


Figure 64. a, Time-waveform of the steady, high-pass filtered background noise stimulus; b, One-third octave-band spectrum of the steady, high-pass filtered background noise stimulus.

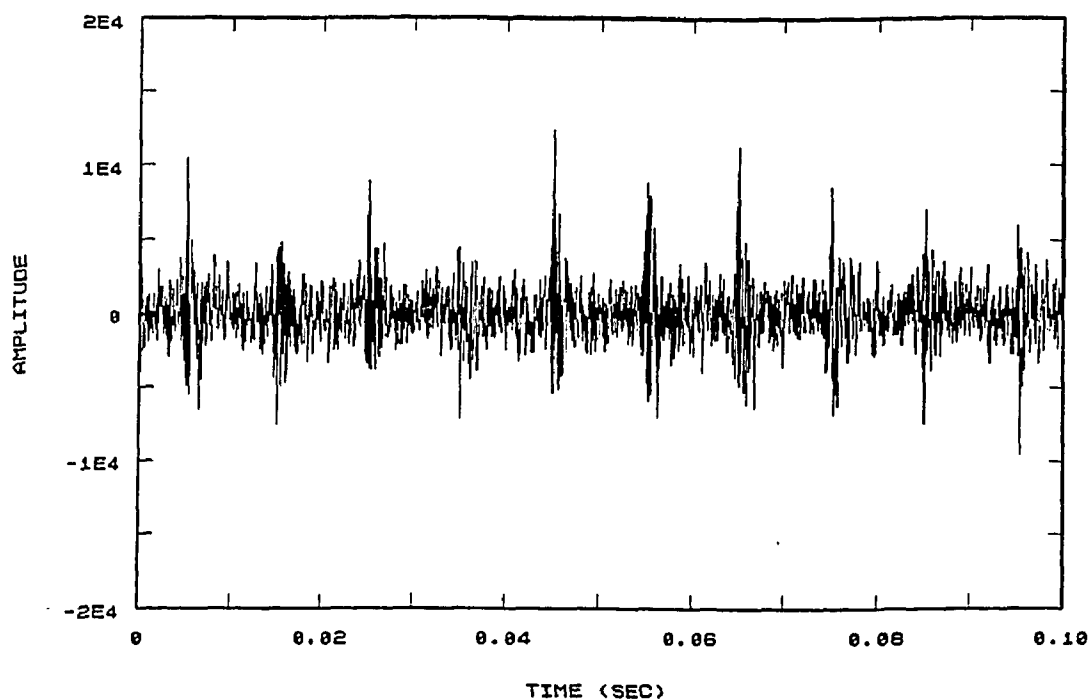


Figure 65. Time-waveform of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

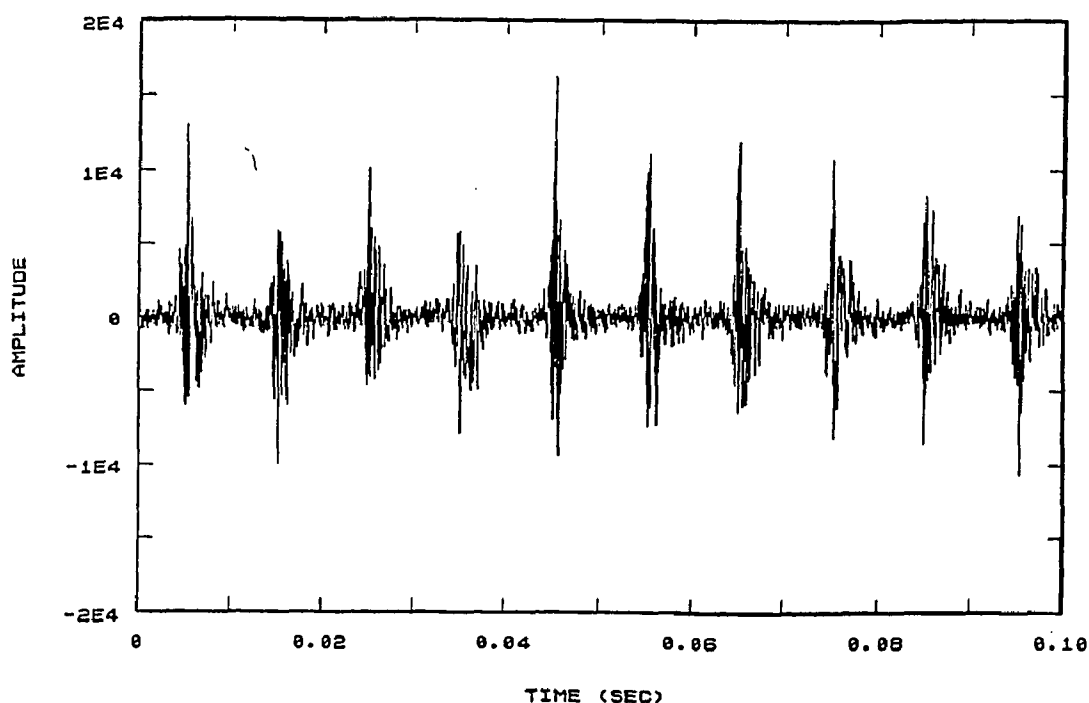


Figure 66. Time-waveform of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady white background noise at a peak-to-background ratio of 20 dB.

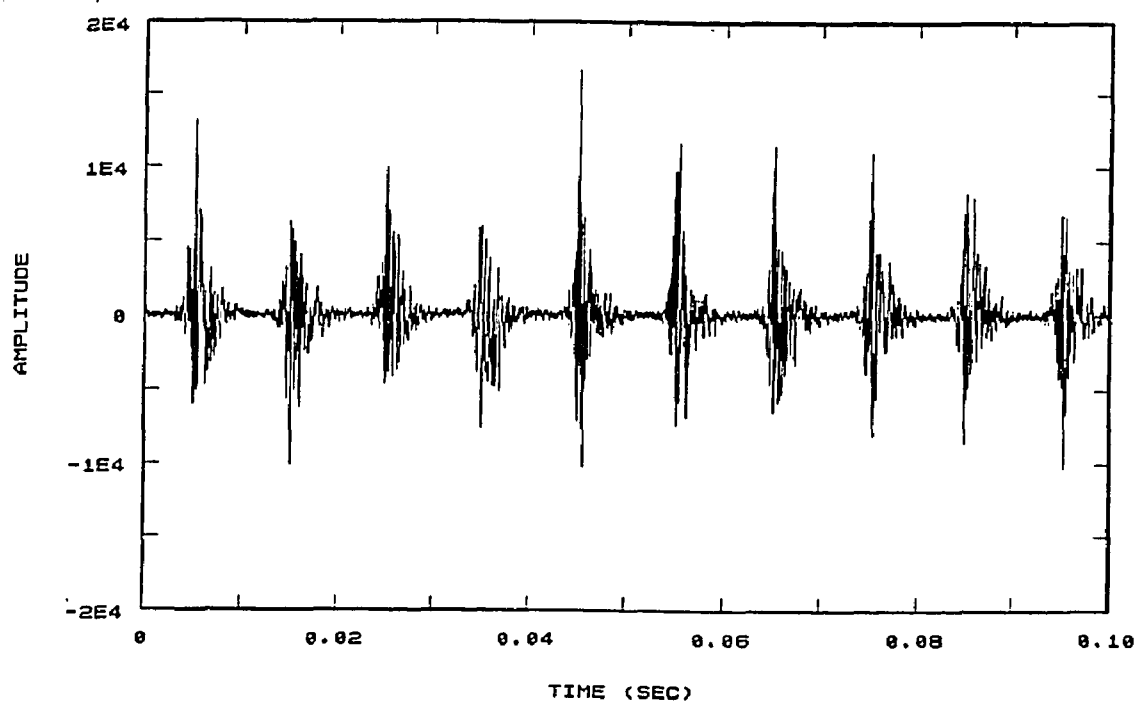


Figure 67. Time-waveform of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady white background noise at a peak-to-background ratio of 30 dB.

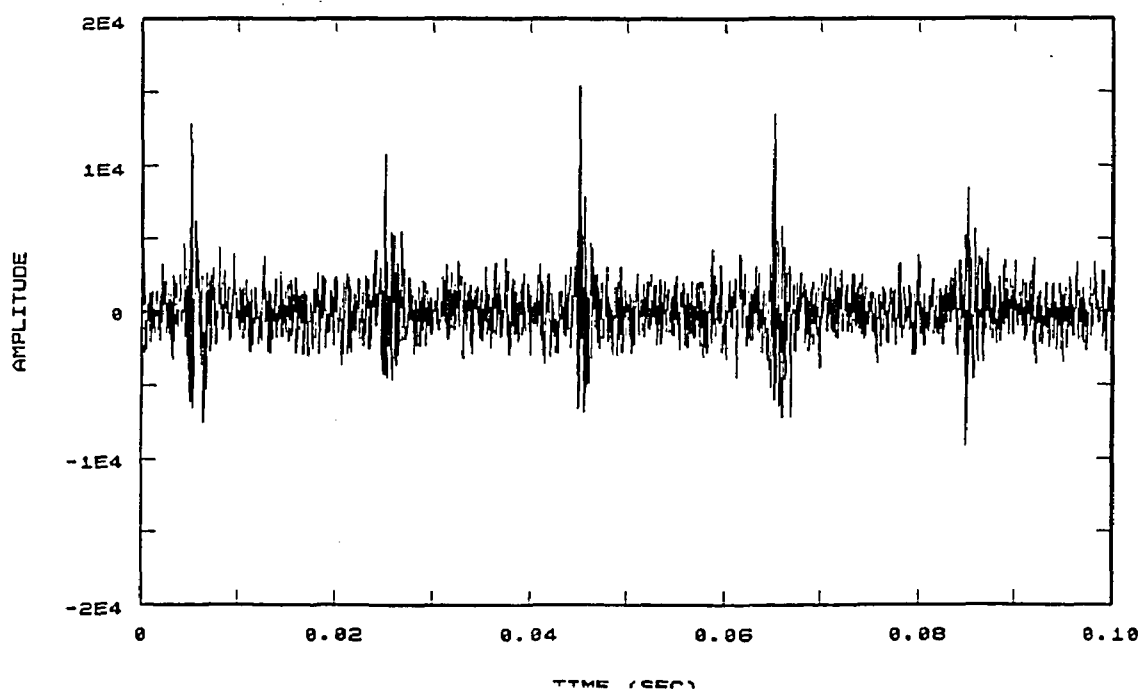


Figure 68. Time-waveform of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 50 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

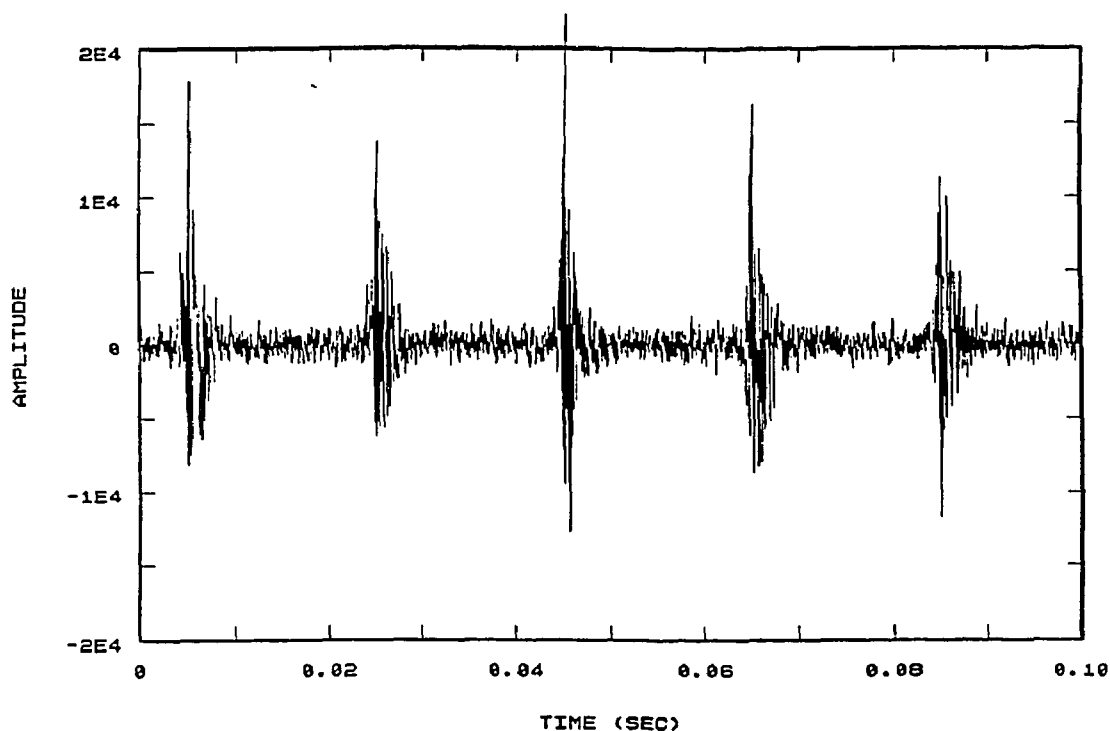


Figure 69. Time-waveform of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 50 Hz, and steady white background noise at a peak-to-background ratio of 20 dB.

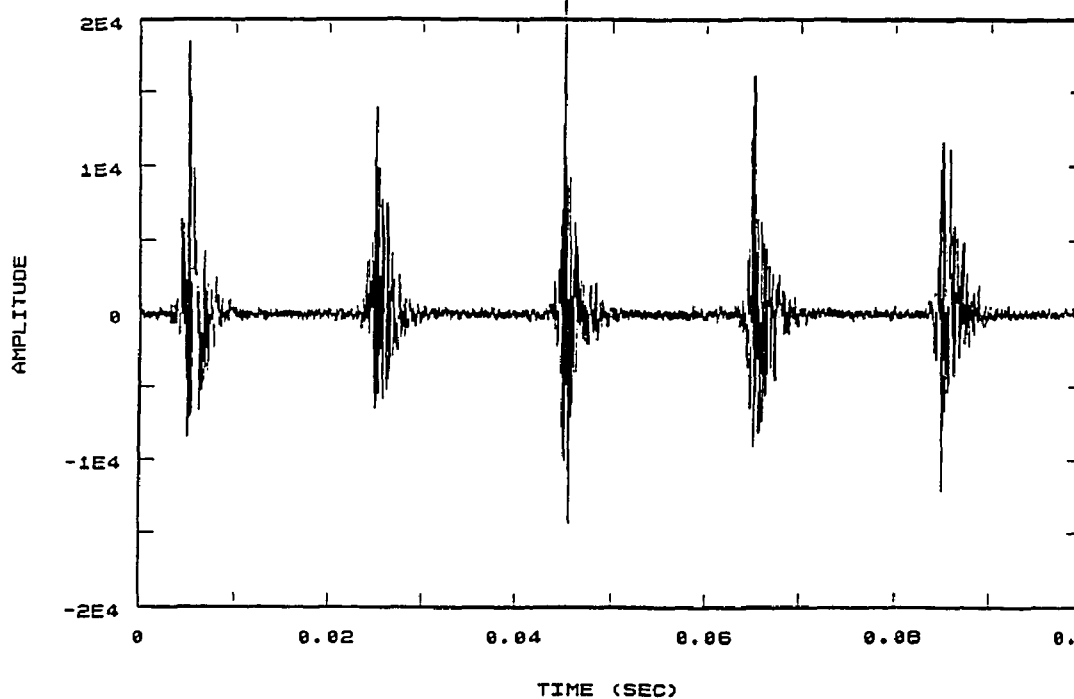


Figure 70. Time-waveform of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 50 Hz, and steady white background noise at a peak-to-background ratio of 30 dB.

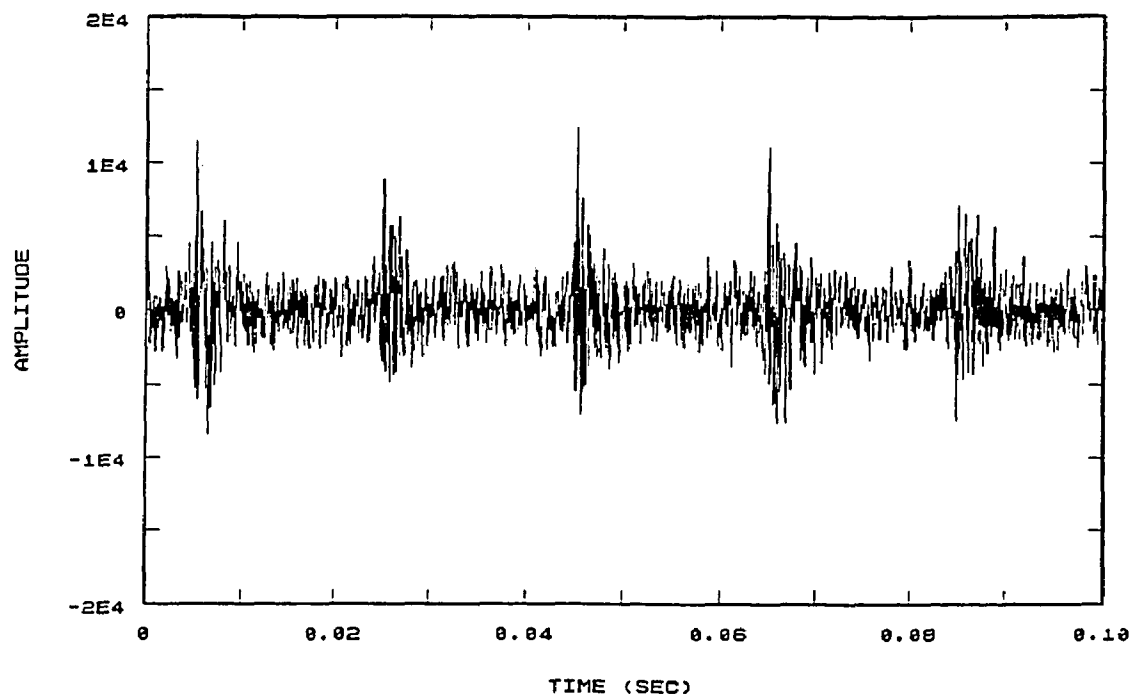


Figure 71. Time-waveform of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

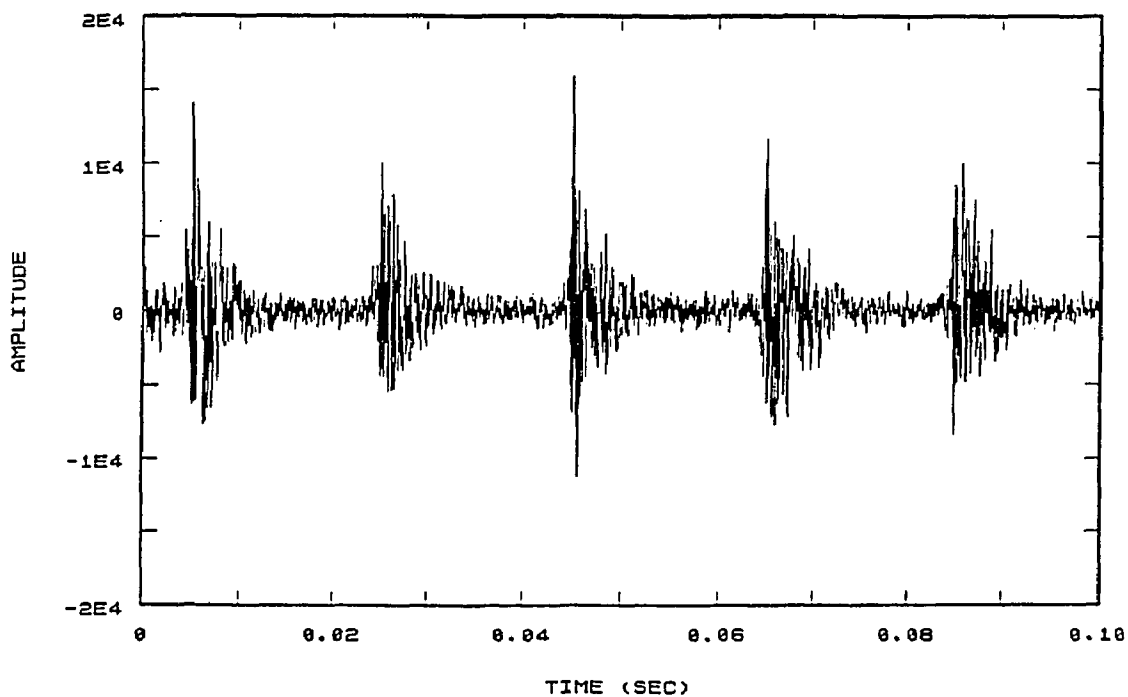


Figure 72. Time-waveform of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady white background noise at a peak-to-background ratio of 20 dB.

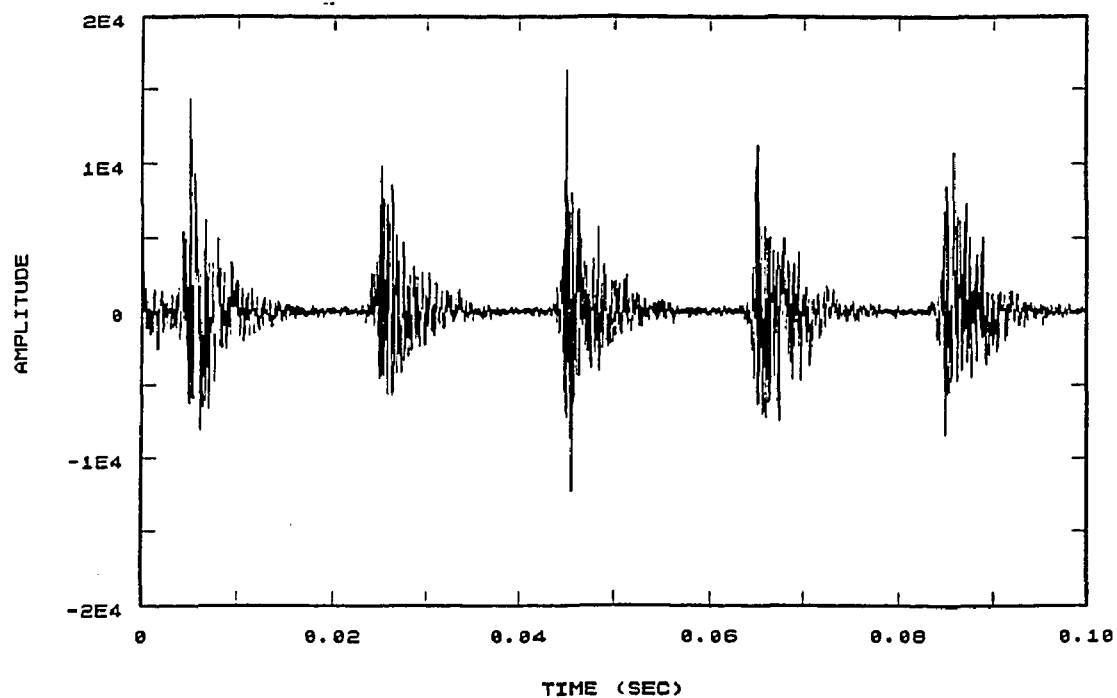


Figure 73. Time-waveform of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady white background noise at a peak-to-background ratio of 30 dB.

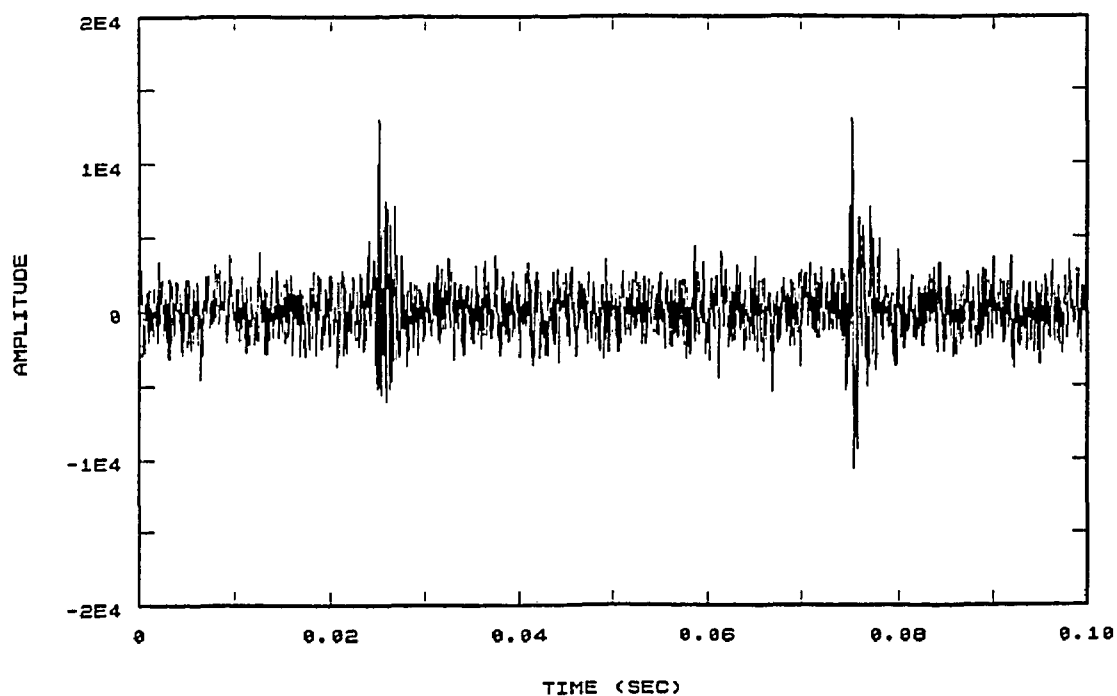


Figure 74. Time-waveform of impulse noise test stimulus with impulse duration of 2 msec, repetition rate of 20 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

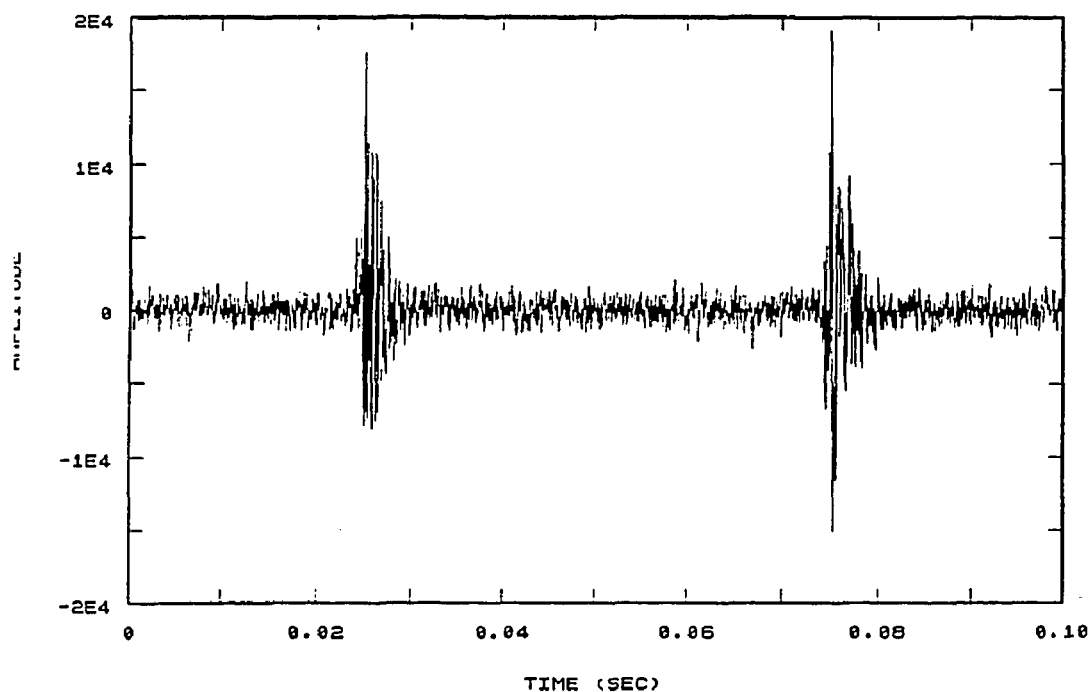


Figure 75. Time-waveform of impulse noise test stimulus with impulse duration of 2 msec, repetition rate of 20 Hz, and steady white background noise at a peak-to-background ratio of 20 dB.

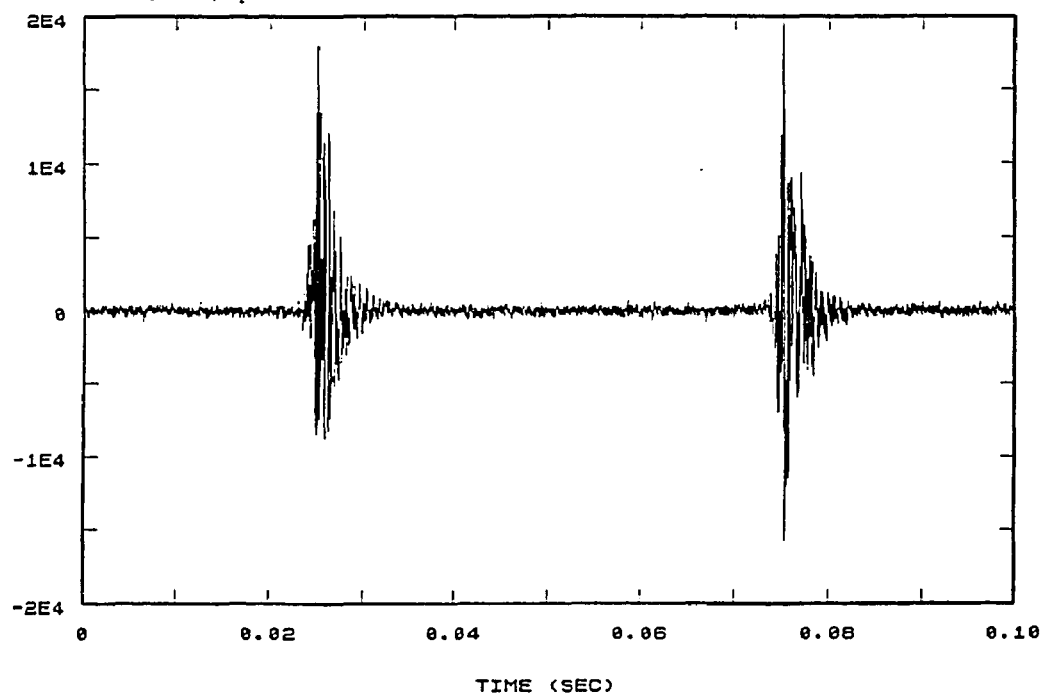


Figure 76. Time-waveform of impulse noise test stimulus with impulse duration of 2 msec, repetition rate of 20 Hz, and steady white background noise at a peak-to-background ratio of 30 dB.

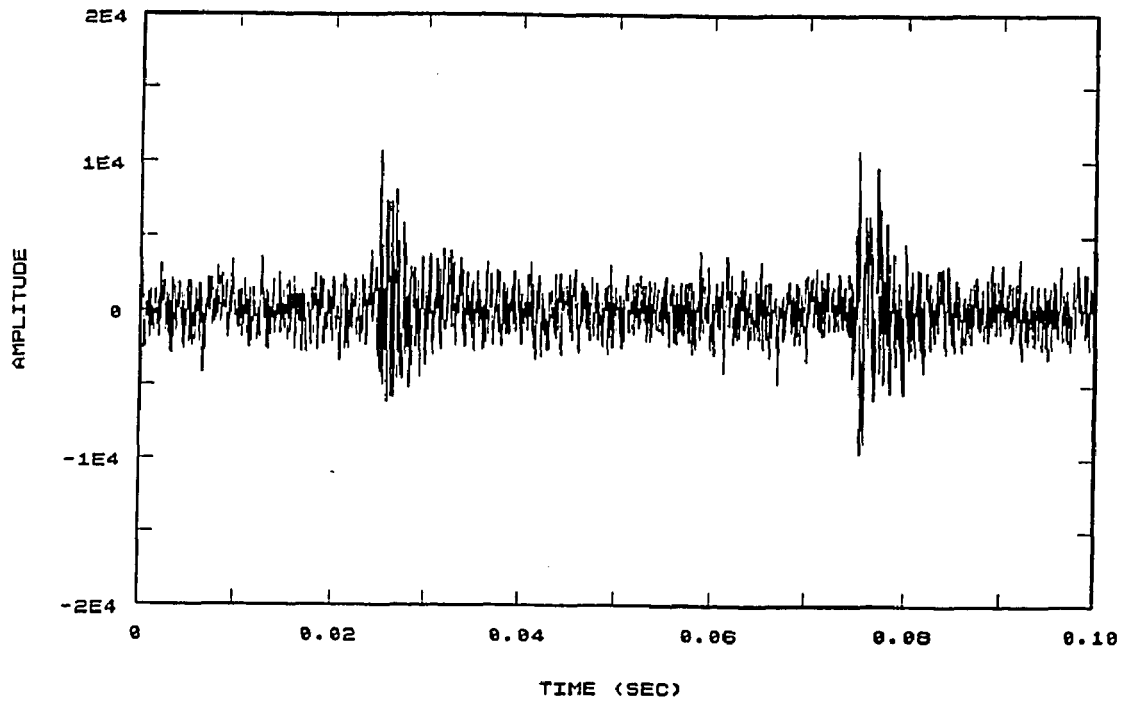


Figure 77. Time-waveform of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

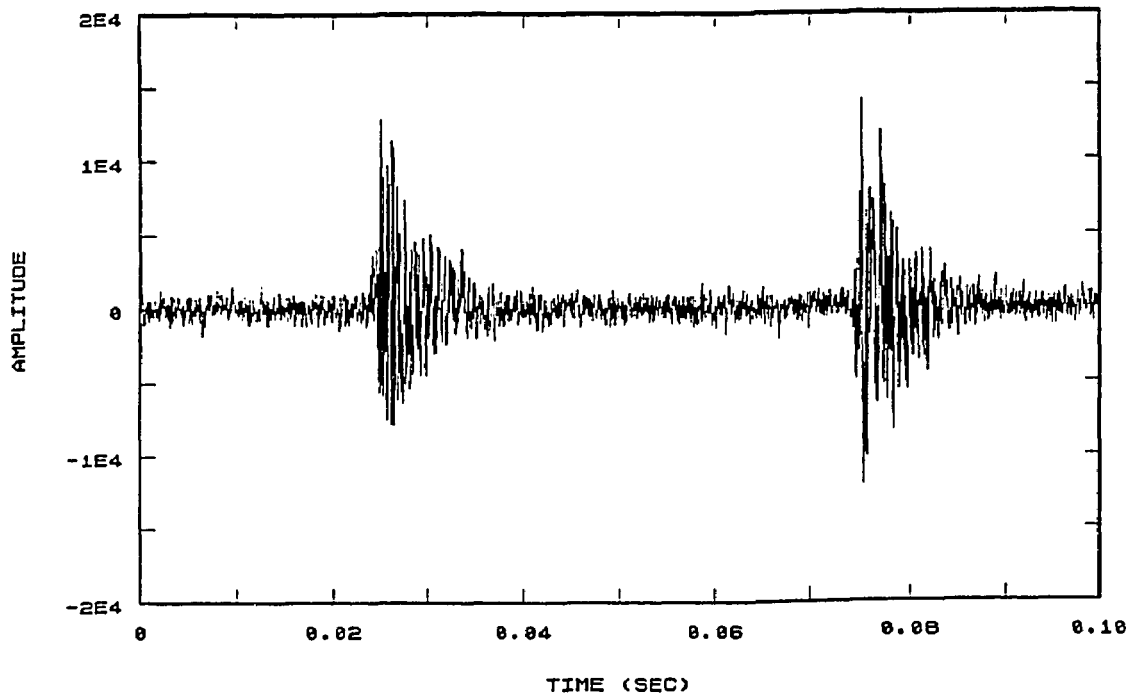


Figure 78. Time-waveform of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady white background noise at a peak-to-background ratio of 20 dB.

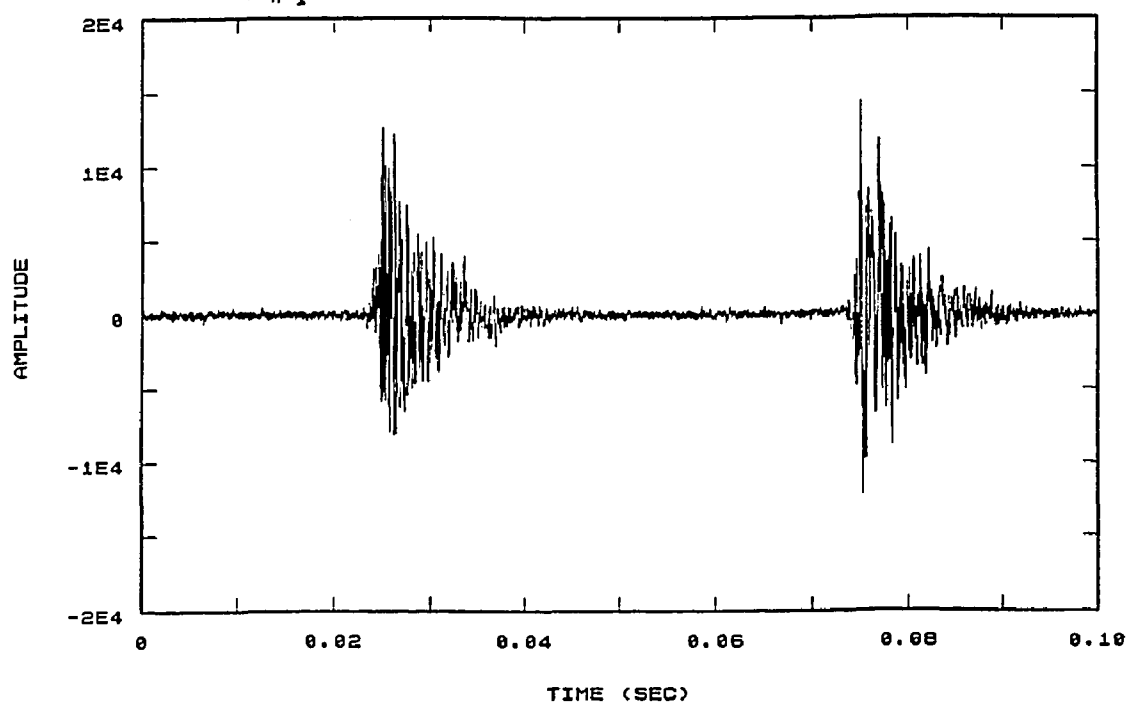


Figure 79. Time-waveform of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady white background noise at a peak-to-background ratio of 30 dB.

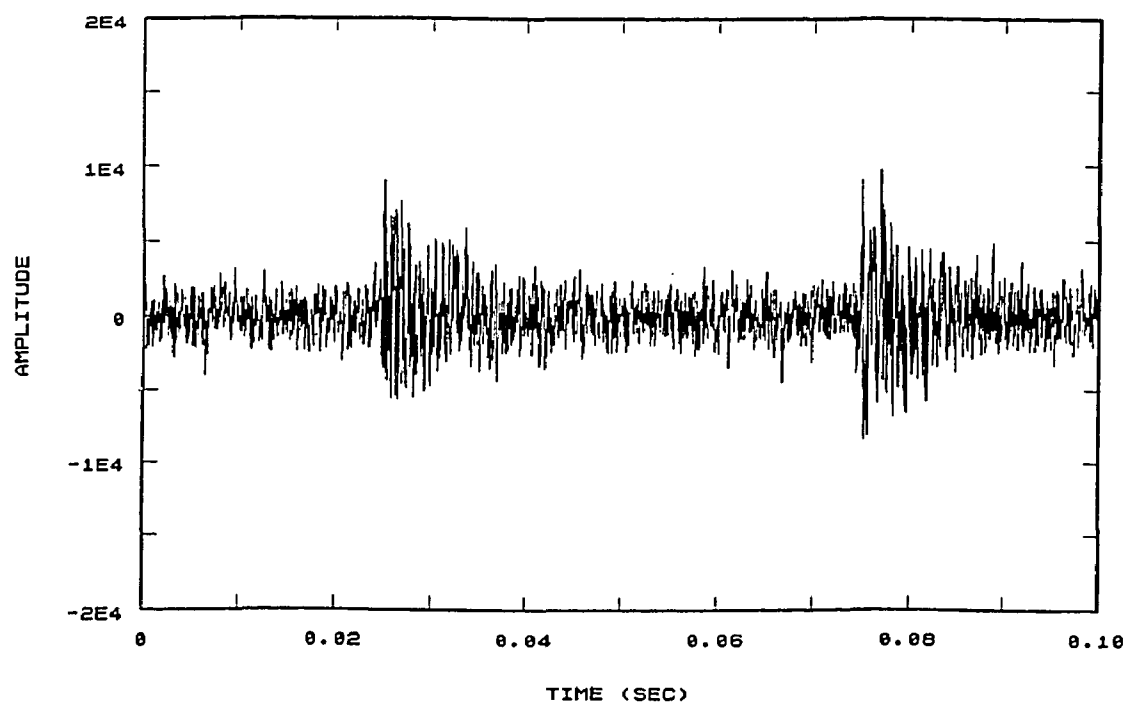


Figure 80. Time-waveform of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 20 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

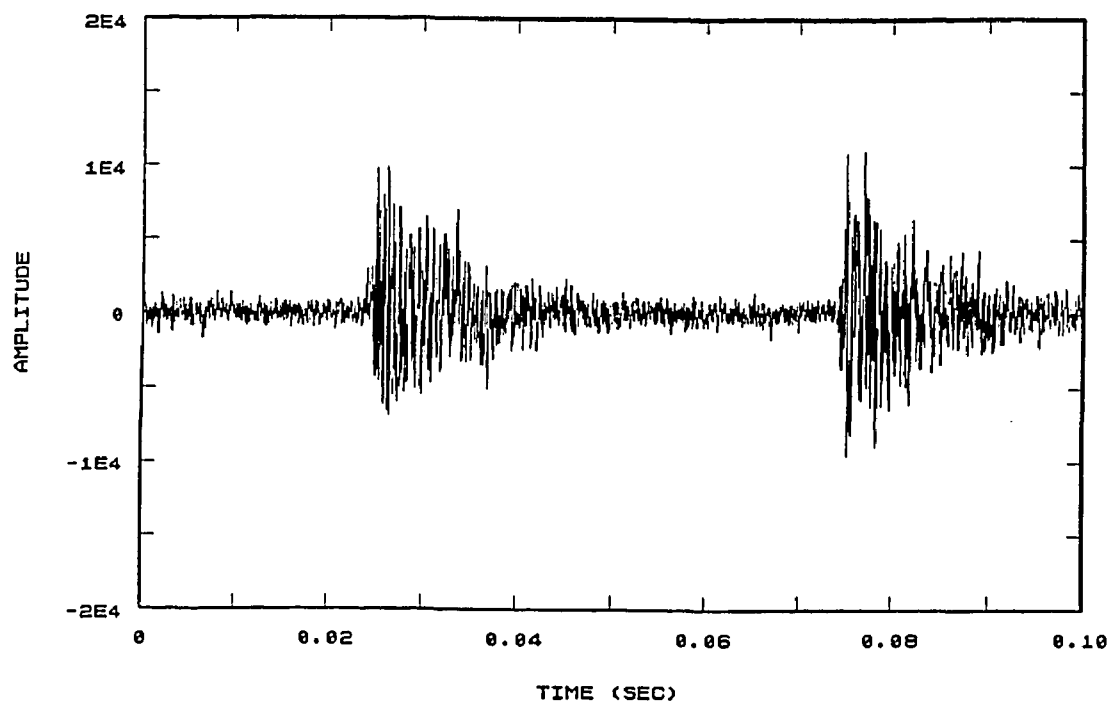


Figure 81. Time-waveform of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 20 Hz, and steady white background noise at a peak-to-background ratio of 20 dB.

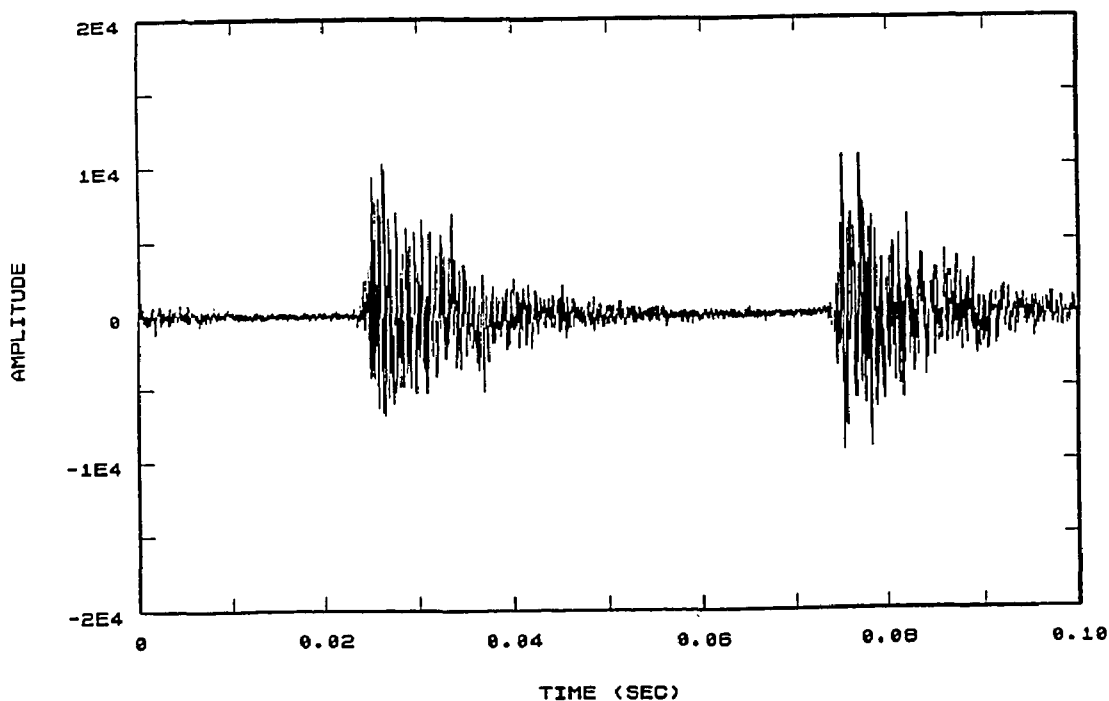


Figure 82. Time-waveform of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 20 Hz, and steady white background noise at a peak-to-background ratio of 30 dB.

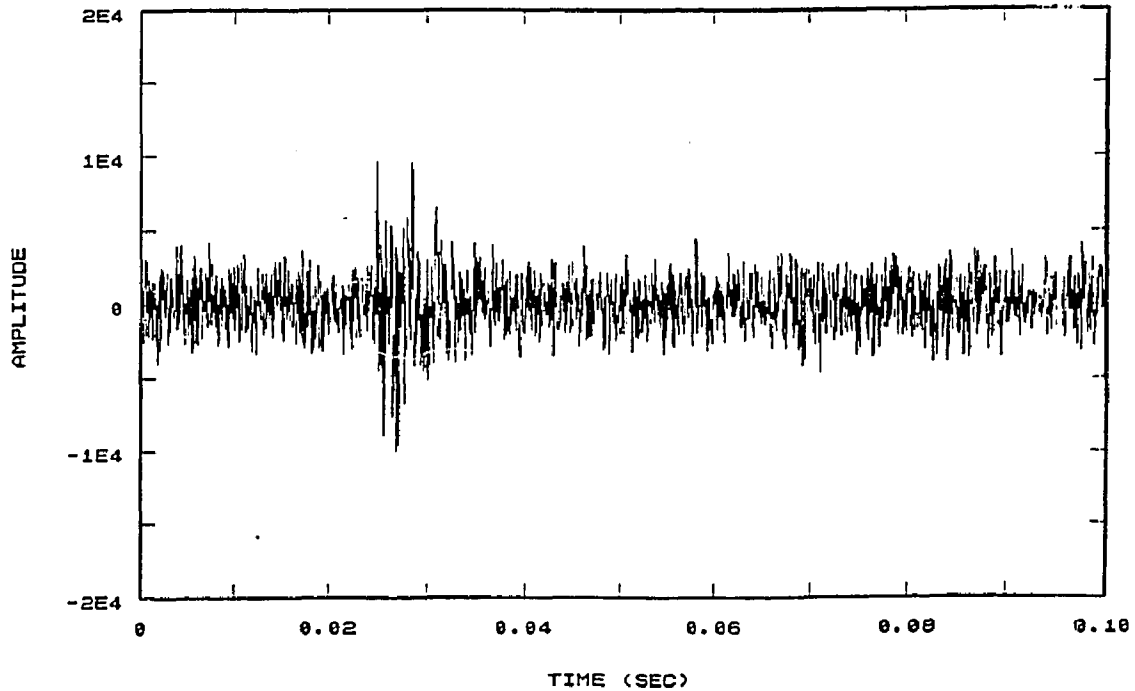


Figure 83. Time-waveform of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 10 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

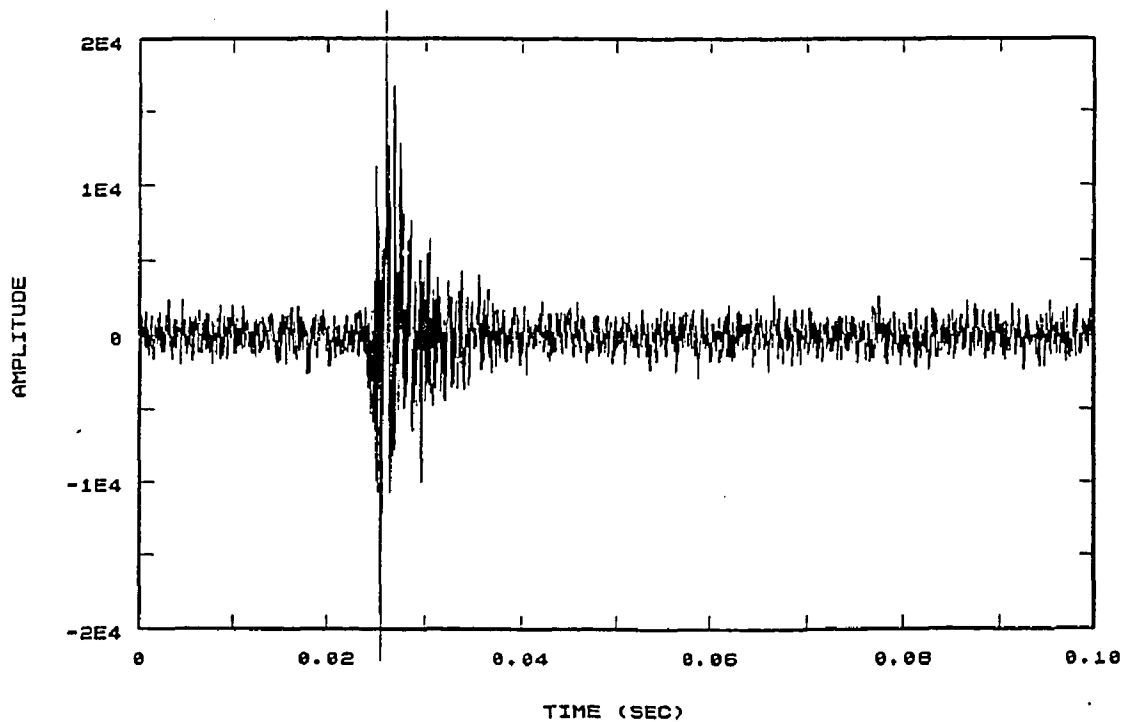


Figure 84. Time-waveform of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 10 Hz, and steady white background noise at a peak-to-background ratio of 20 dB.

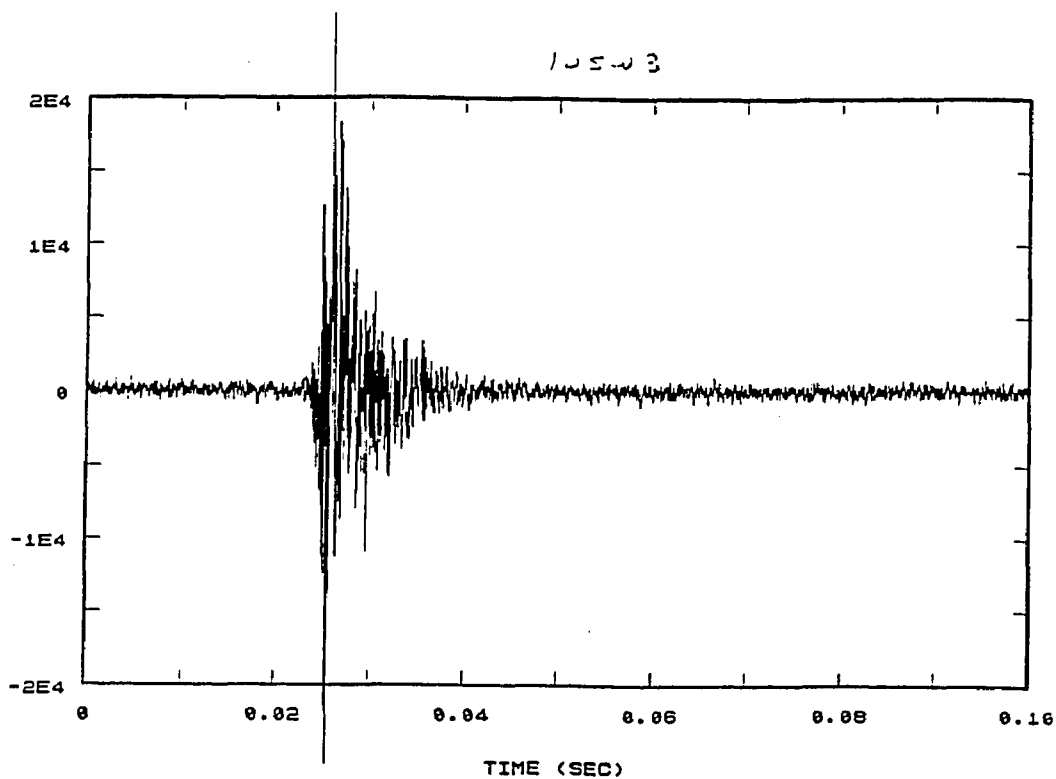


Figure 85. Time-waveform of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 10 Hz, and steady white background noise at a peak-to-background ratio of 30 dB.

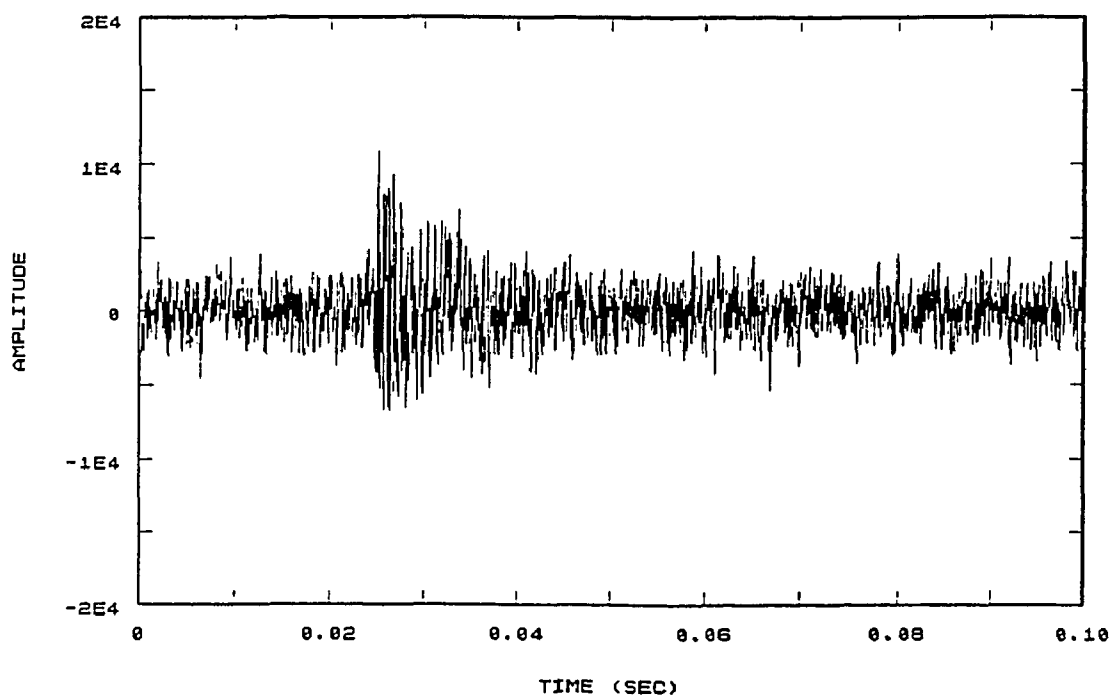


Figure 86. Time-waveform of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

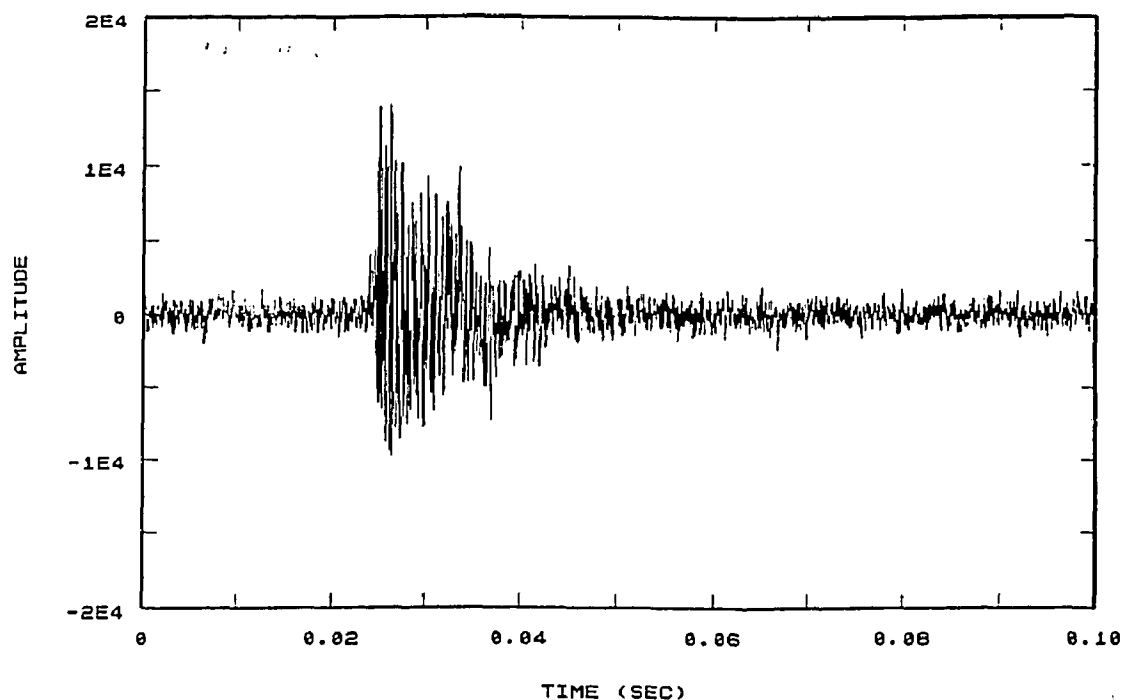


Figure 87. Time-waveform of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady white background noise at a peak-to-background ratio of 20 dB.

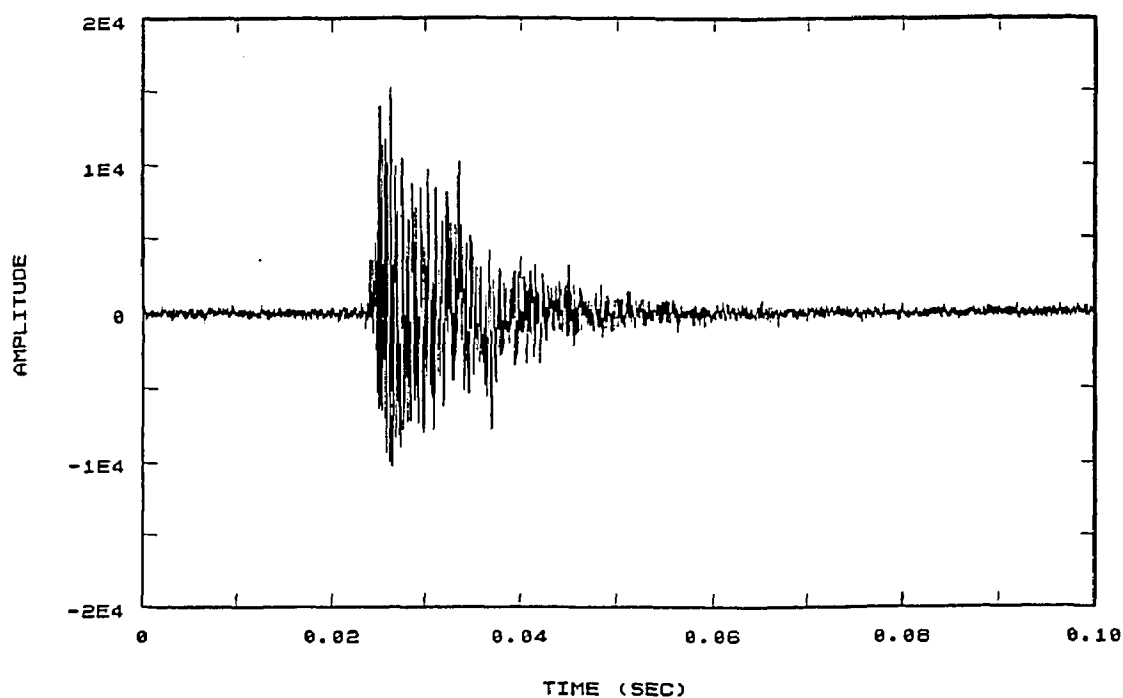


Figure 88. Time-waveform of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady white background noise at a peak-to-background ratio of 30 dB.

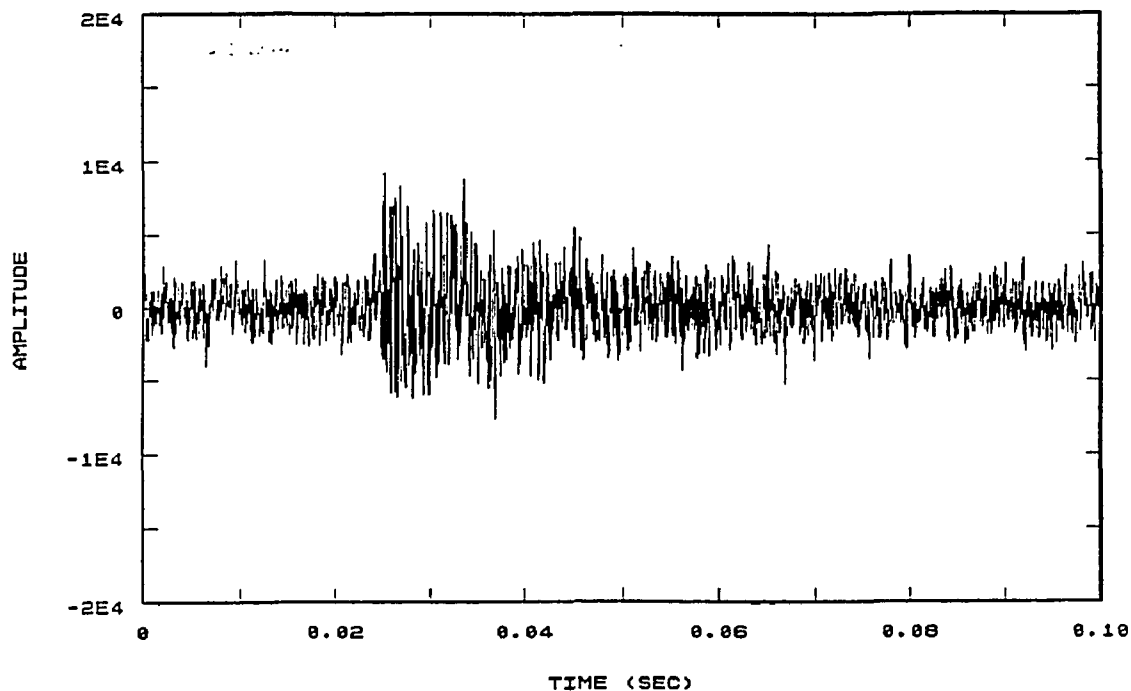


Figure 89. Time-waveform of impulse noise test stimulus with impulse duration of 20 msec, repetition rate of 10 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

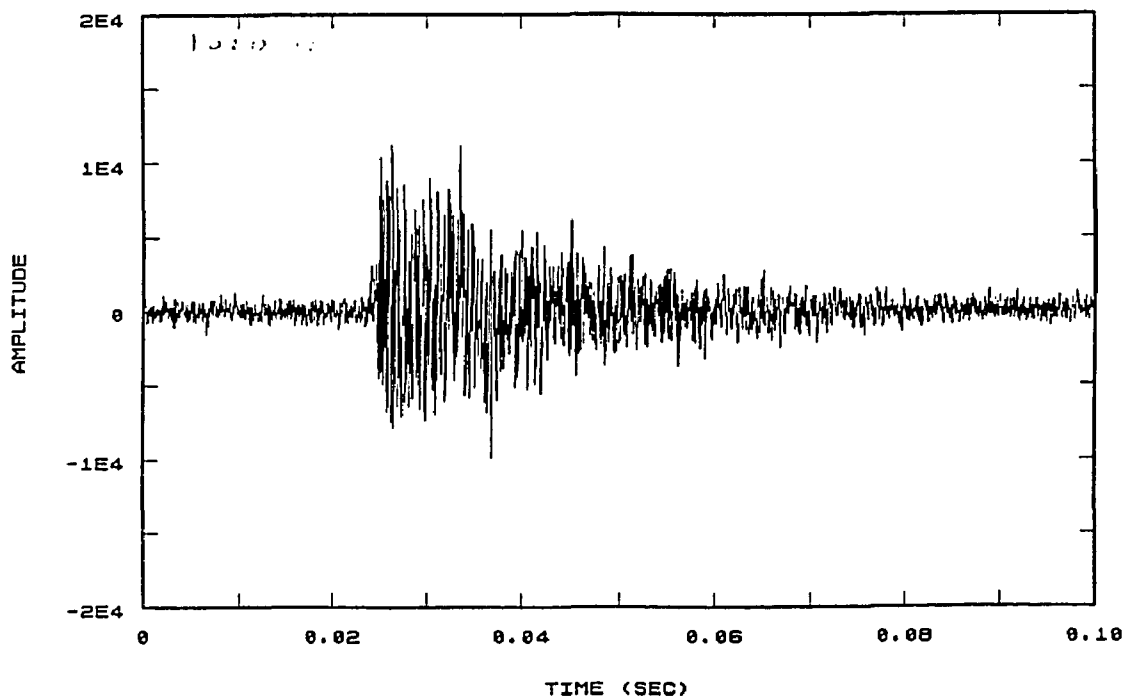


Figure 90. Time-waveform of impulse noise test stimulus with impulse duration of 20 msec, repetition rate of 10 Hz, and steady white background noise at a peak-to-background ratio of 20 dB.

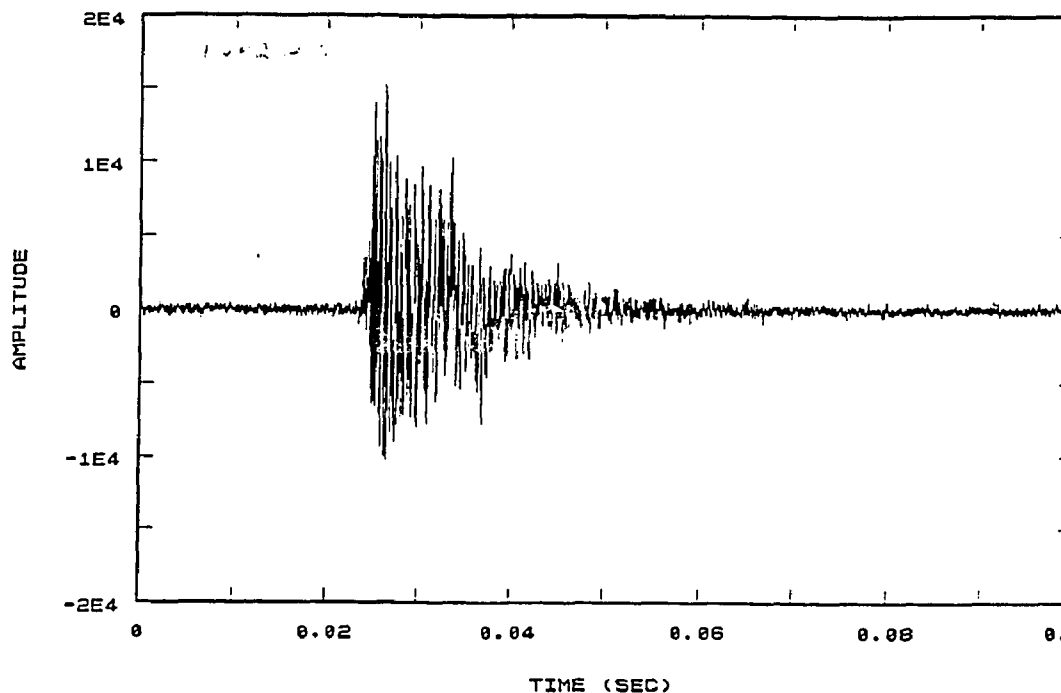


Figure 91. Time-waveform of impulse noise test stimulus with impulse duration of 20 msec, repetition rate of 10 Hz, and steady white background noise at a peak-to-background ratio of 30 dB.

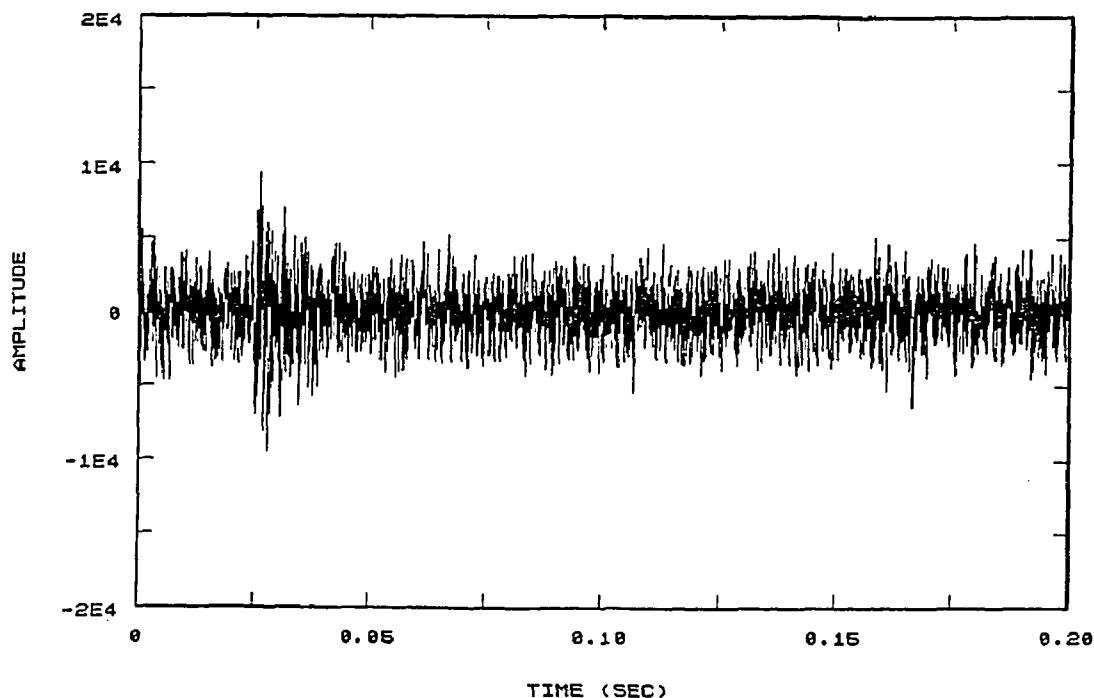


Figure 92. Time-waveform of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 5 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

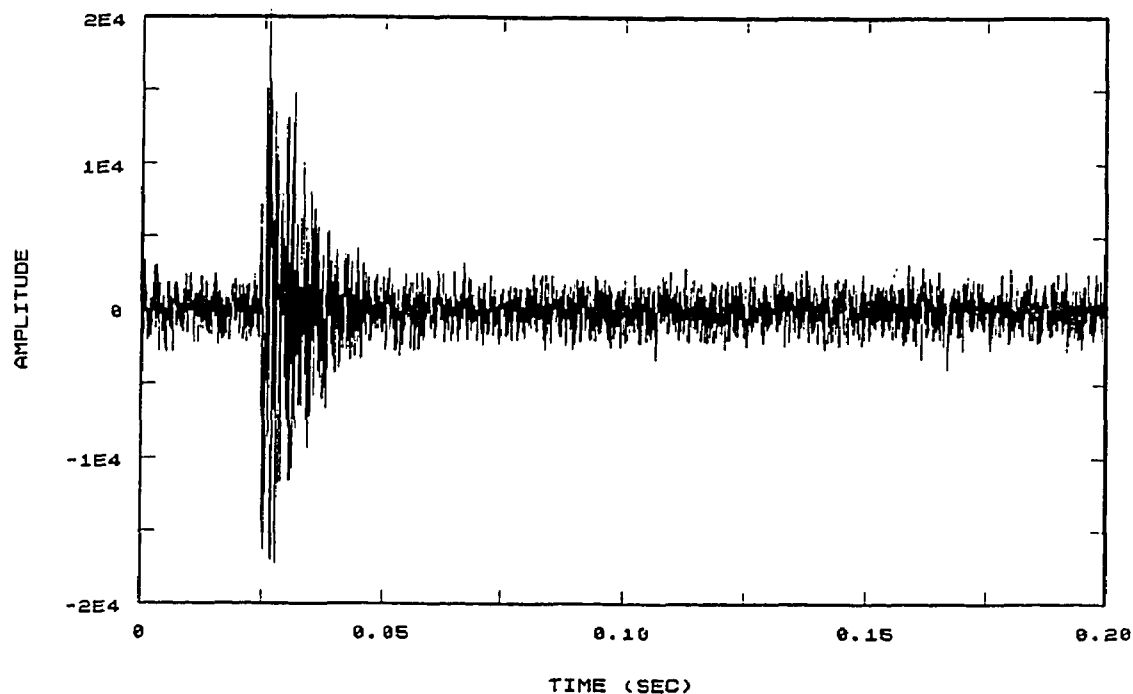


Figure 93. Time-waveform of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 5 Hz, and steady white background noise at a peak-to-background ratio of 20 dB.

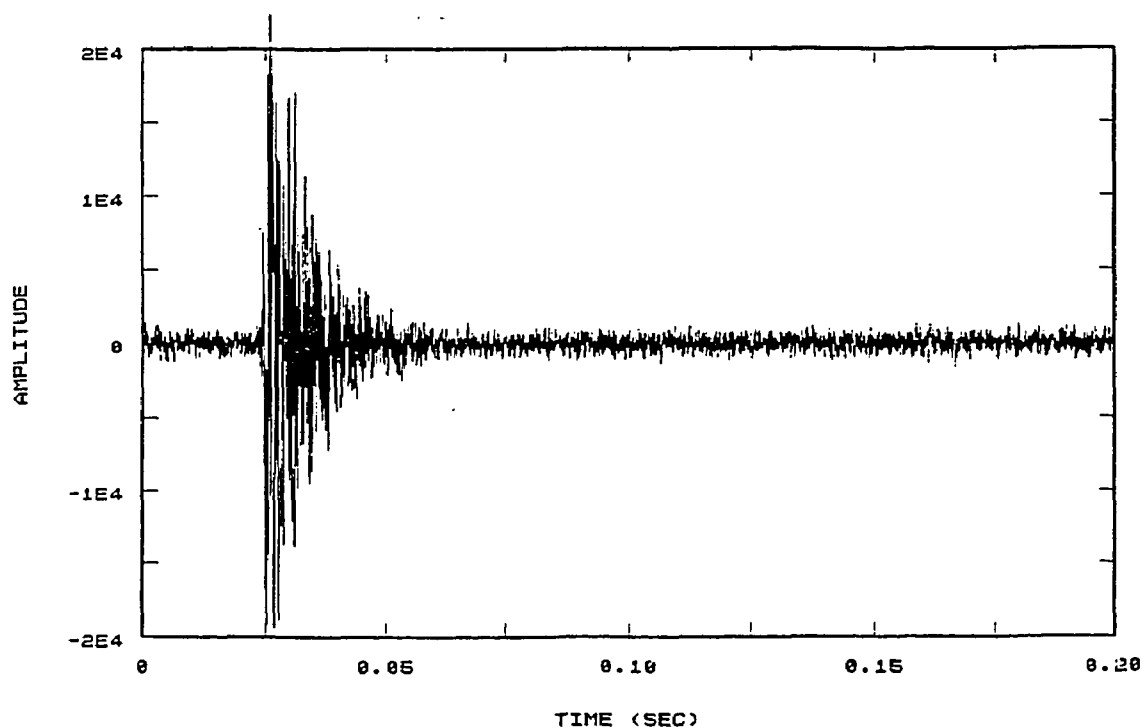


Figure 94. Time-waveform of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 5 Hz, and steady white background noise at a peak-to-background ratio of 30 dB.

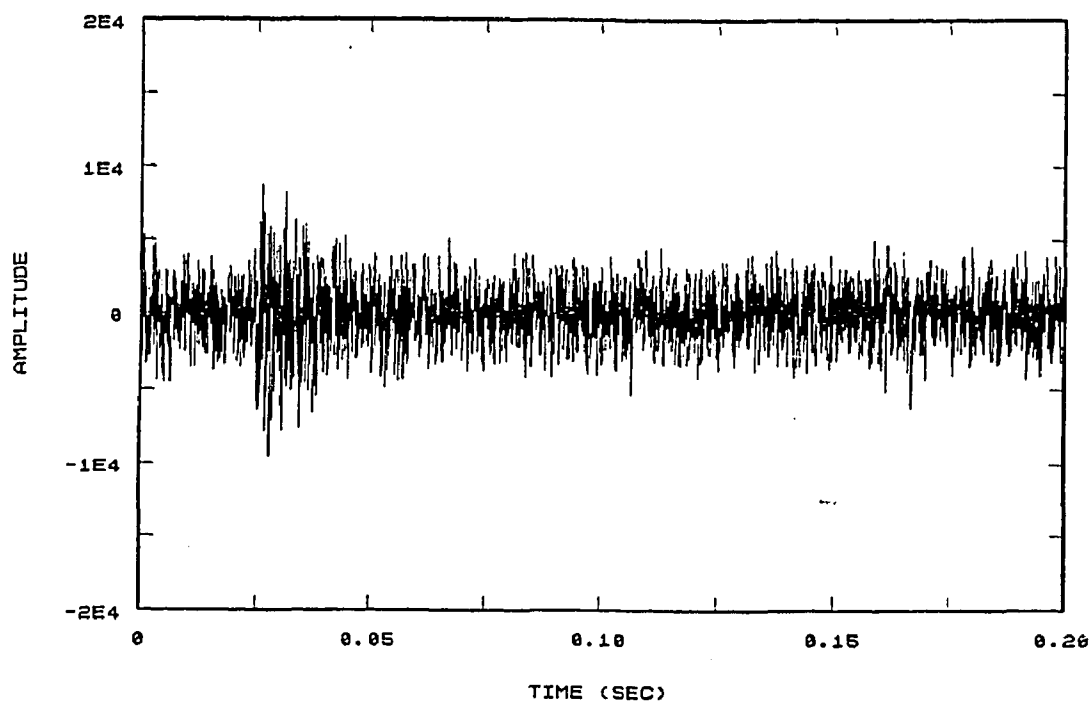


Figure 95. Time-waveform of impulse noise test stimulus with impulse duration of 20 msec, repetition rate of 5 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

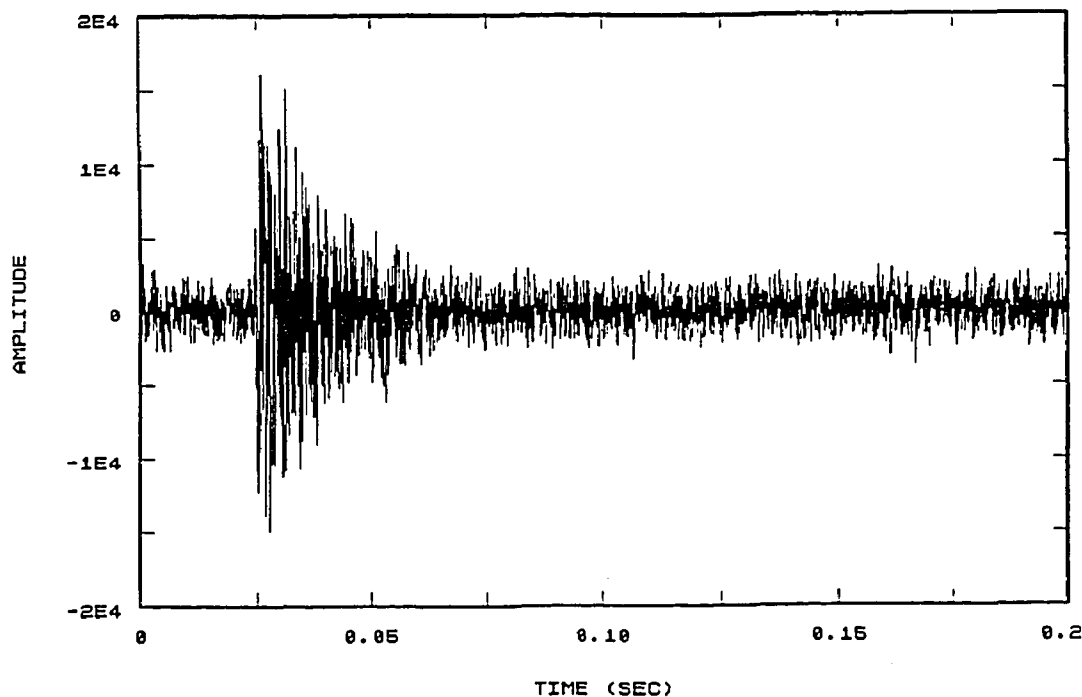


Figure 96. Time-waveform of impulse noise test stimulus with impulse duration of 20 msec, repetition rate of 5 Hz, and steady white background noise at a peak-to-background ratio of 20 dB.

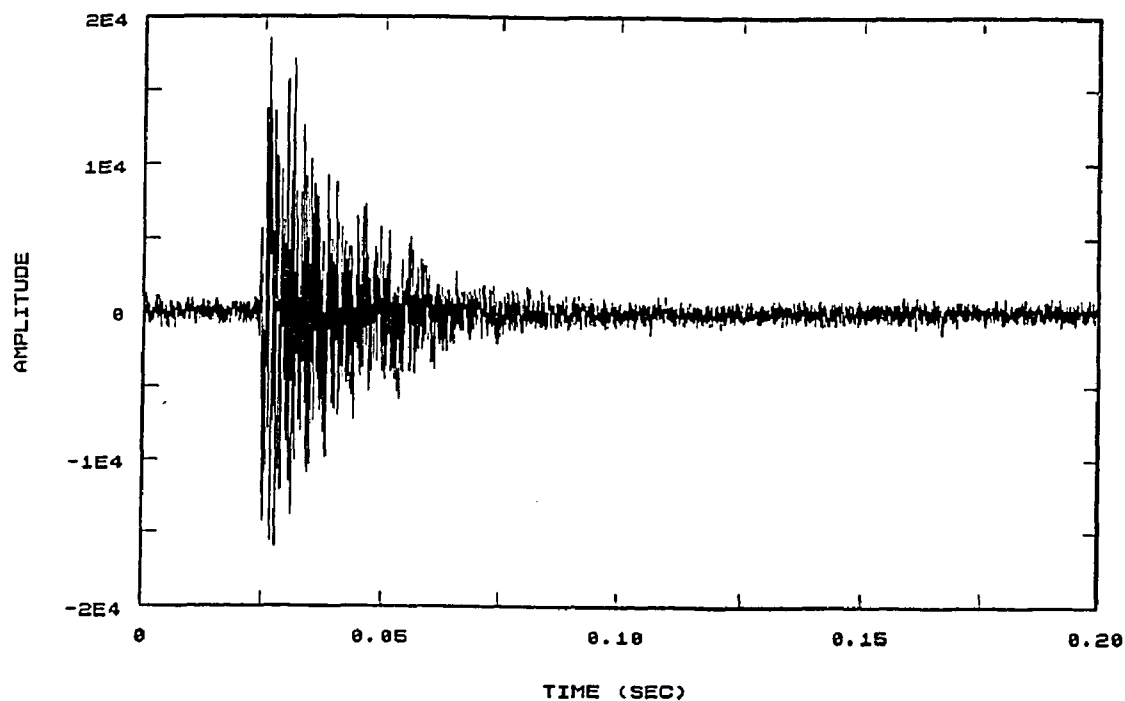


Figure 97. Time-waveform of impulse noise test stimulus with impulse duration of 20 msec, repetition rate of 5 Hz, and steady white background noise at a peak-to-background ratio of 30 dB.

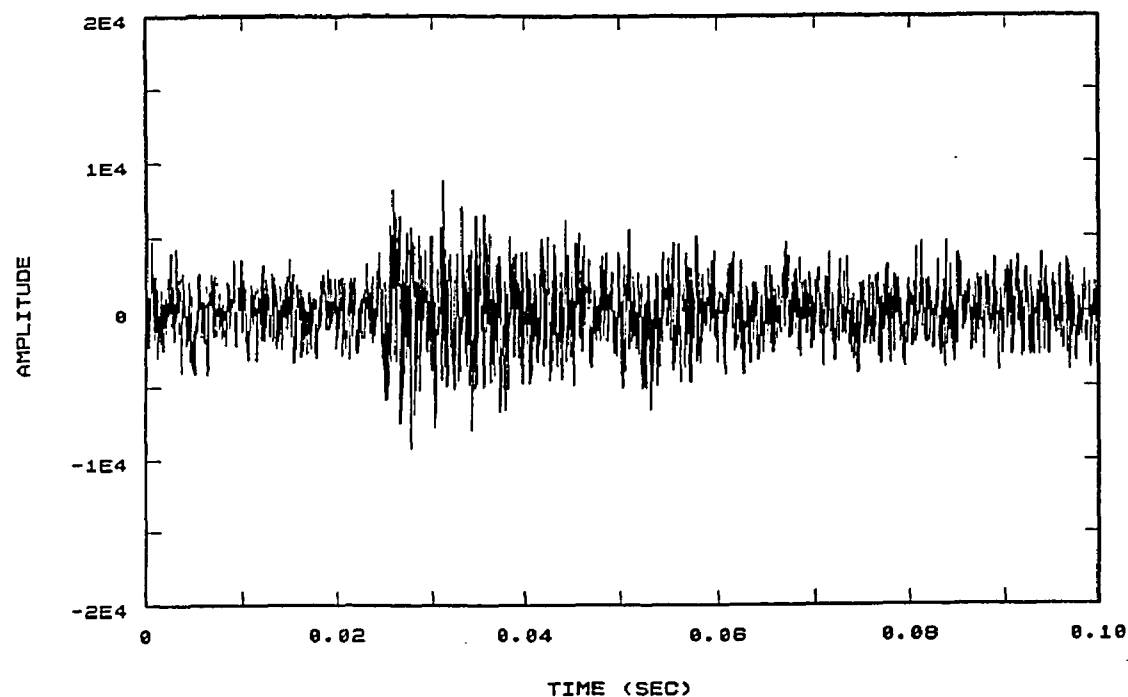


Figure 98. Time-waveform of impulse noise test stimulus with impulse duration of 40 msec, repetition rate of 5 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

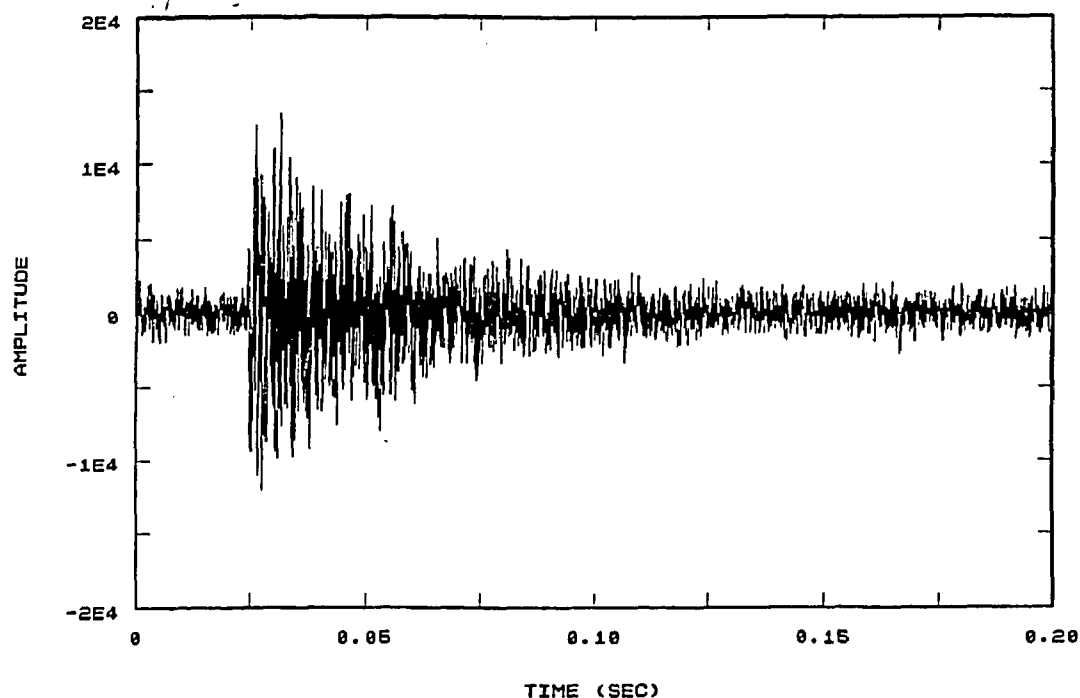


Figure 99. Time-waveform of impulse noise test stimulus with impulse duration of 40 msec, repetition rate of 5 Hz, and steady white background noise at a peak-to-background ratio of 20 dB.

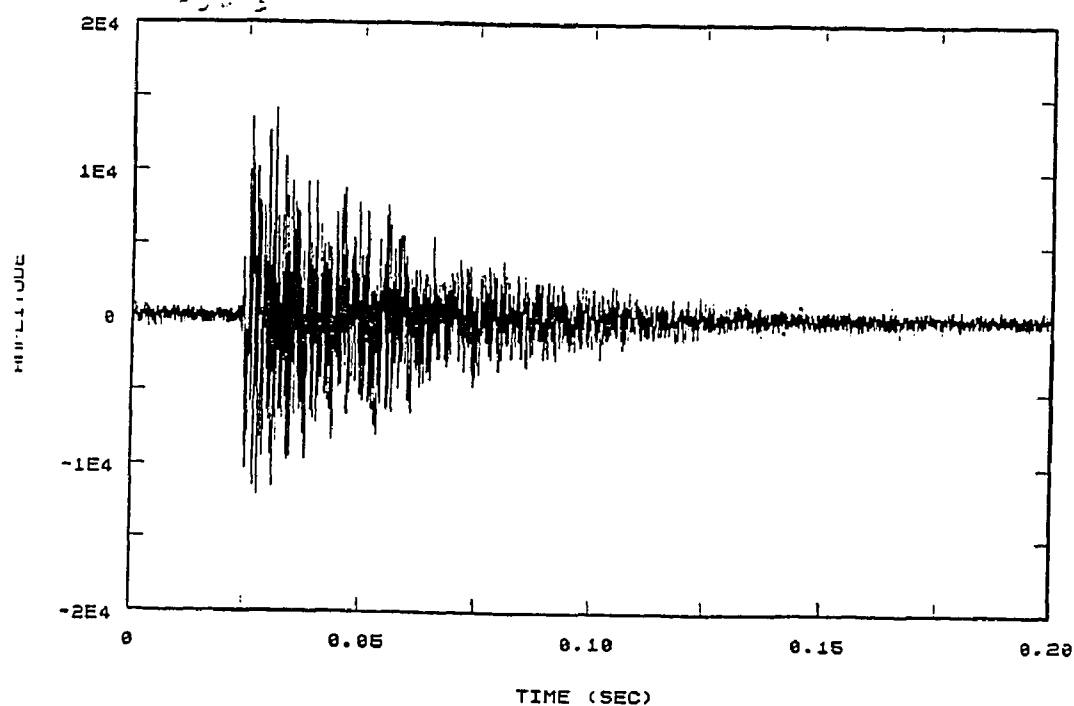


Figure 100. Time-waveform of impulse noise test stimulus with impulse duration of 40 msec, repetition rate of 5 Hz, and steady white background noise at a peak-to-background ratio of 30 dB.

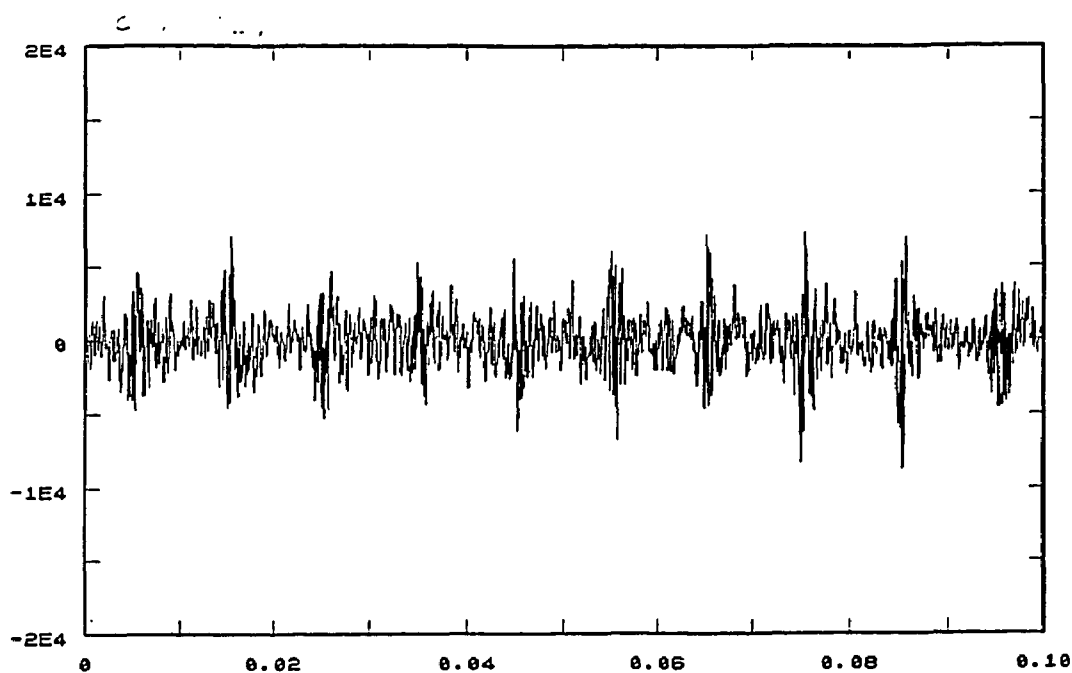


Figure 101. Time-waveform of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 10 dB.

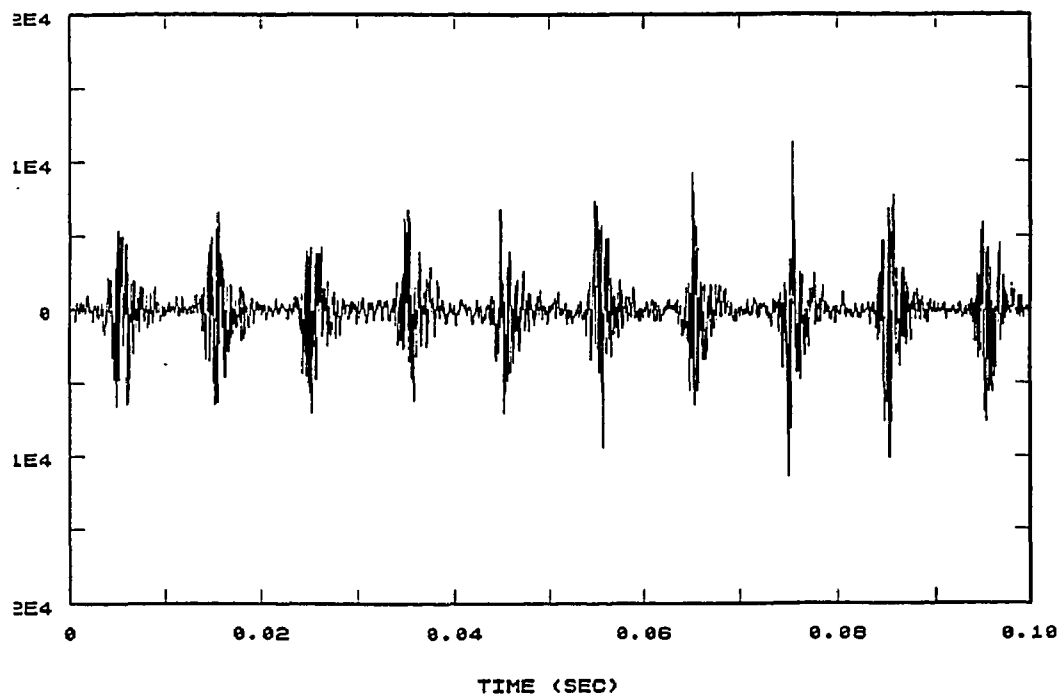


Figure 102. Time-waveform of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 20 dB.

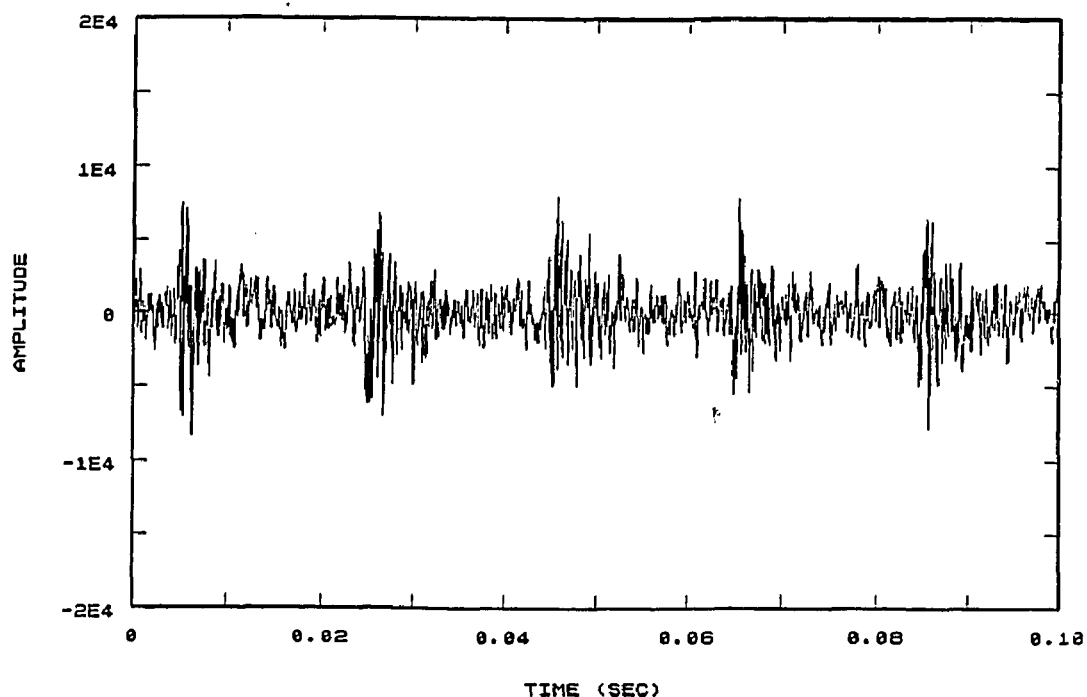


Figure 103. Time-waveform of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 10 dB.

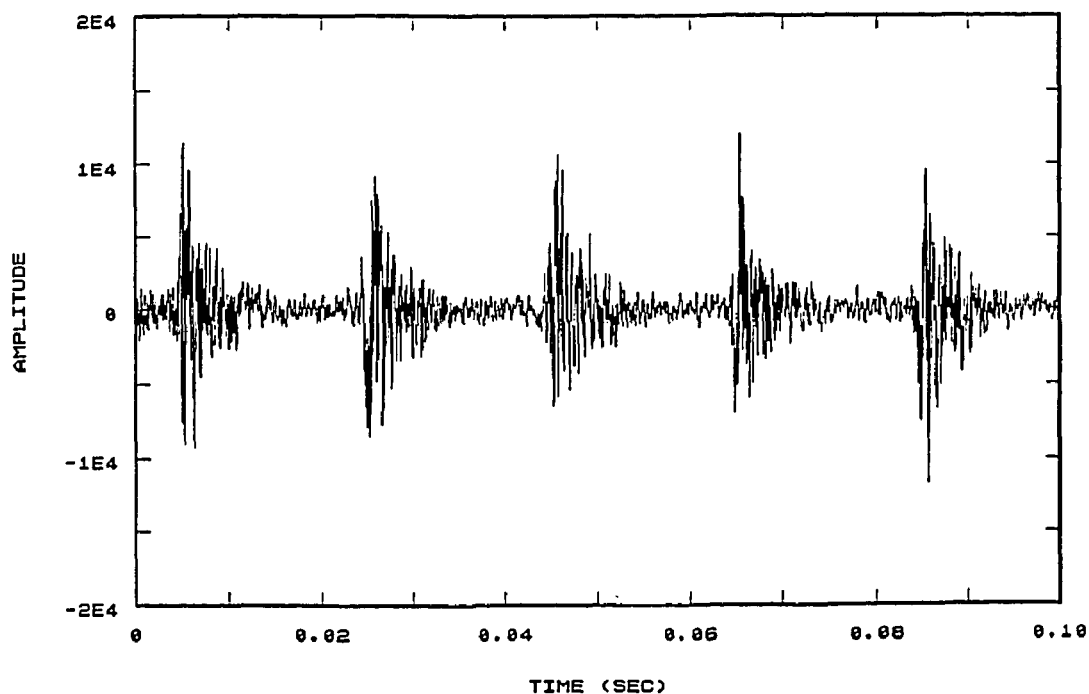


Figure 104. Time-waveform of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 20 dB.

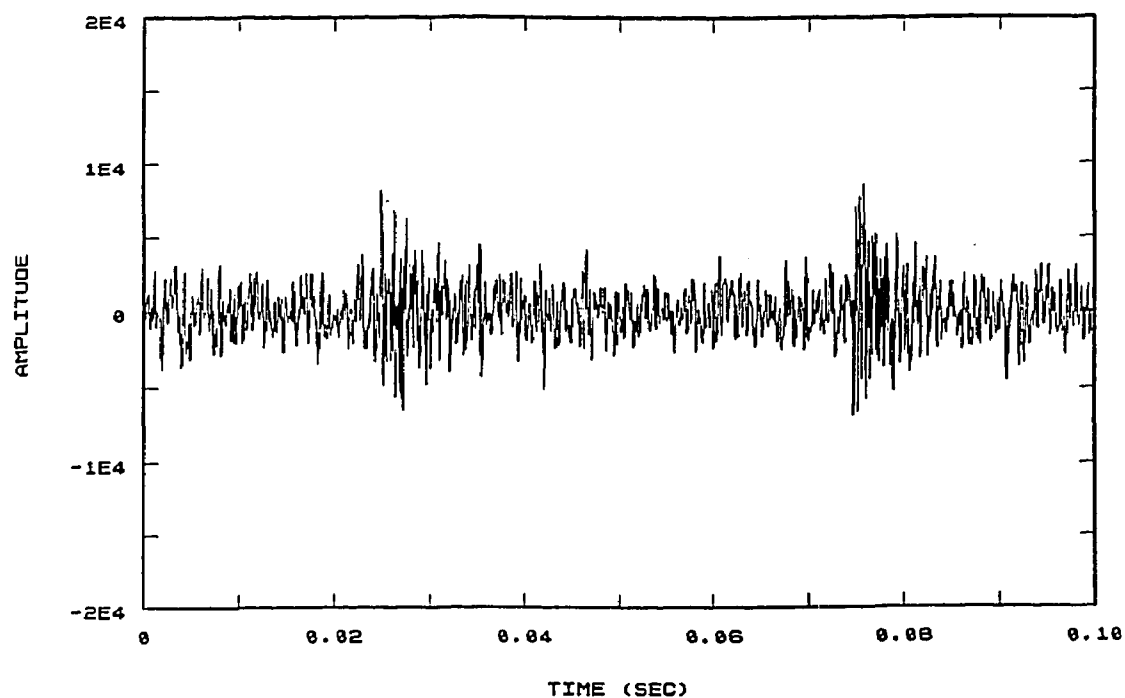


Figure 105. Time-waveform of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 10 dB.

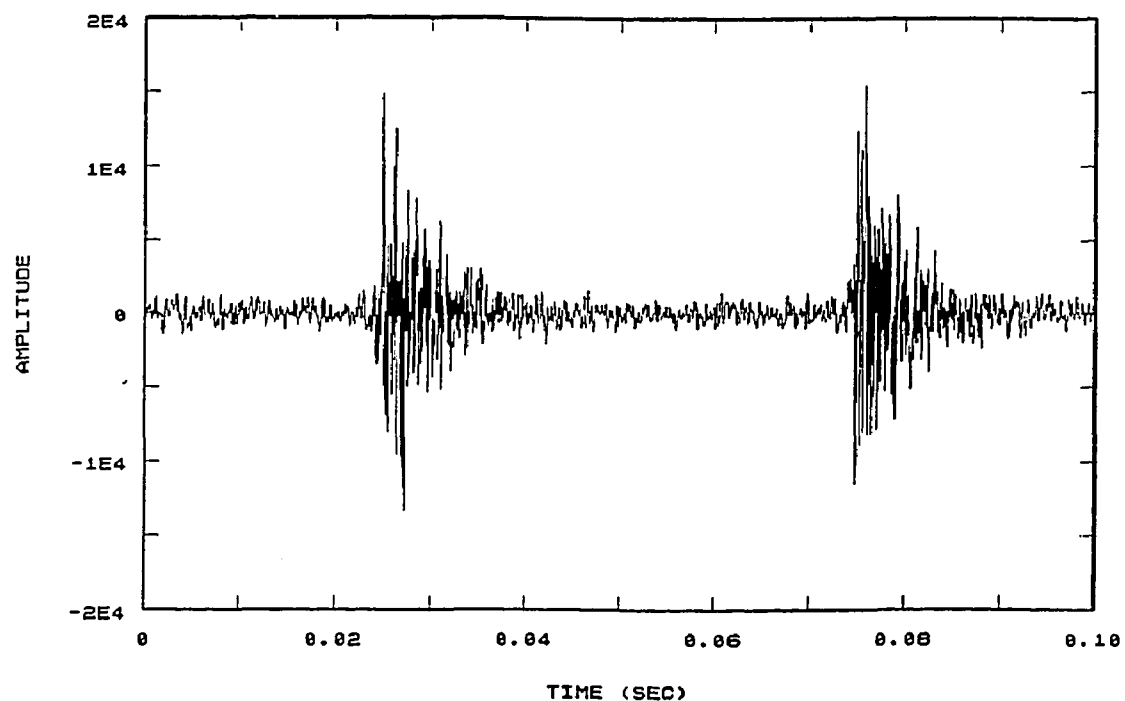


Figure 106. Time-waveform of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 20 dB.

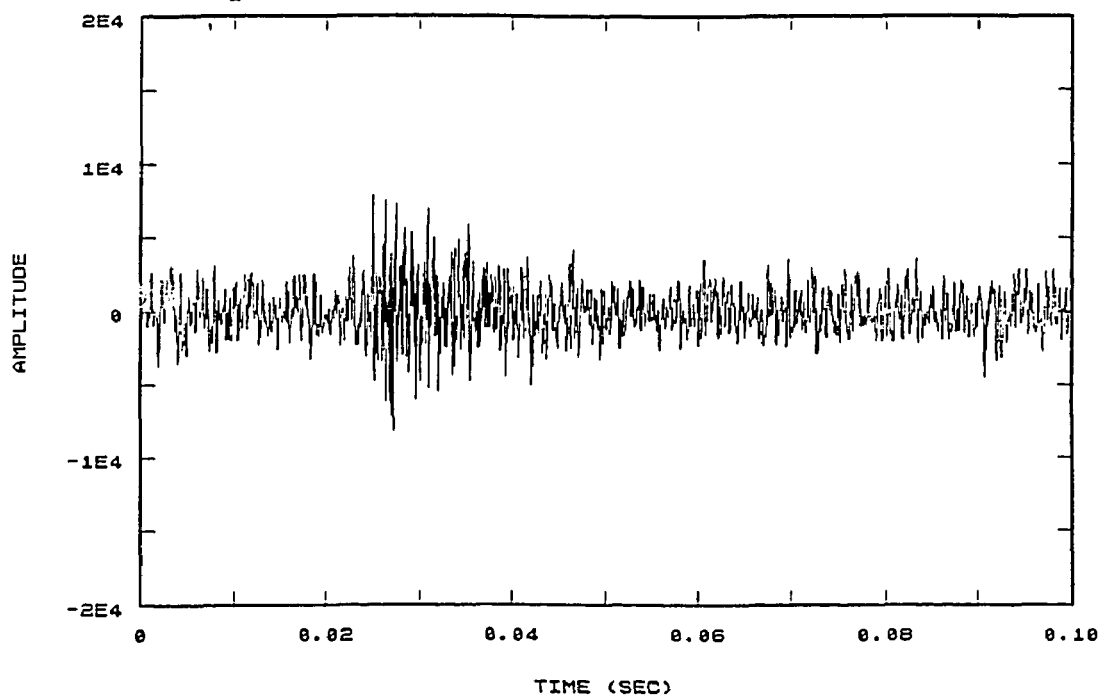


Figure 107. Time-waveform of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 10 dB.

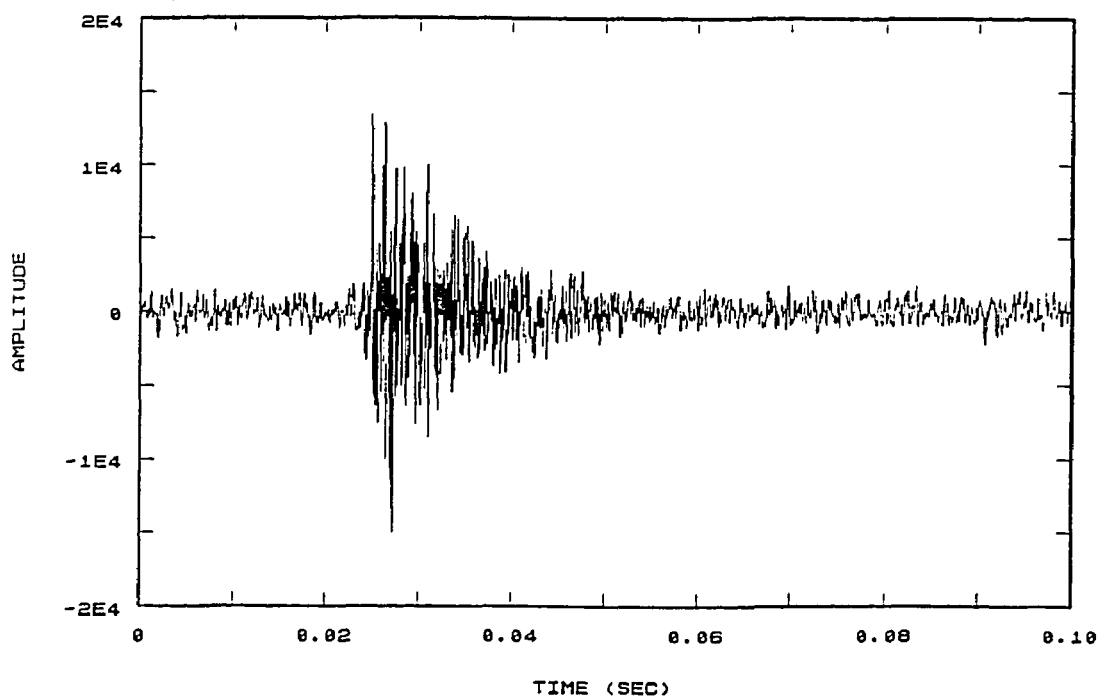


Figure 108. Time-waveform of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 20 dB.

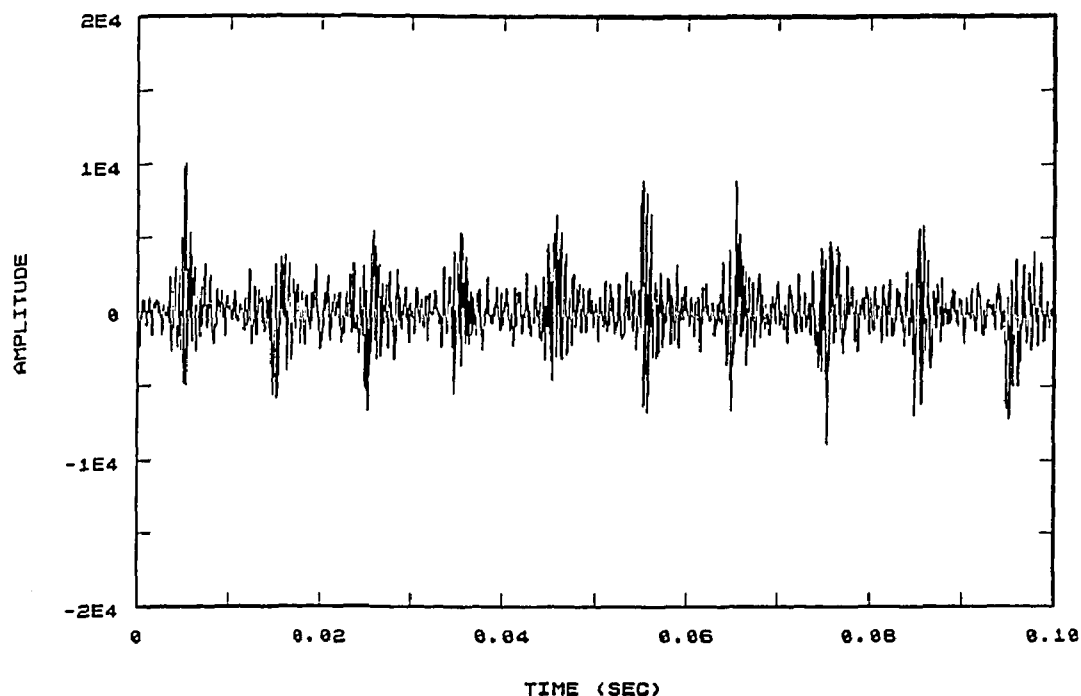


Figure 109. Time-waveform of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 10 dB.

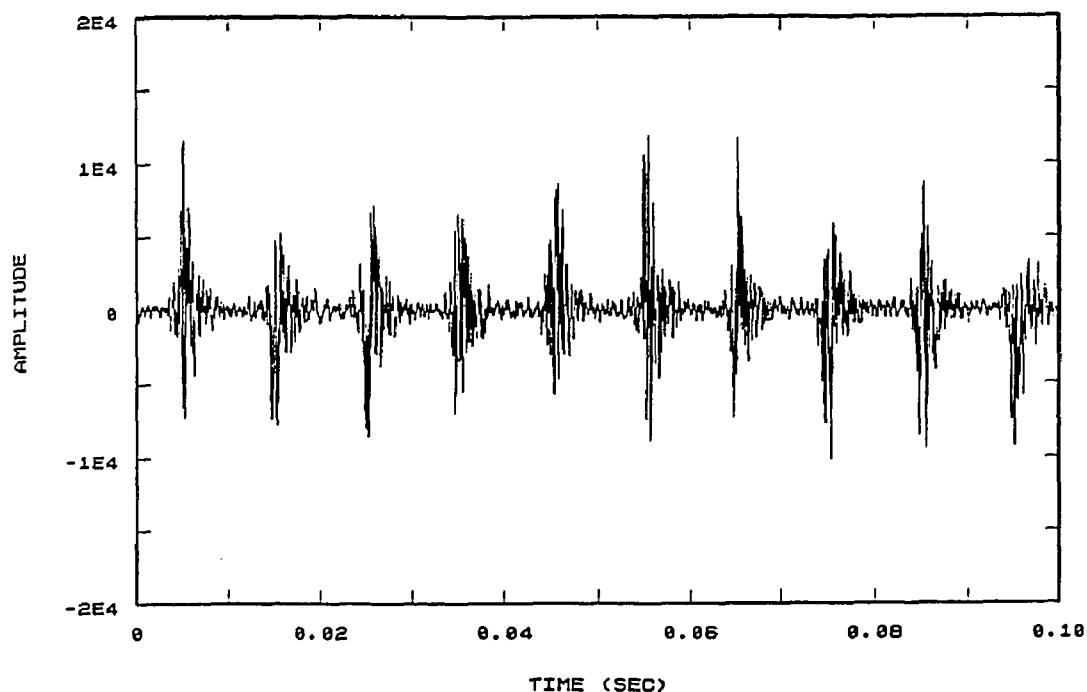


Figure 110. Time-waveform of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 20 dB.

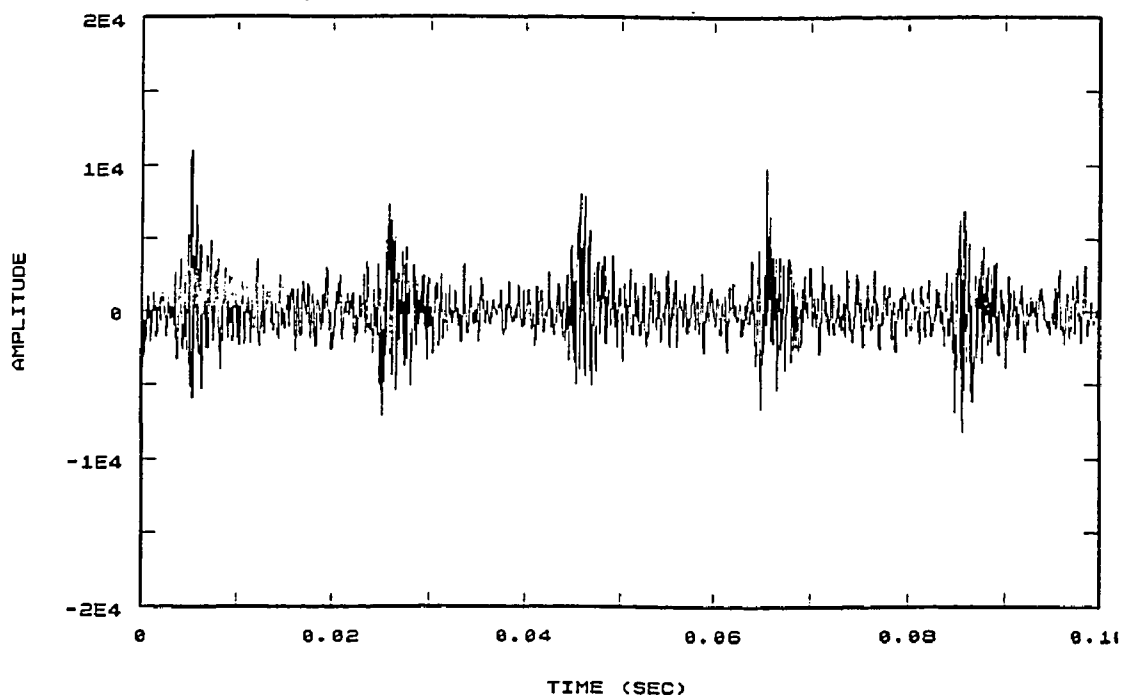


Figure 111. Time-waveform of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 10 dB.

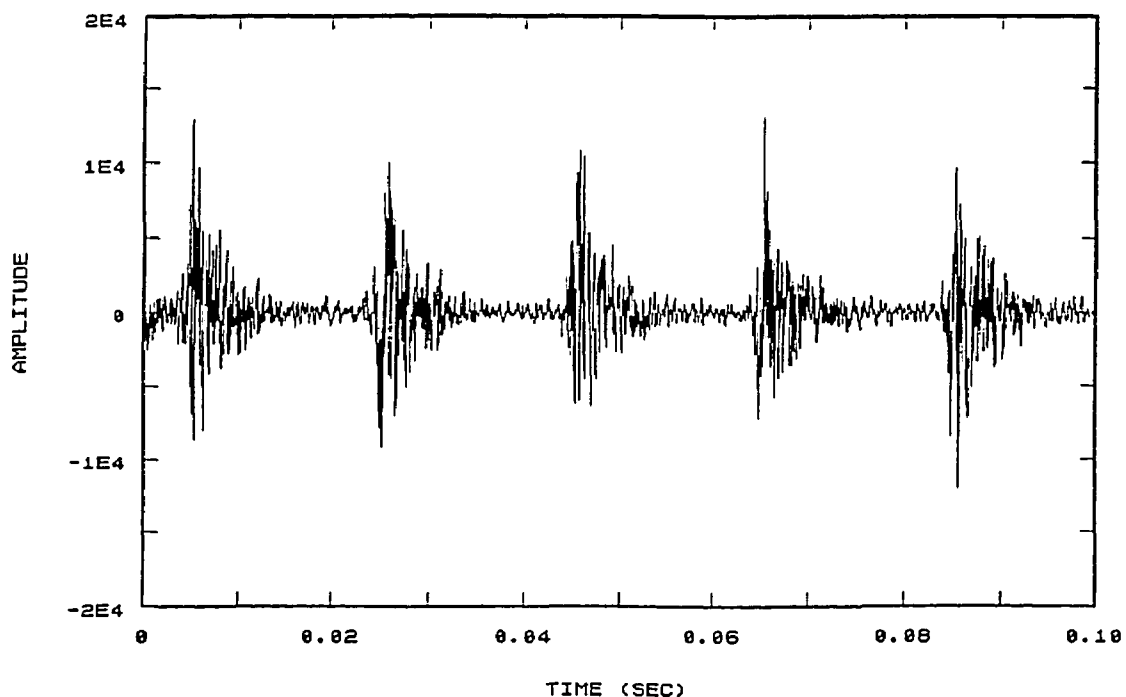


Figure 112. Time-waveform of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 20 dB.

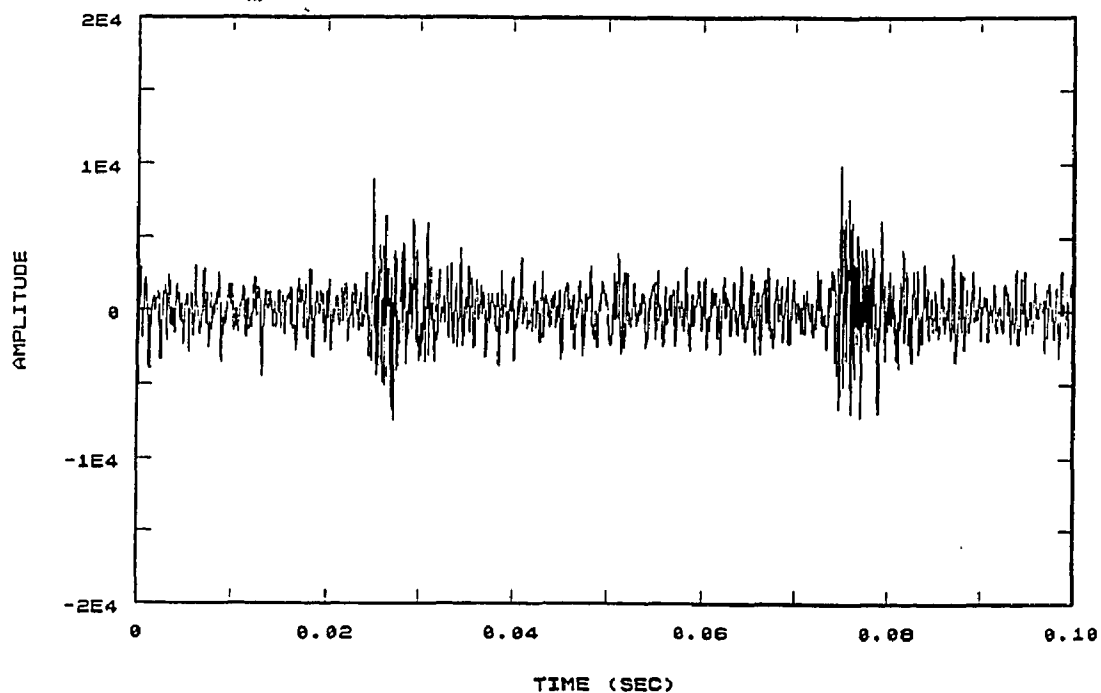


Figure 113. Time-waveform of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 10 dB.

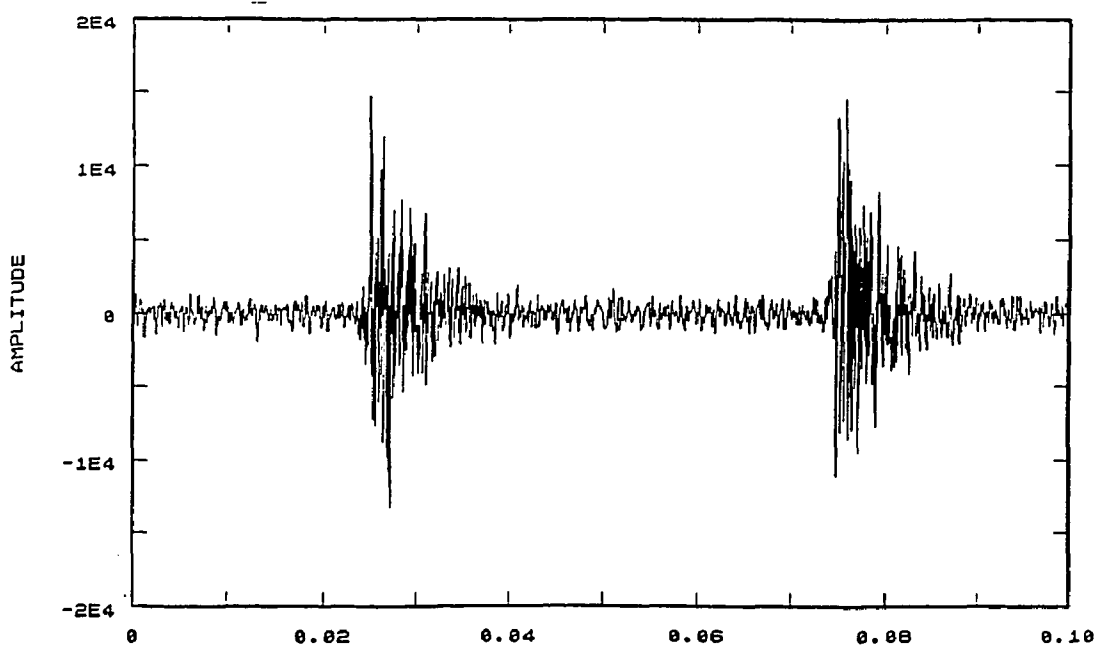


Figure 114. Time-waveform of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 20 dB.

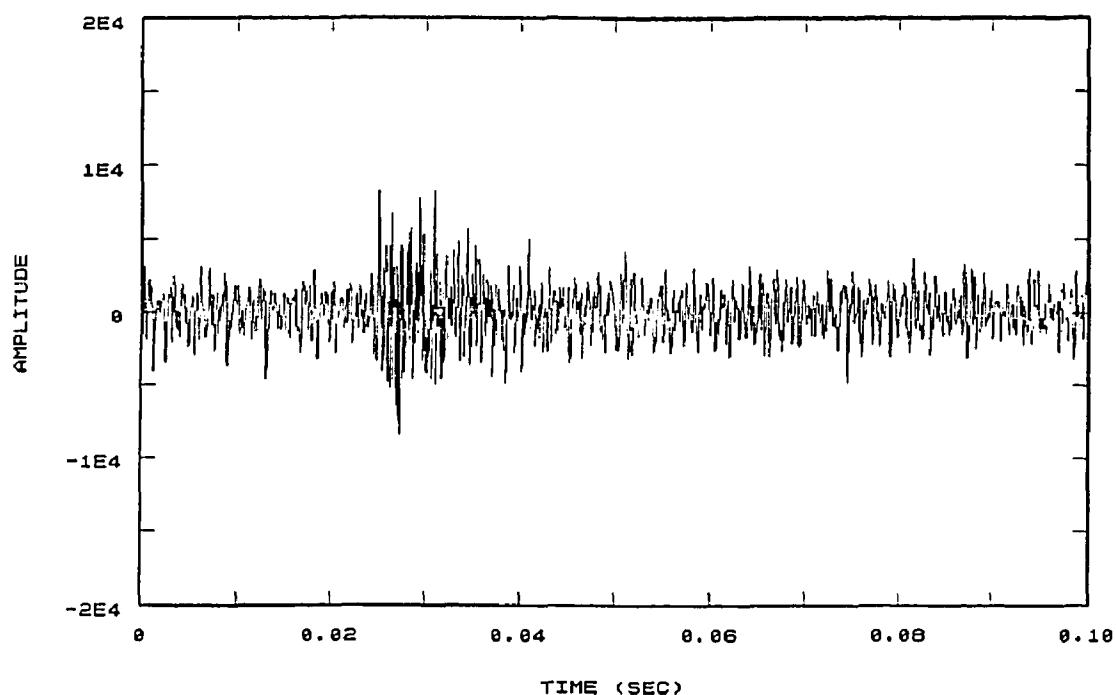


Figure 115. Time-waveform of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 10 dB.

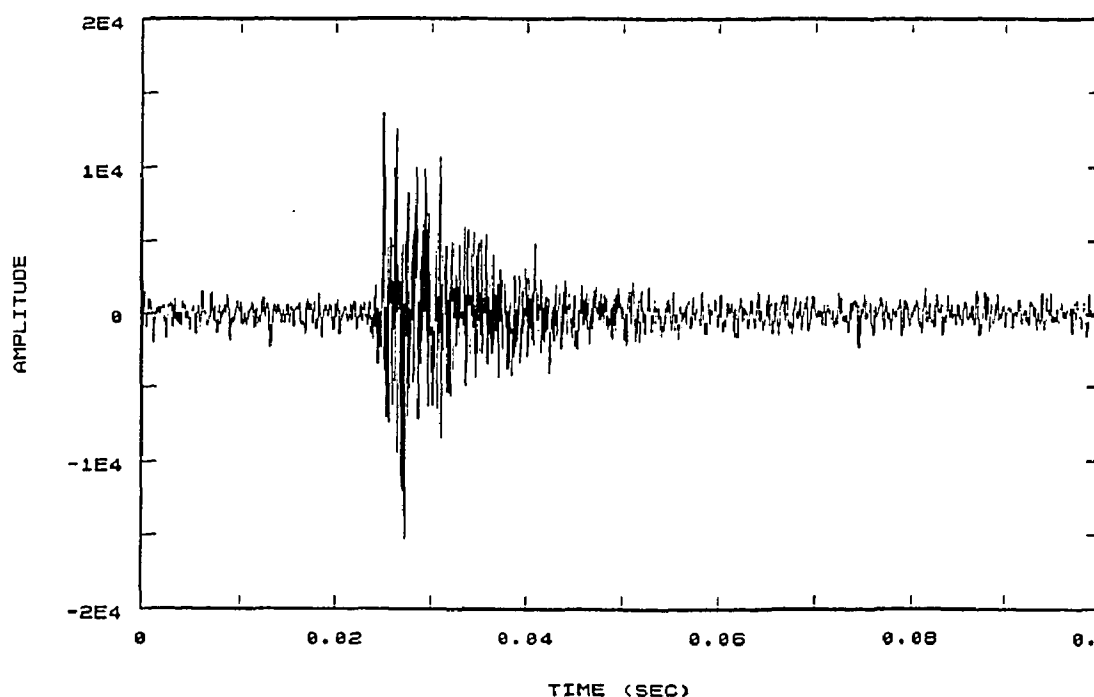


Figure 116. Time-waveform of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 20 dB.

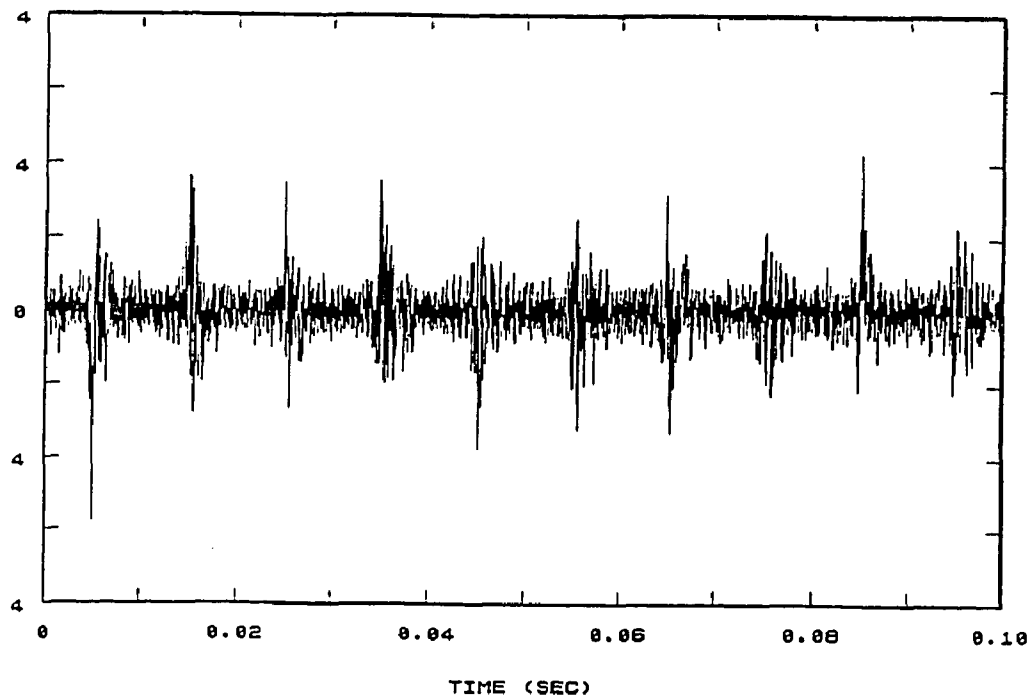


Figure 117. Time-waveform of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 10 dB.

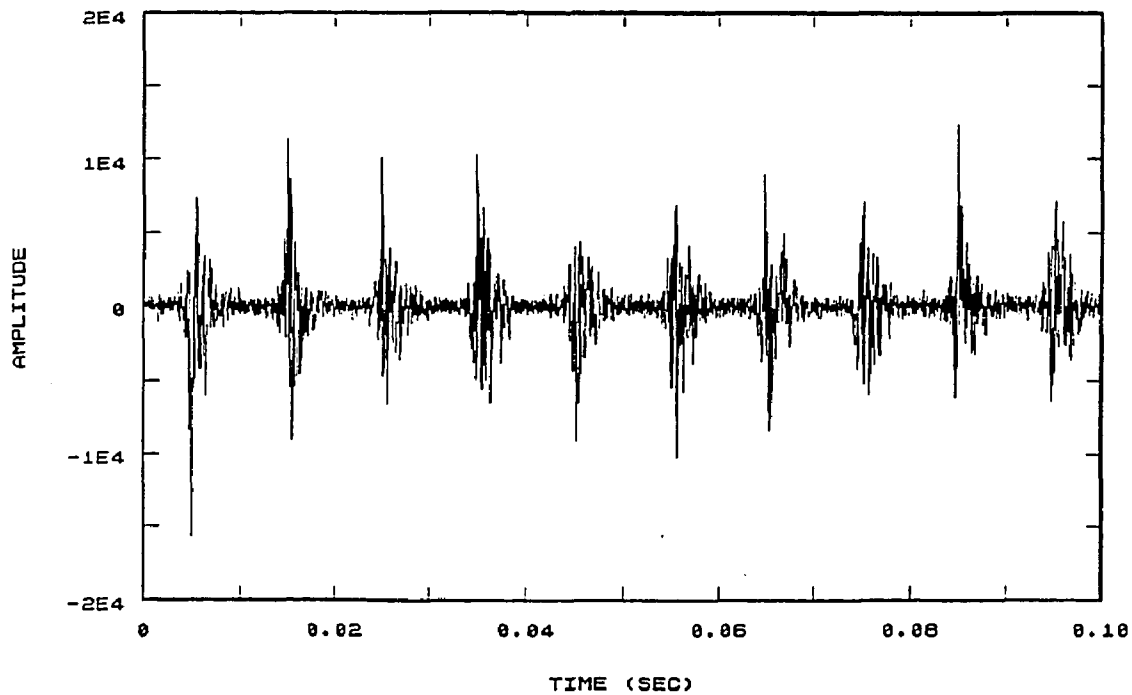


Figure 118. Time-waveform of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 20 dB.

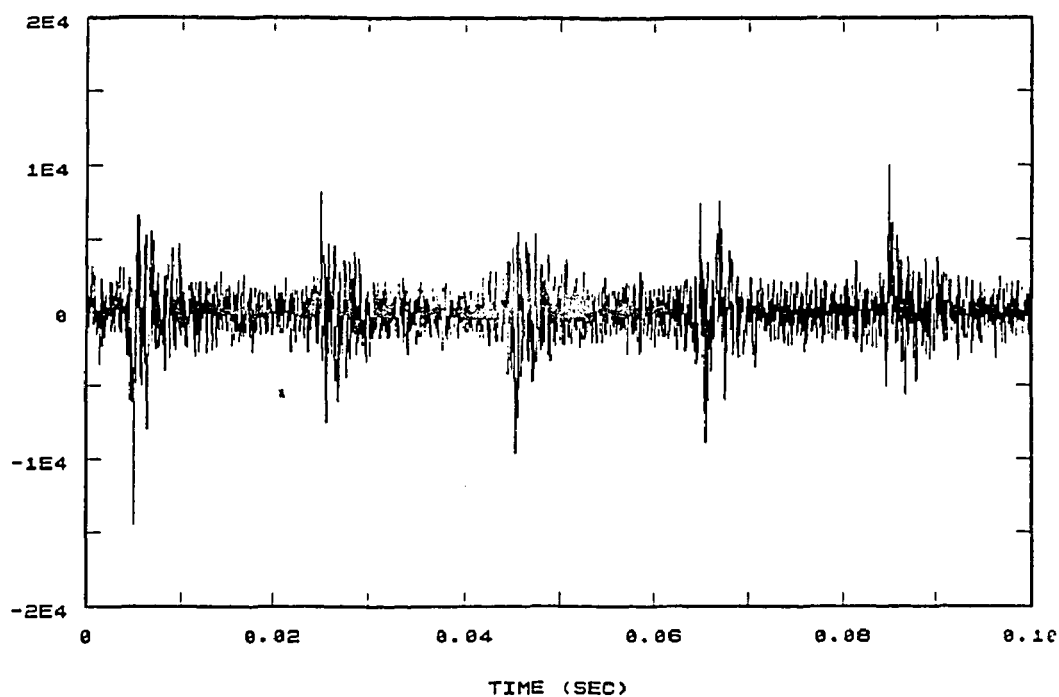


Figure 119. Time-waveform of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 10 dB.

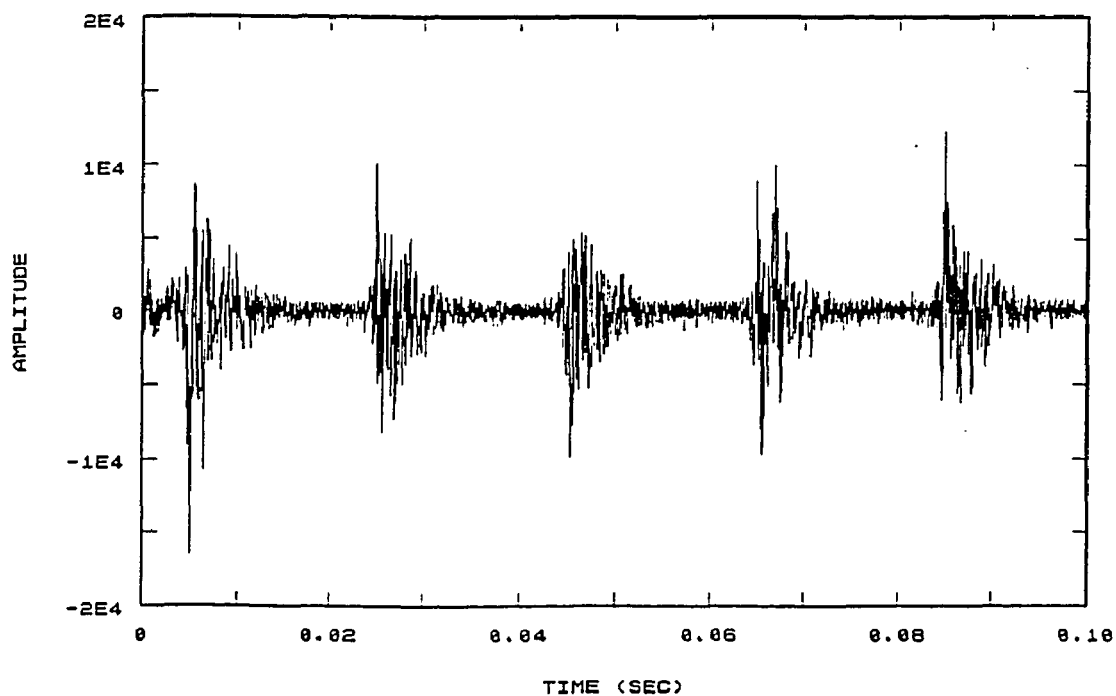


Figure 120. Time-waveform of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 20 dB.

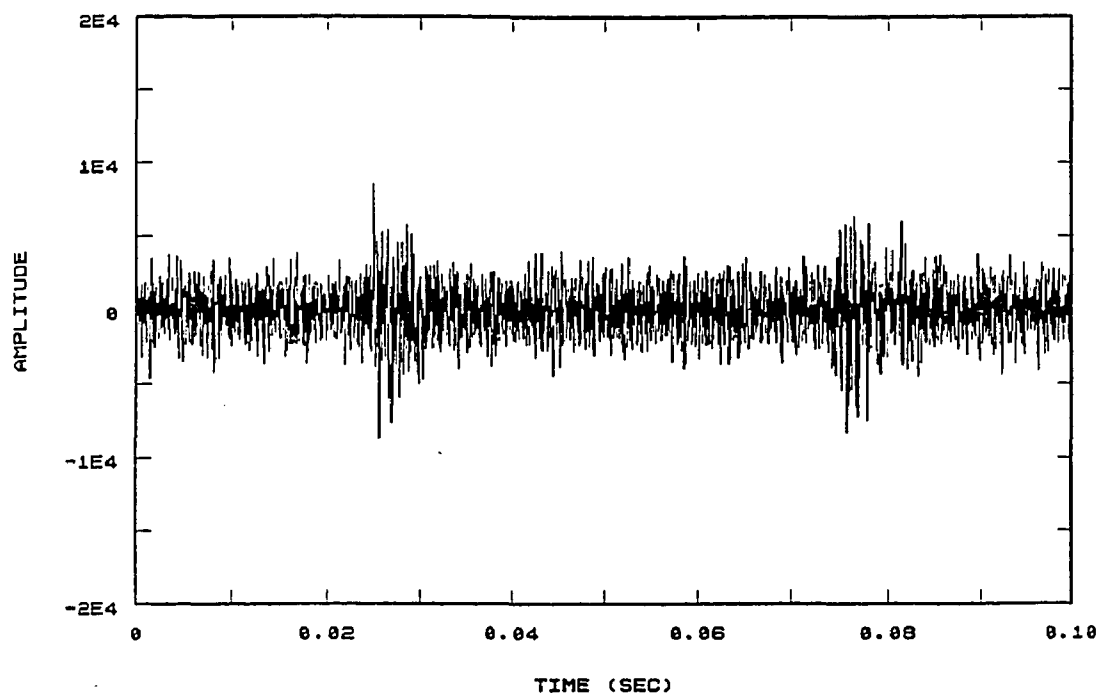


Figure 121. Time-waveform of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 10 dB.

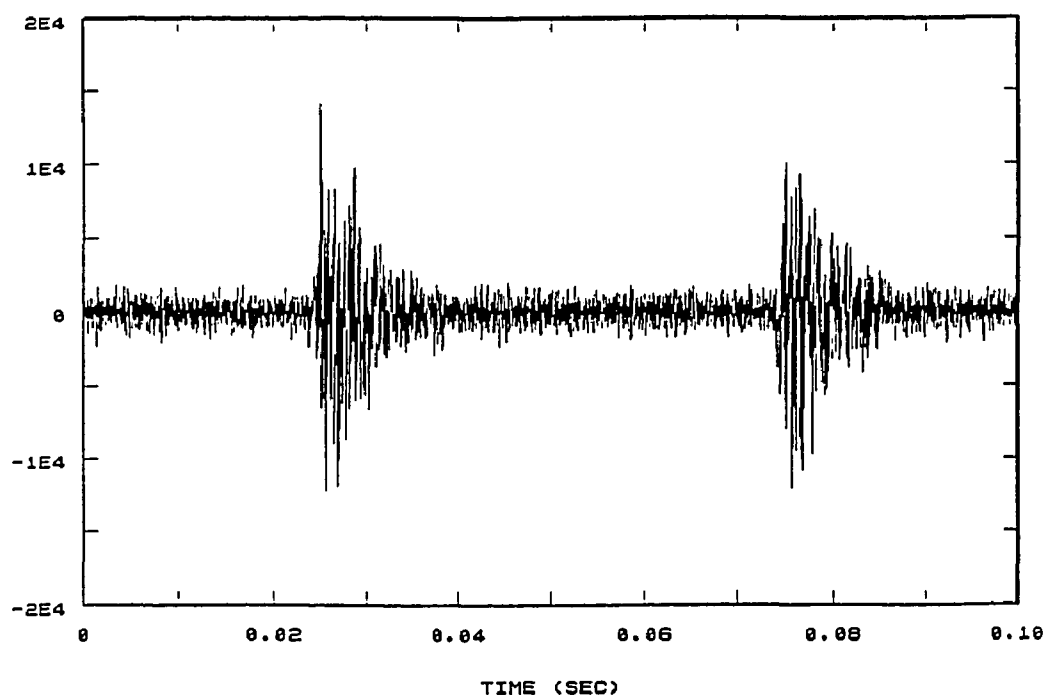


Figure 122. Time-waveform of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 20 dB.

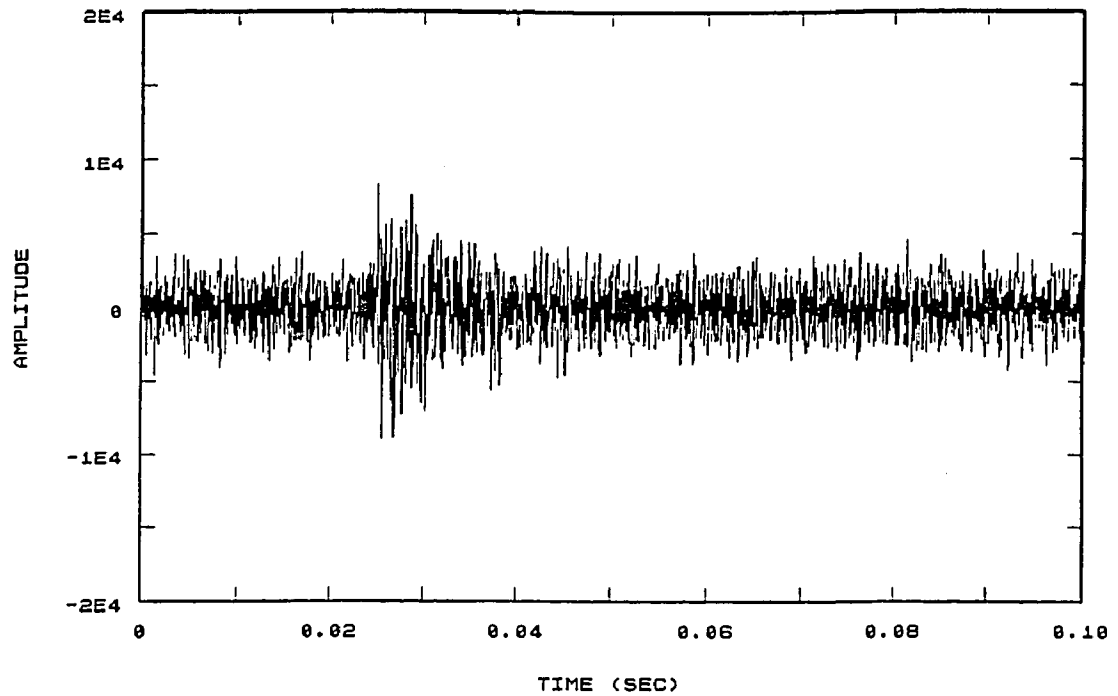


Figure 123. Time-waveform of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 10 dB.

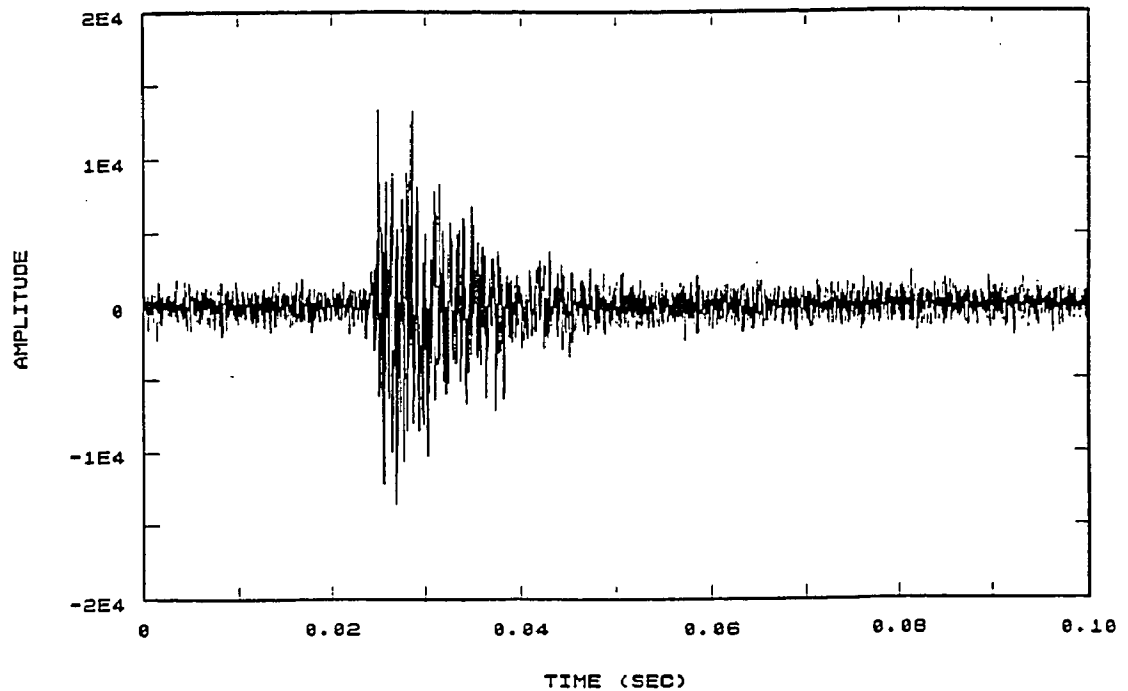


Figure 124. Time-waveform of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 20 dB.

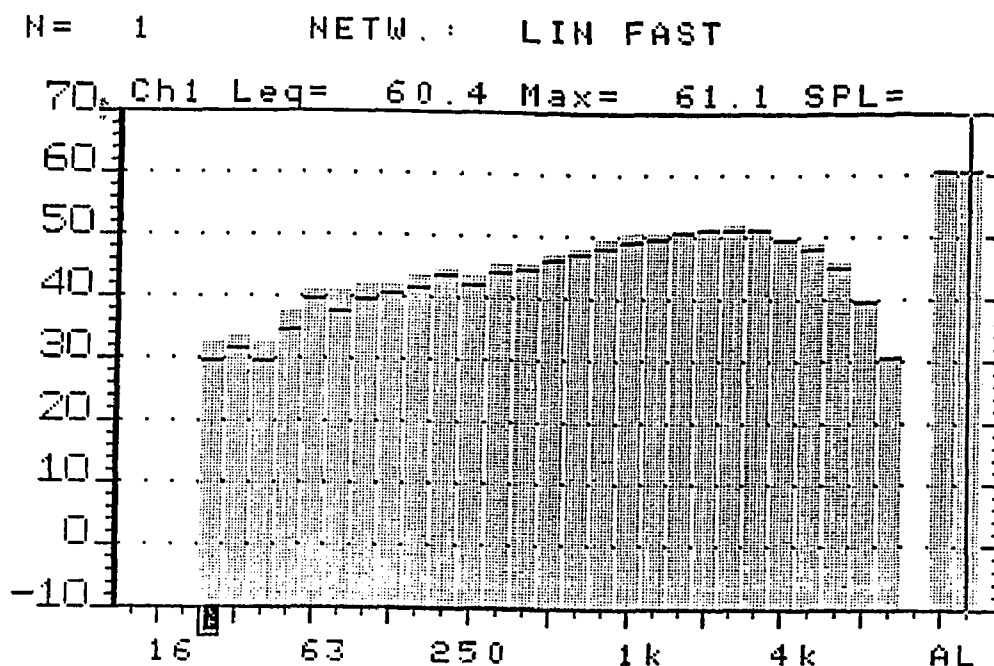


Figure 125. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 10 dB.

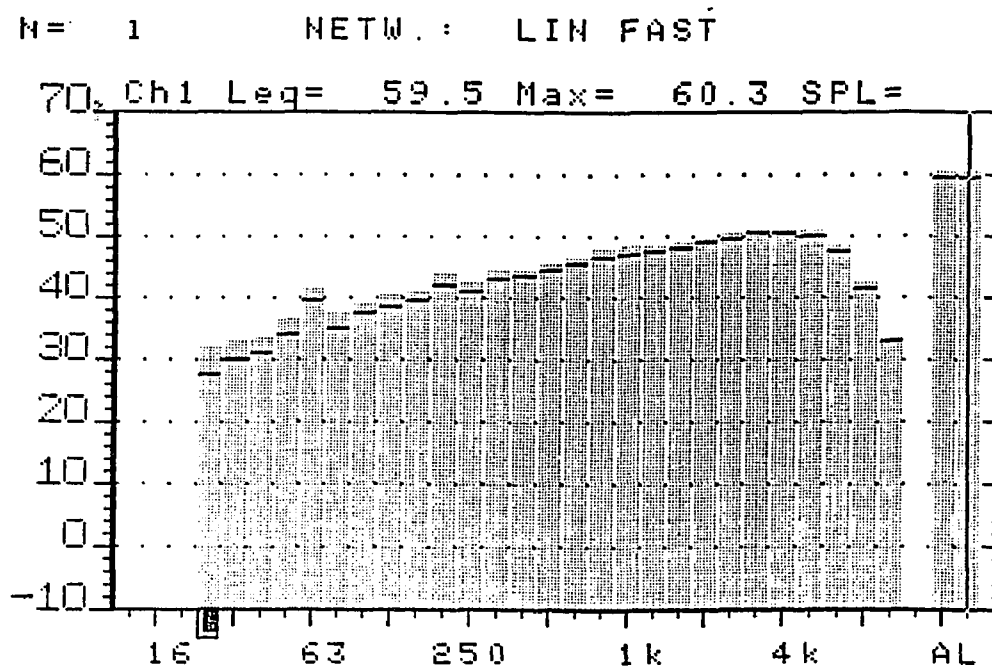


Figure 126. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 20 dB.

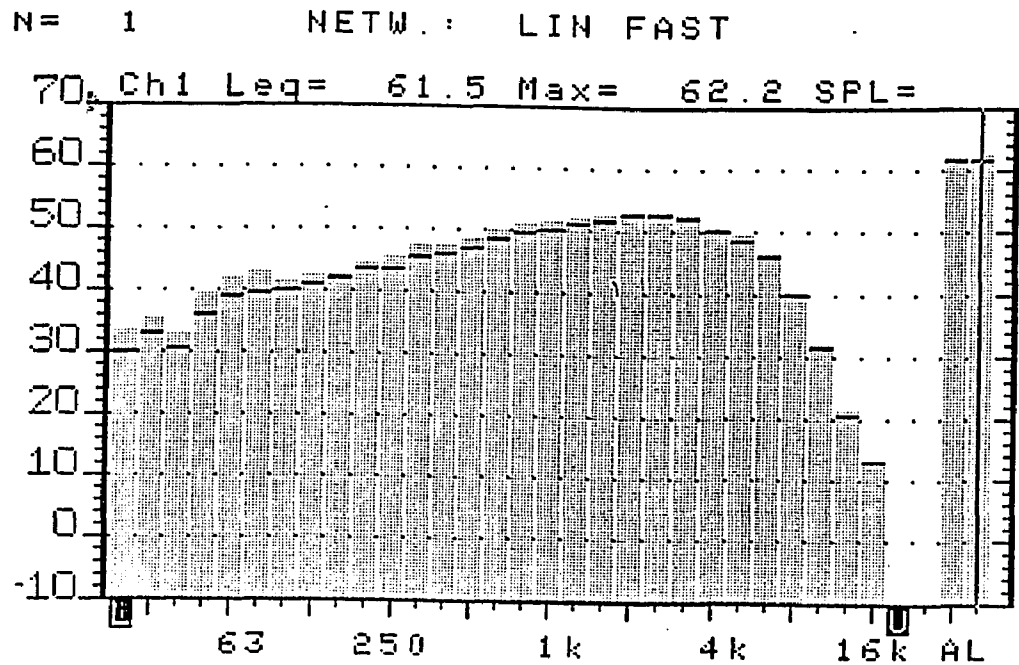


Figure 127. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 10 dB.

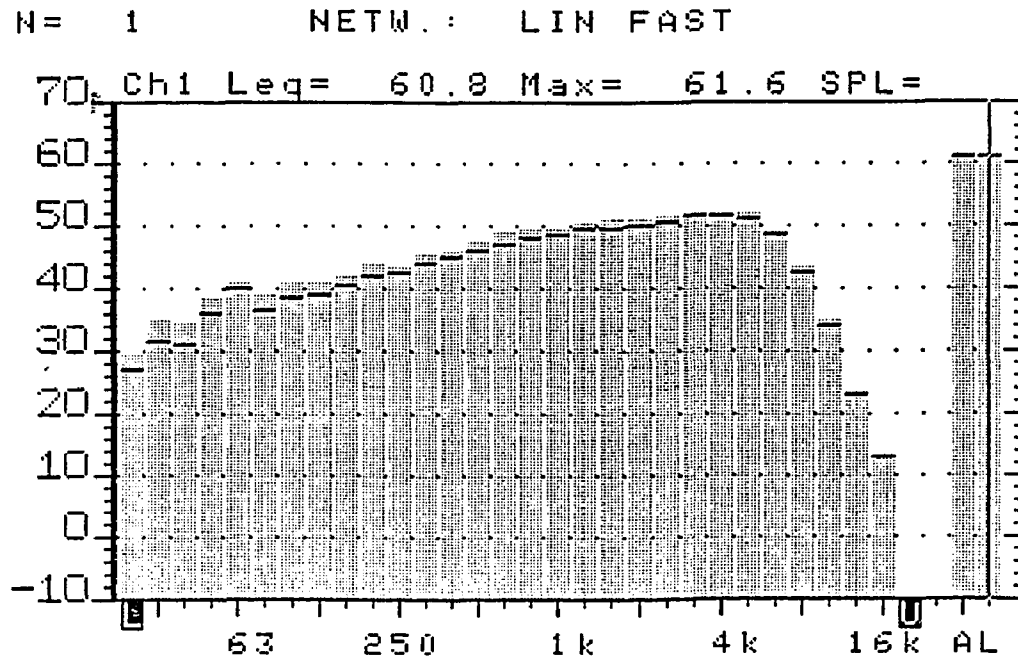


Figure 128. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 20 dB.

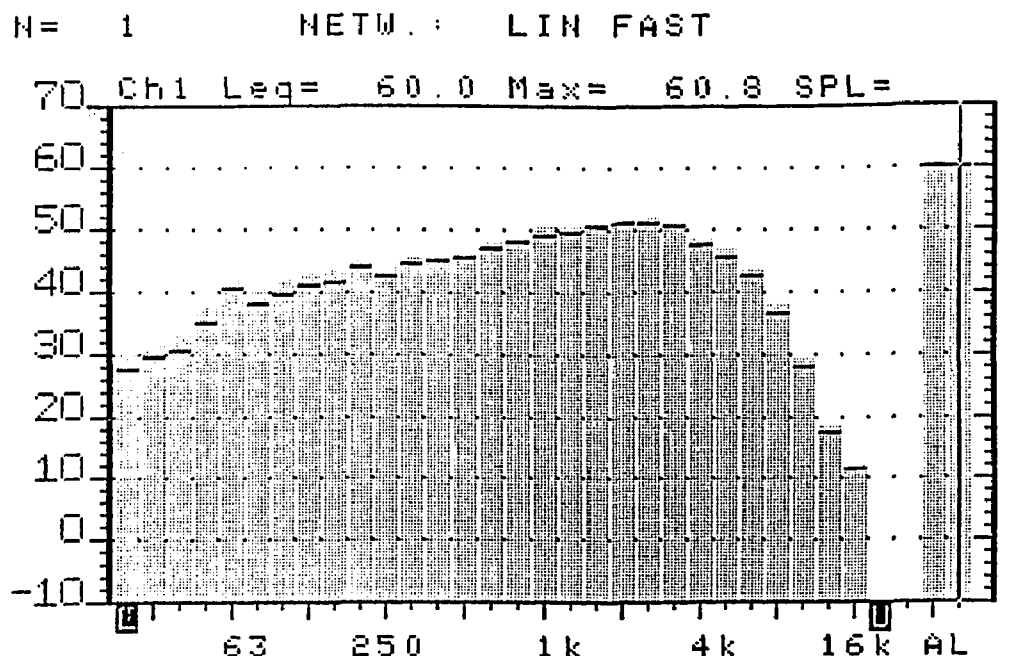


Figure 129. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 10 dB.

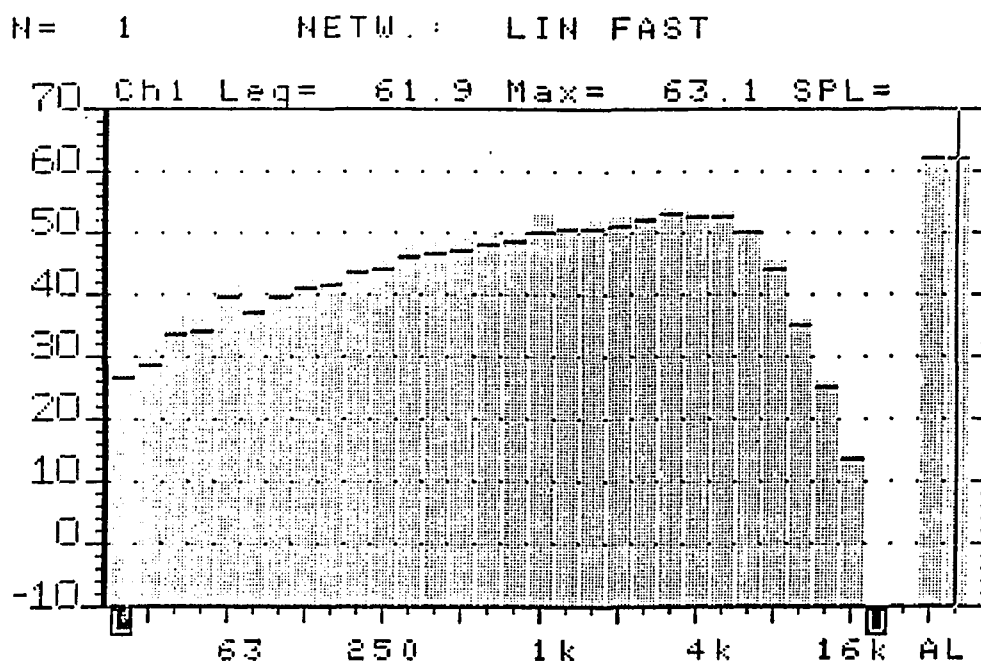


Figure 130. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 20 dB.

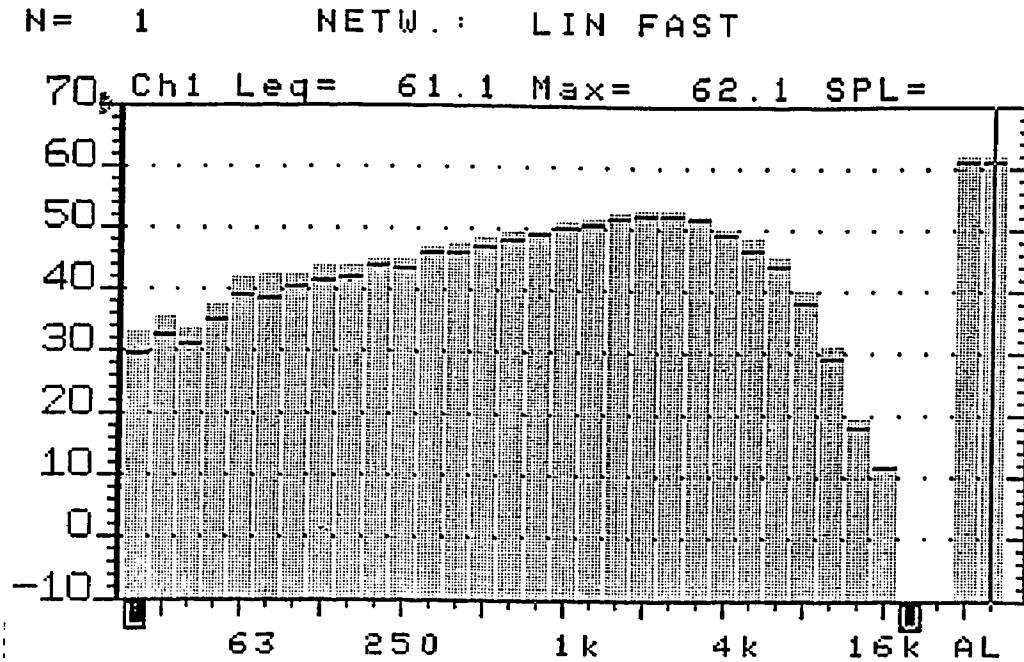


Figure 131. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 10 dB.

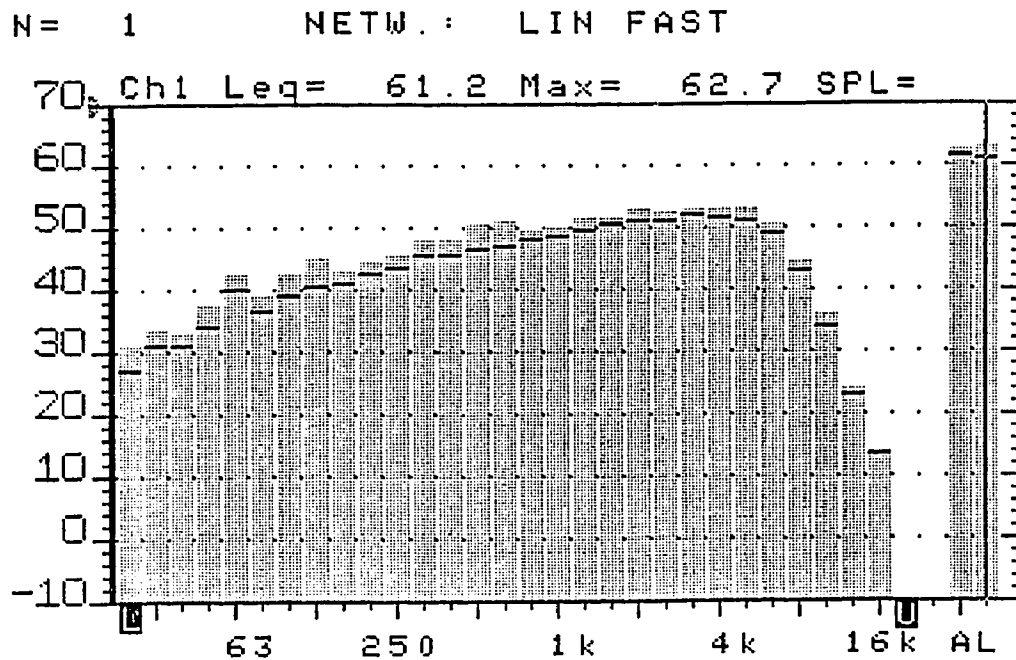


Figure 132. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady, low-pass filtered background noise at a peak-to-background ratio of 20 dB.

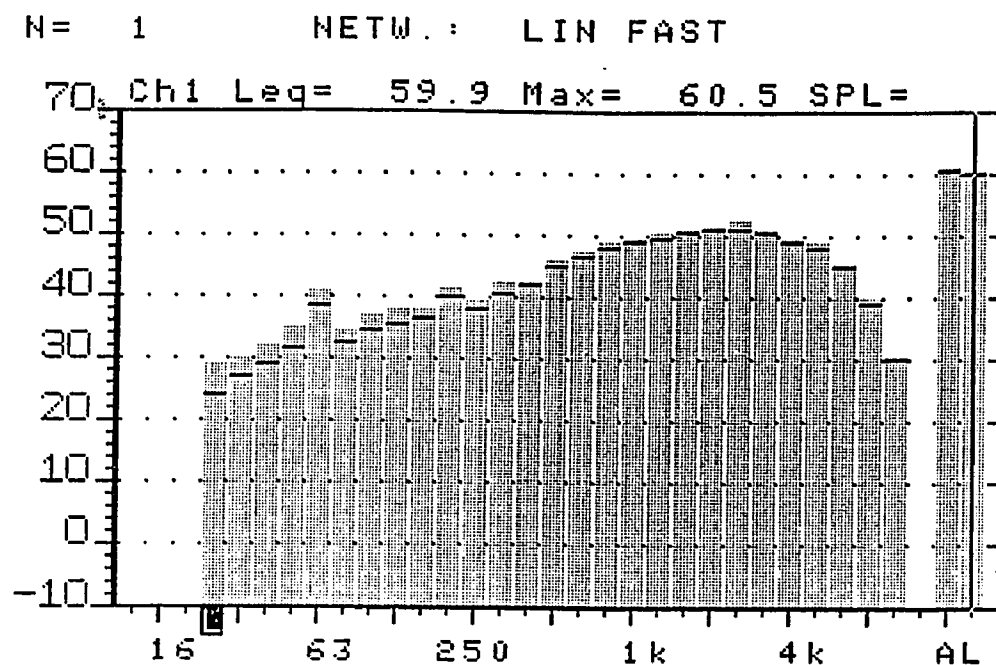


Figure 133. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 10 dB.

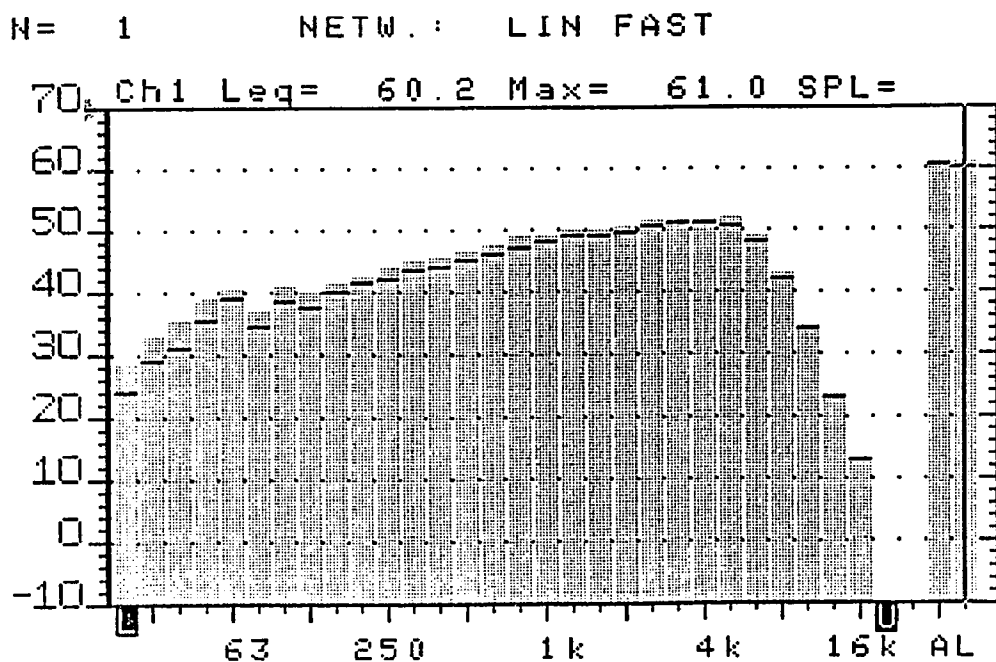


Figure 134. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 20 dB.

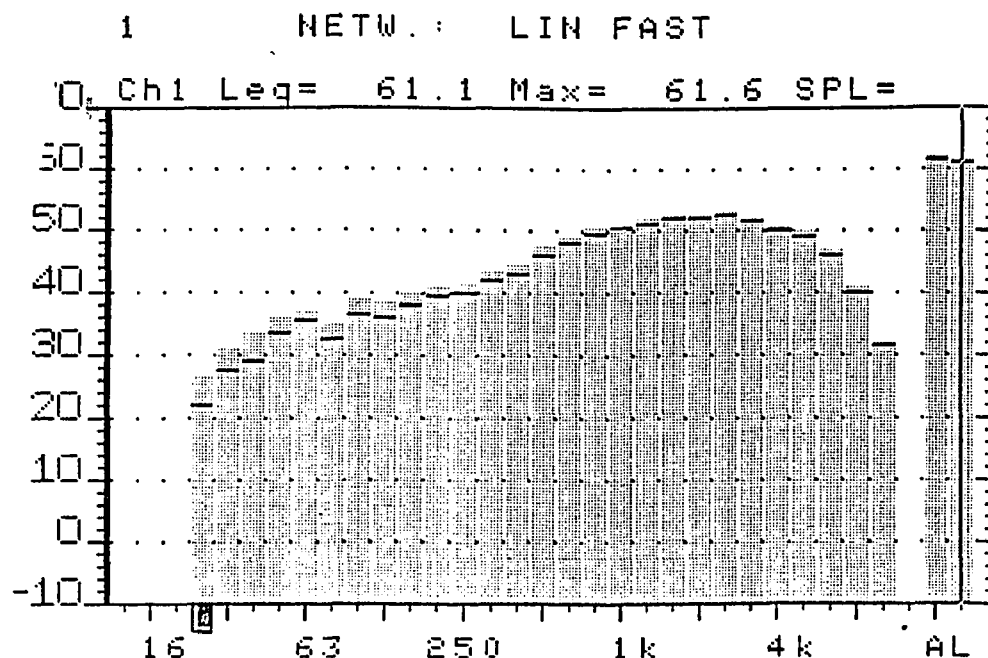


Figure 135. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 10 dB.

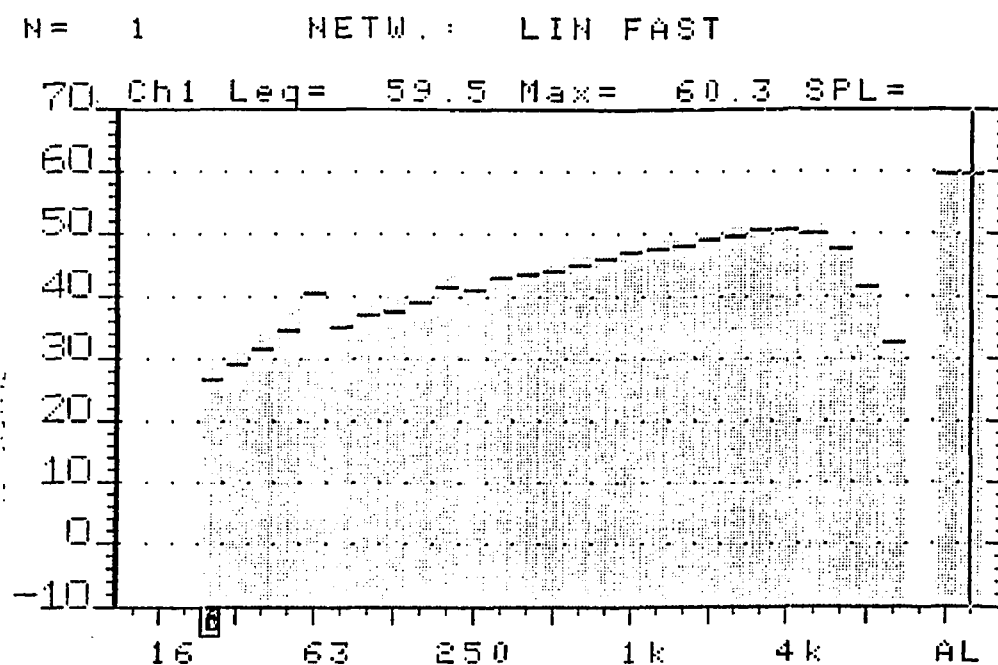


Figure 136. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 20 dB.

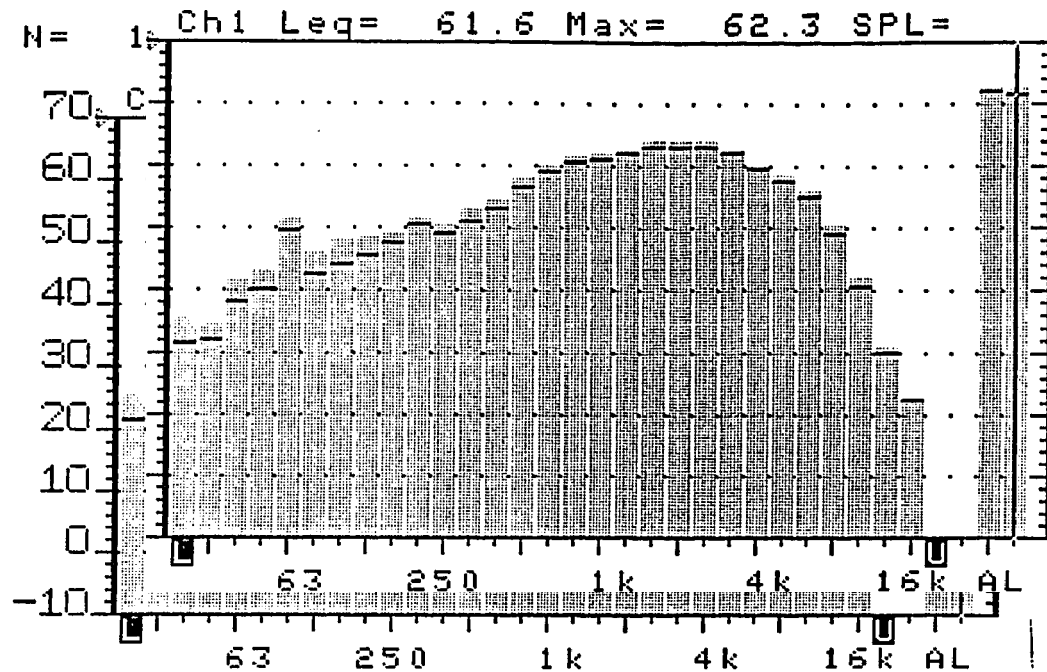


Figure 137. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 10 dB.

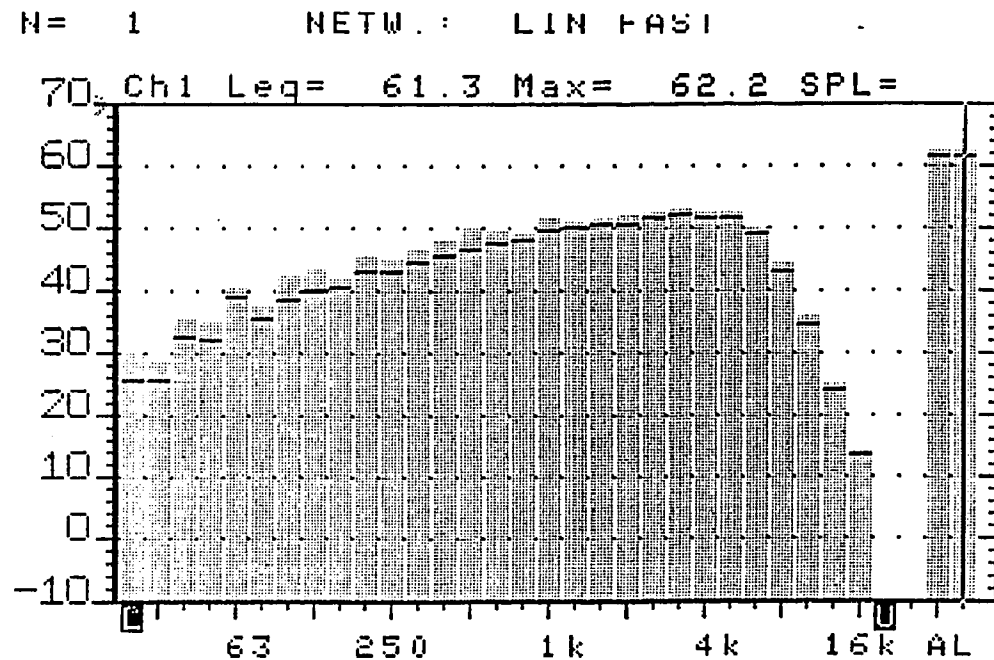


Figure 138. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 20 dB.

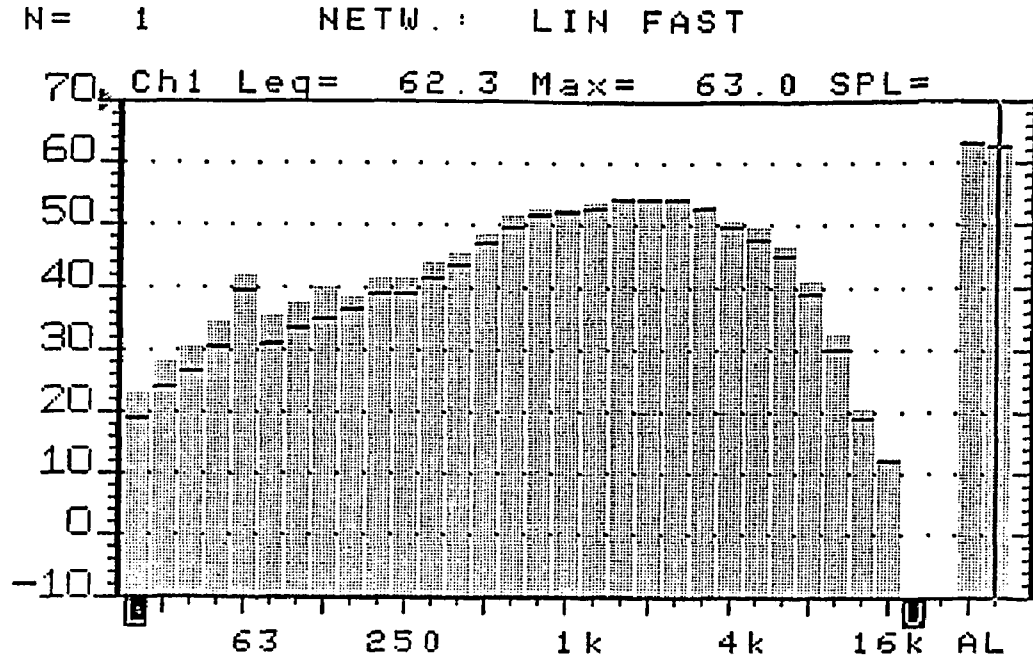


Figure 139. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 10 dB.

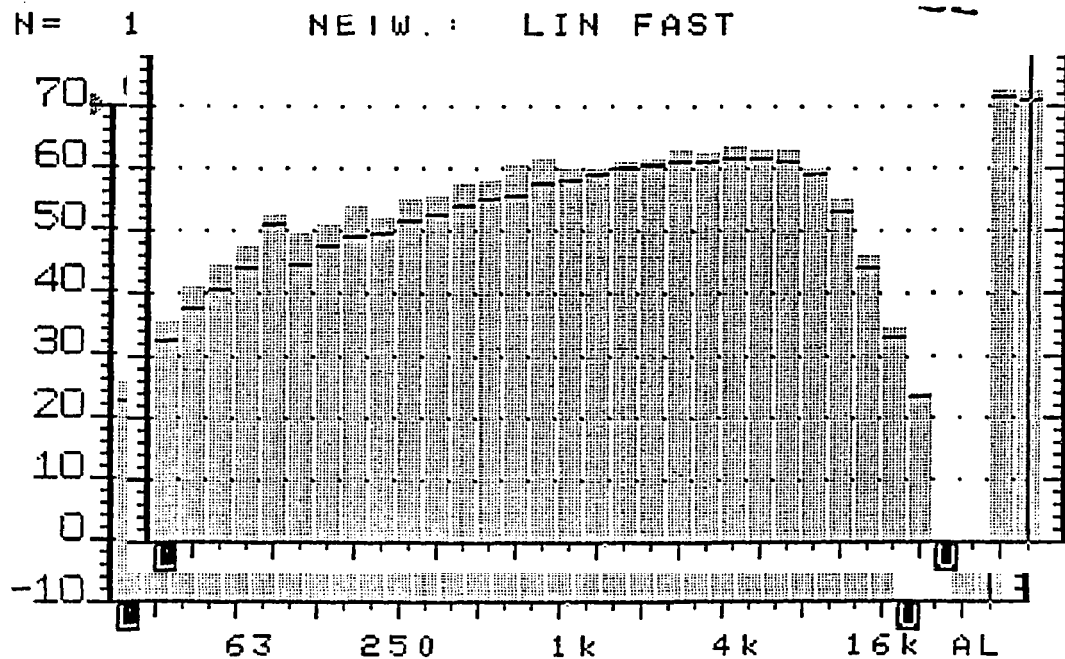


Figure 140. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady, band-pass filtered background noise at a peak-to-background ratio of 20 dB.

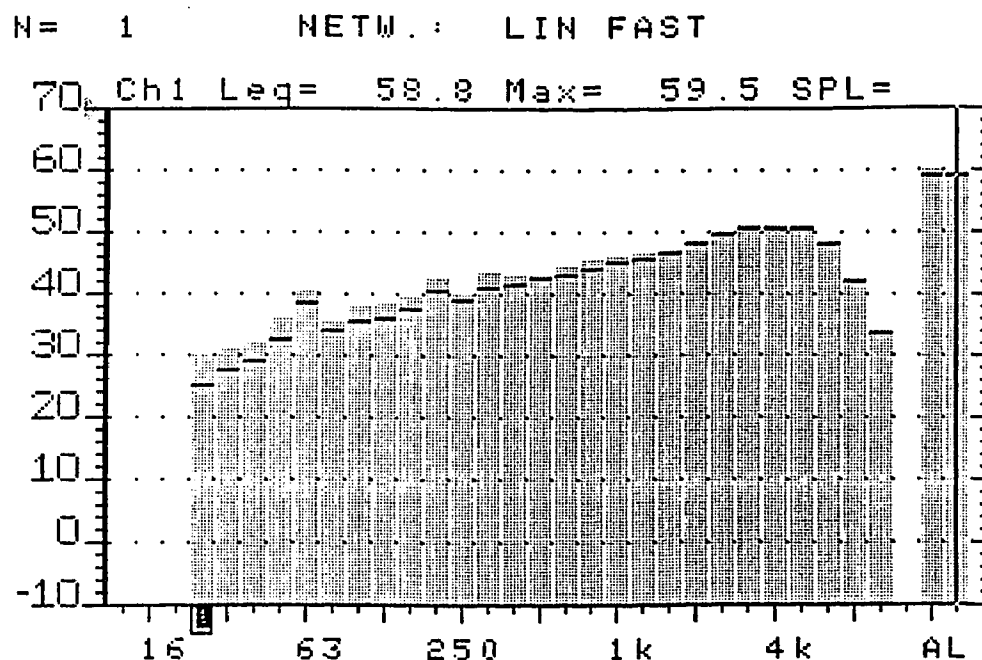


Figure 141. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 10 dB.

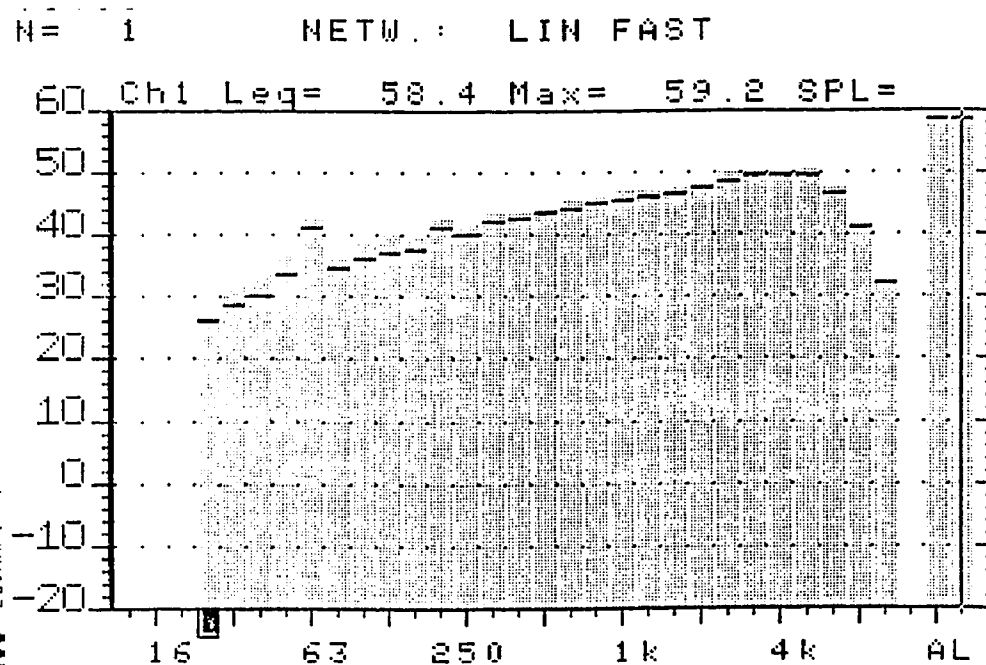


Figure 142. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 20 dB.

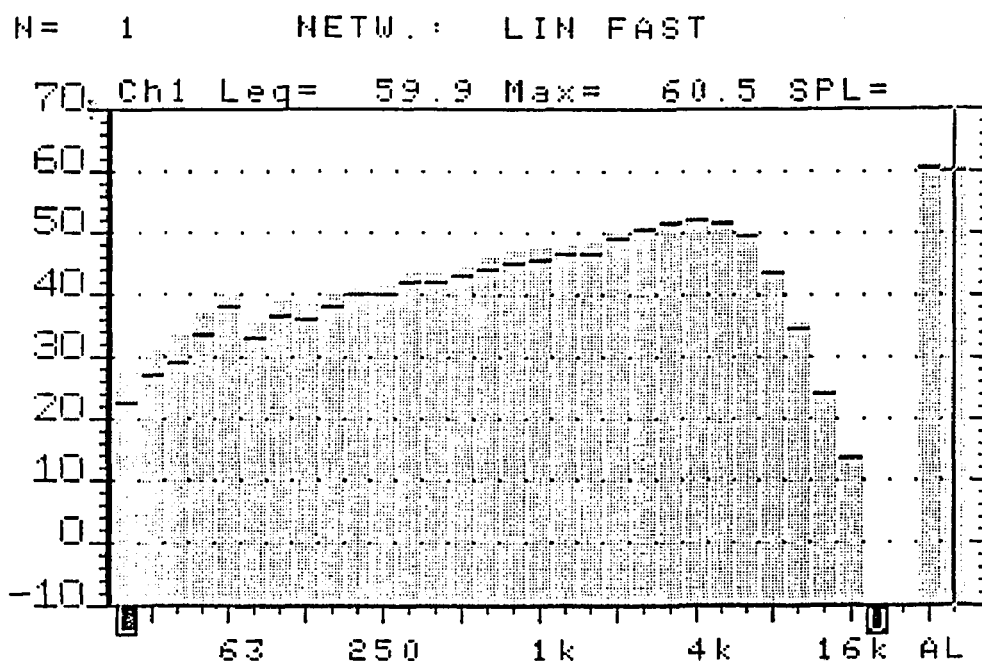


Figure 143. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 10 dB.

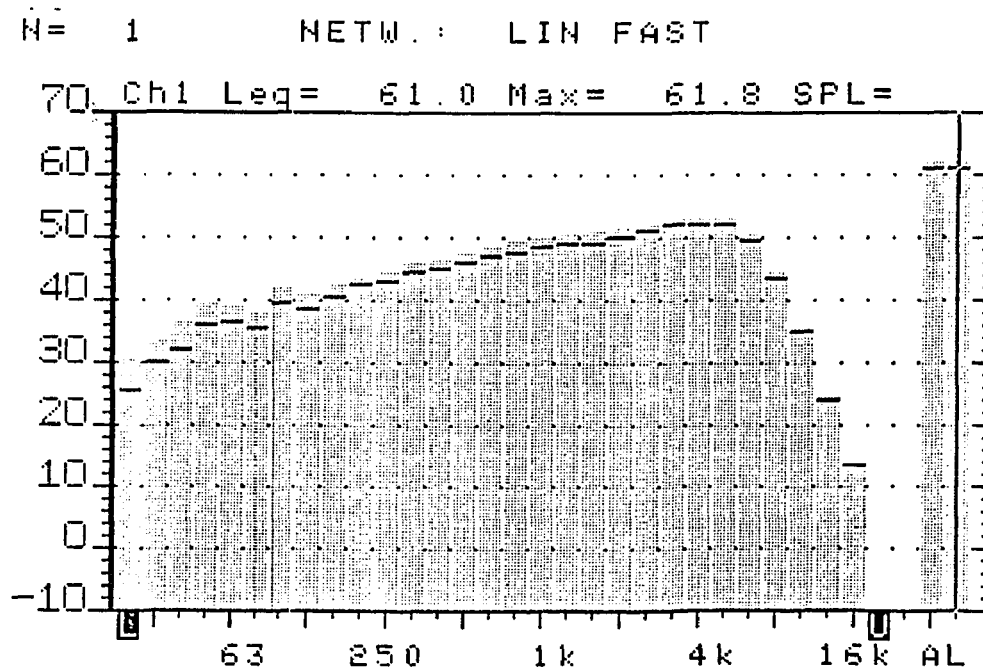


Figure 144. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 20 dB.

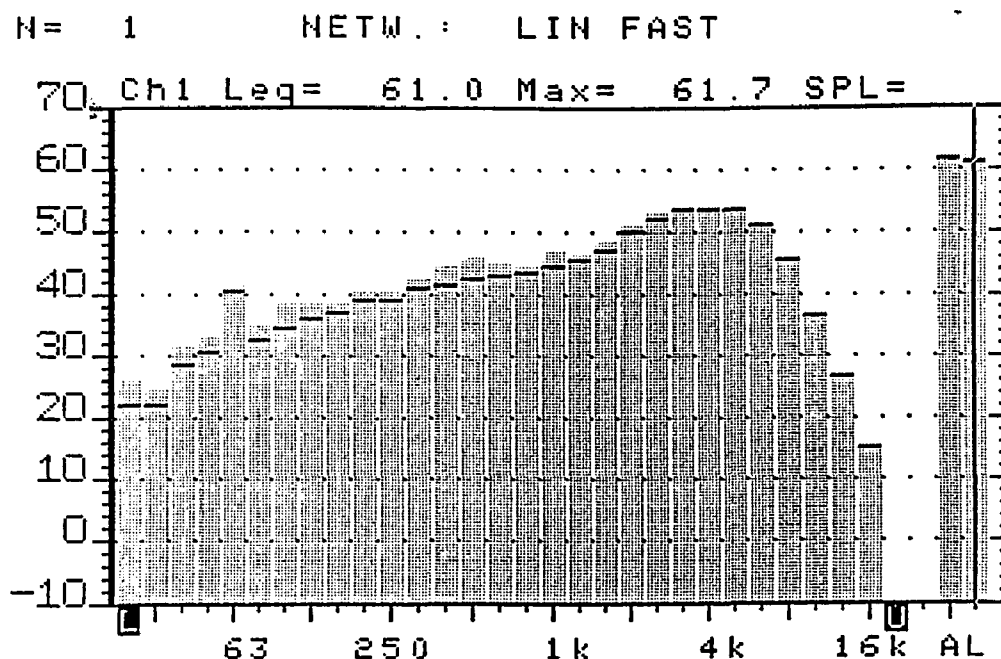


Figure 145. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 10 dB.

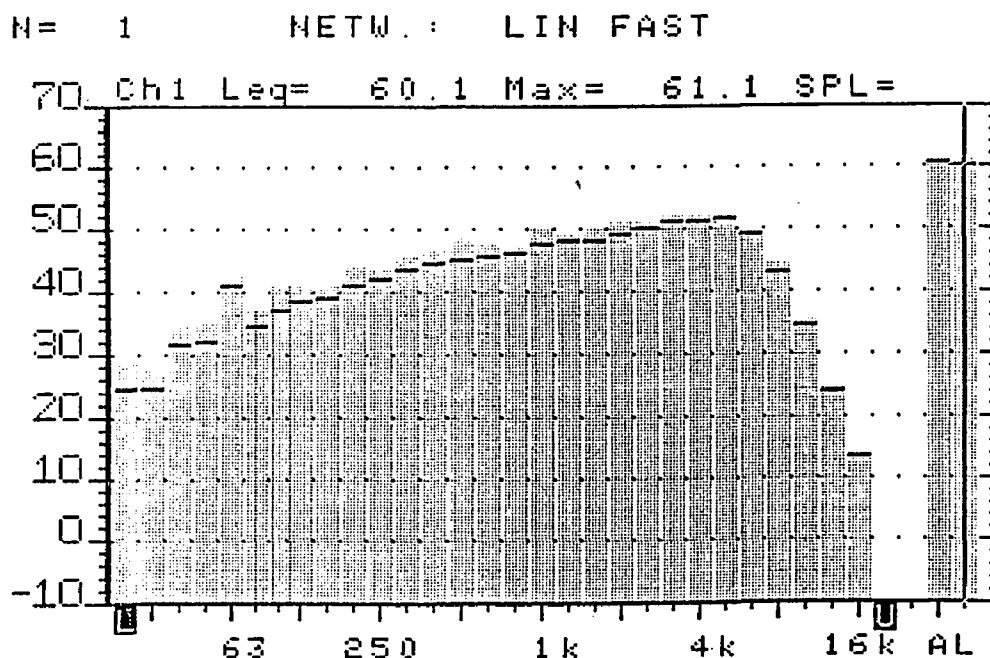


Figure 146. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 20 dB.

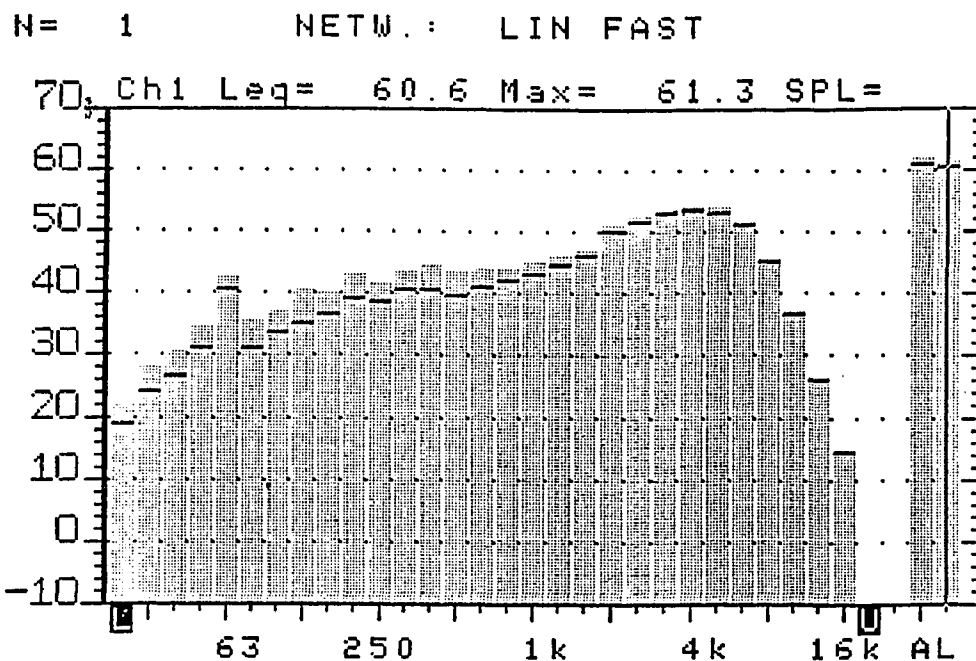


Figure 147. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 10 dB.

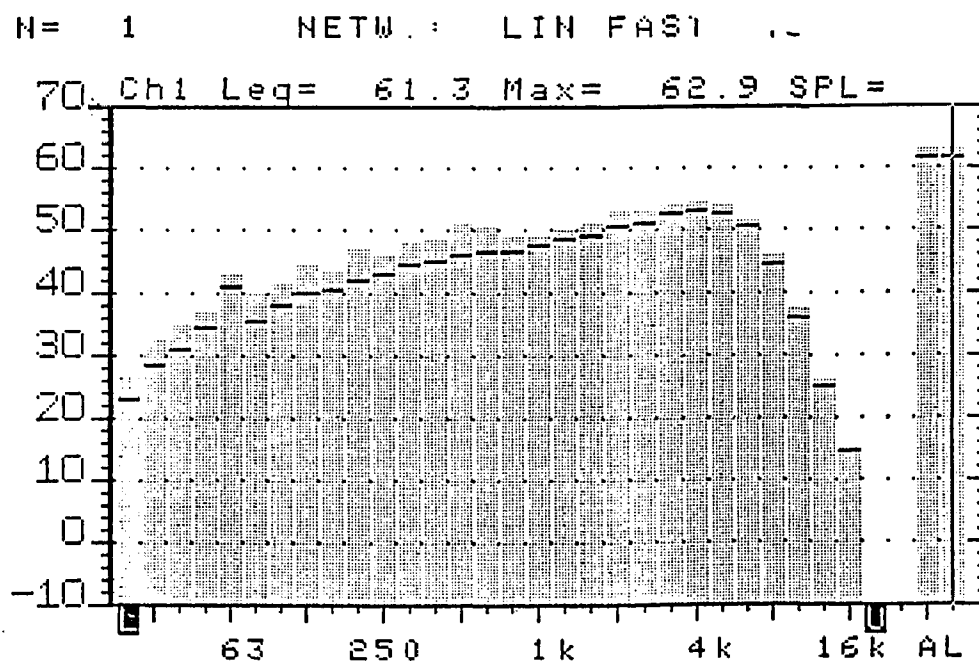


Figure 148. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady, high-pass filtered background noise at a peak-to-background ratio of 20 dB.

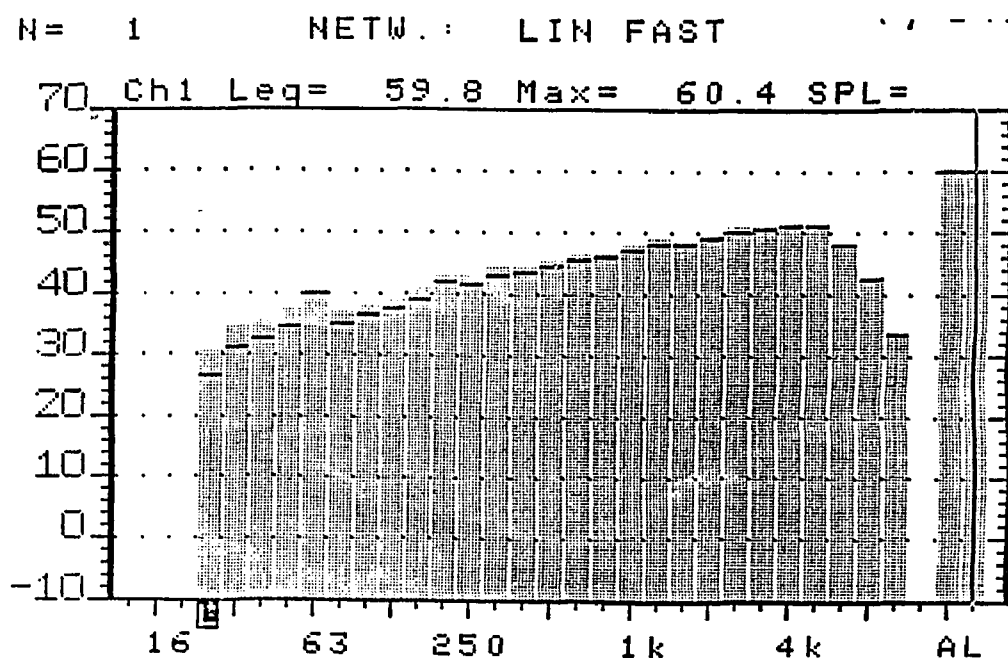


Figure 149. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

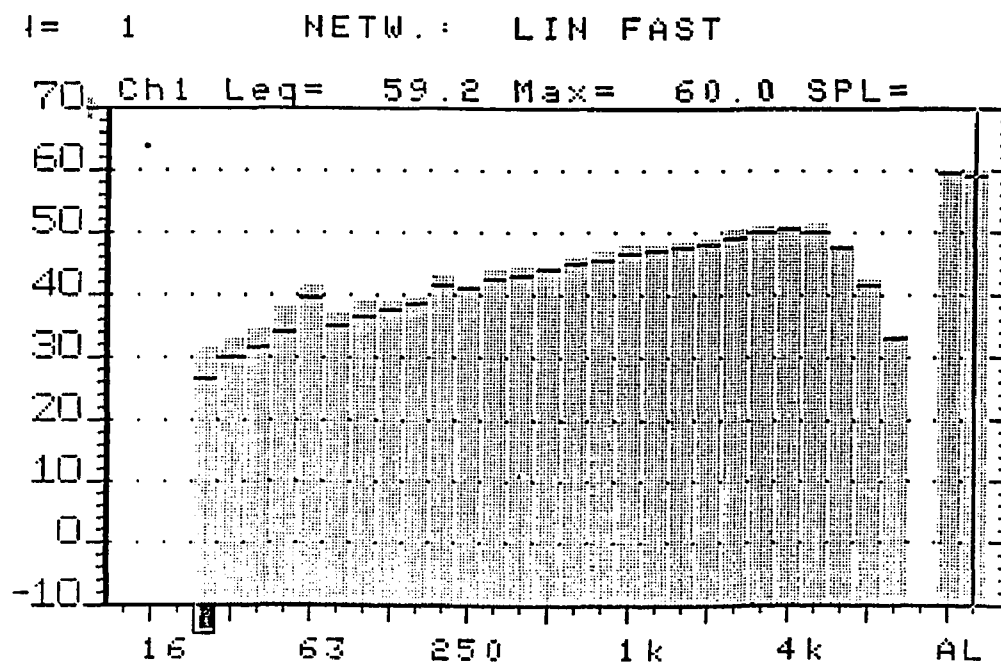


Figure 150. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 1.5 msec, repetition rate of 100 Hz, and steady, white background noise at a peak-to-background ratio of 20 dB.

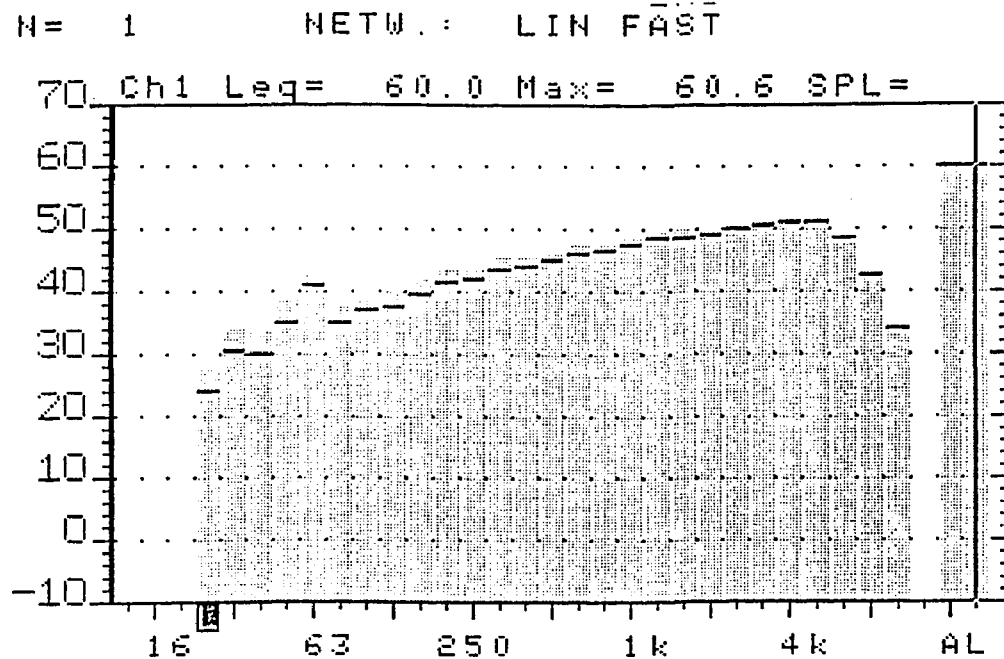


Figure 151. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

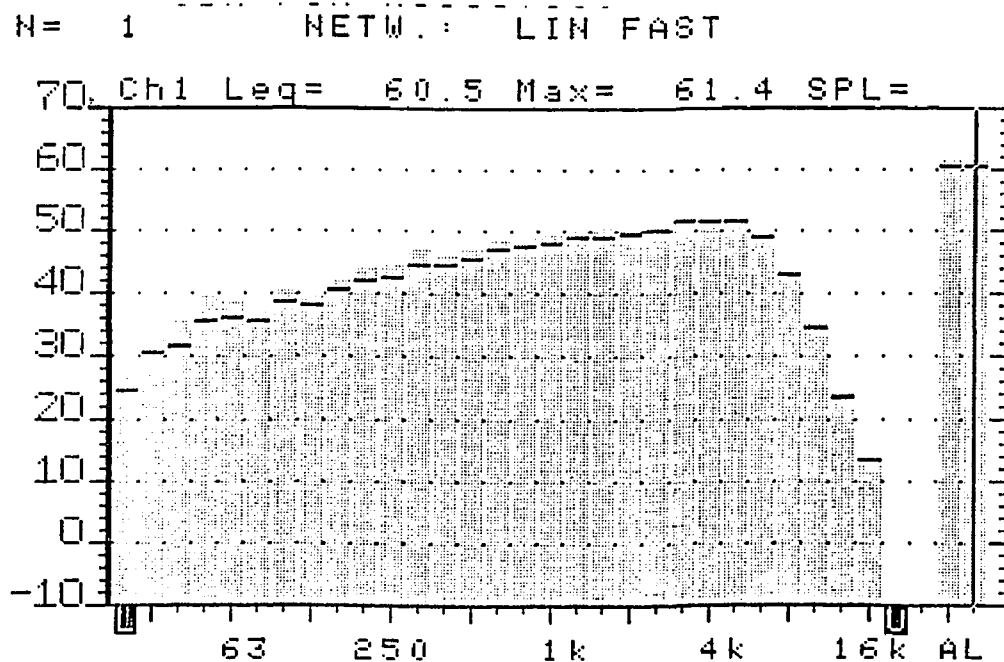


Figure 152. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 3.5 msec, repetition rate of 50 Hz, and steady white background noise at a peak-to-background ratio of 20 dB.

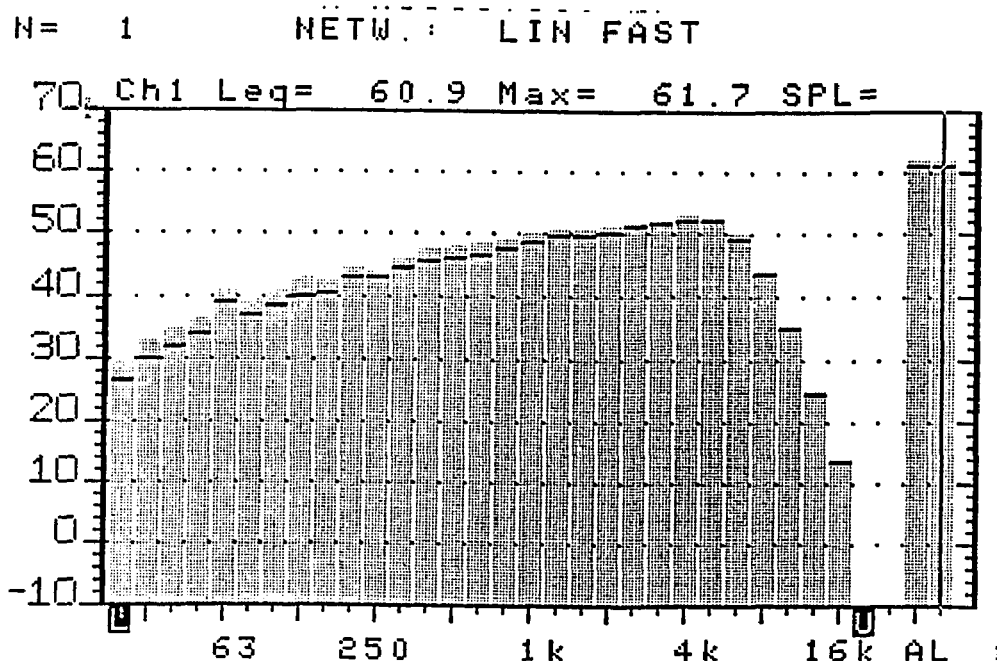


Figure 153. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

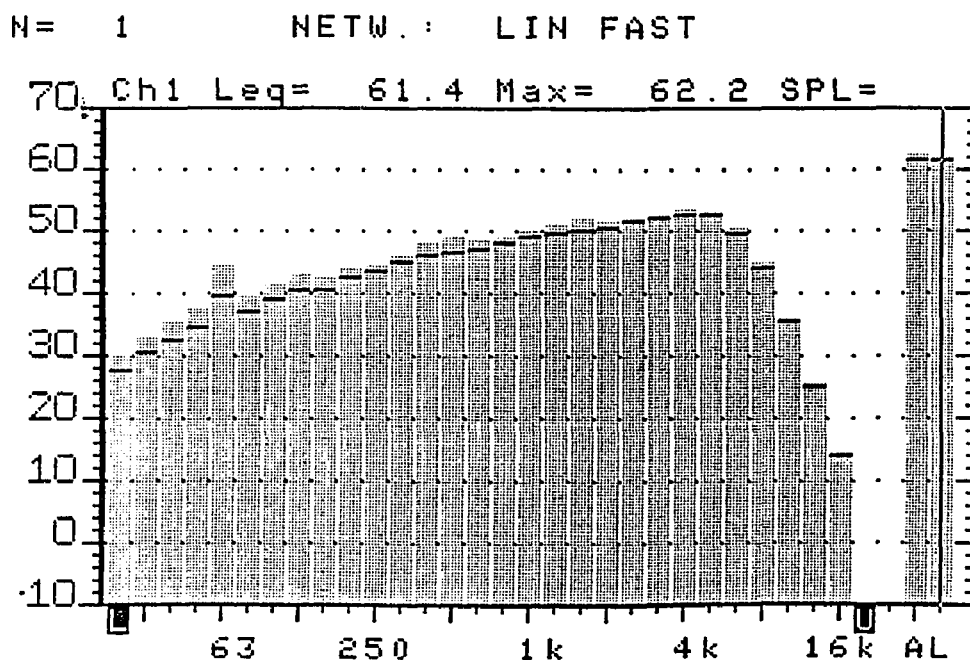


Figure 154. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 5 msec, repetition rate of 20 Hz, and steady white background noise at a peak-to-background ratio of 20 dB.

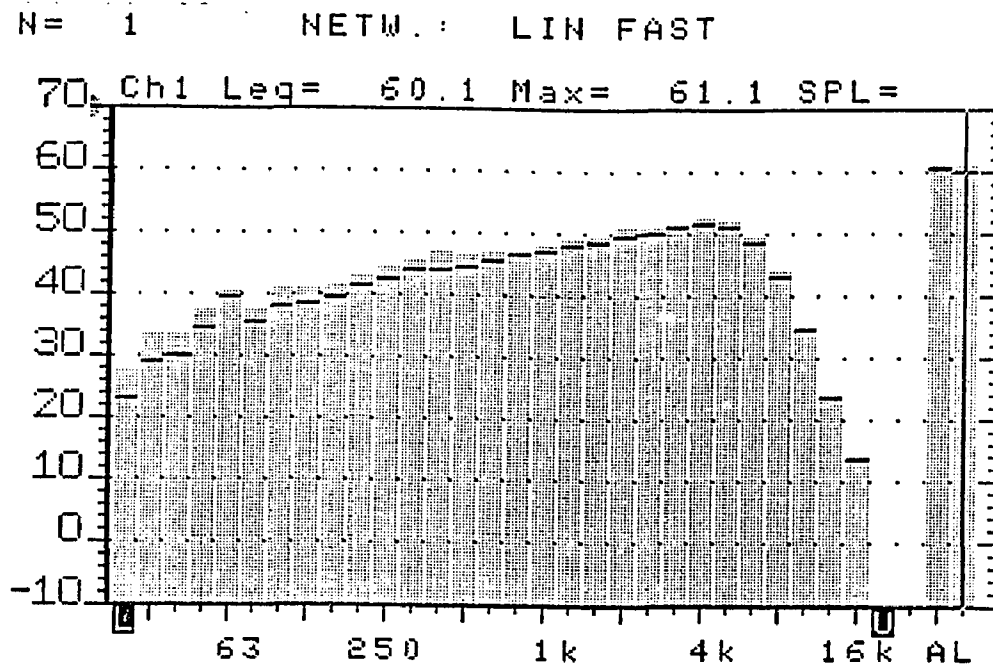


Figure 155. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady white background noise at a peak-to-background ratio of 10 dB.

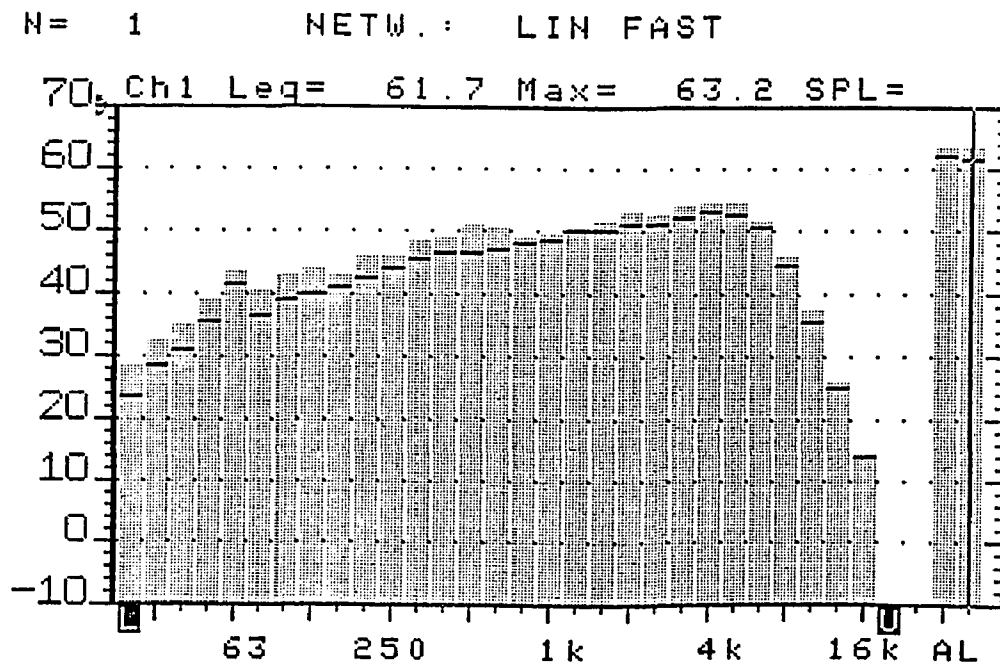


Figure 156. One-third octave-band spectrum of impulse noise test stimulus with impulse duration of 10 msec, repetition rate of 10 Hz, and steady, white background noise at a peak-to-background ratio of 20 dB.

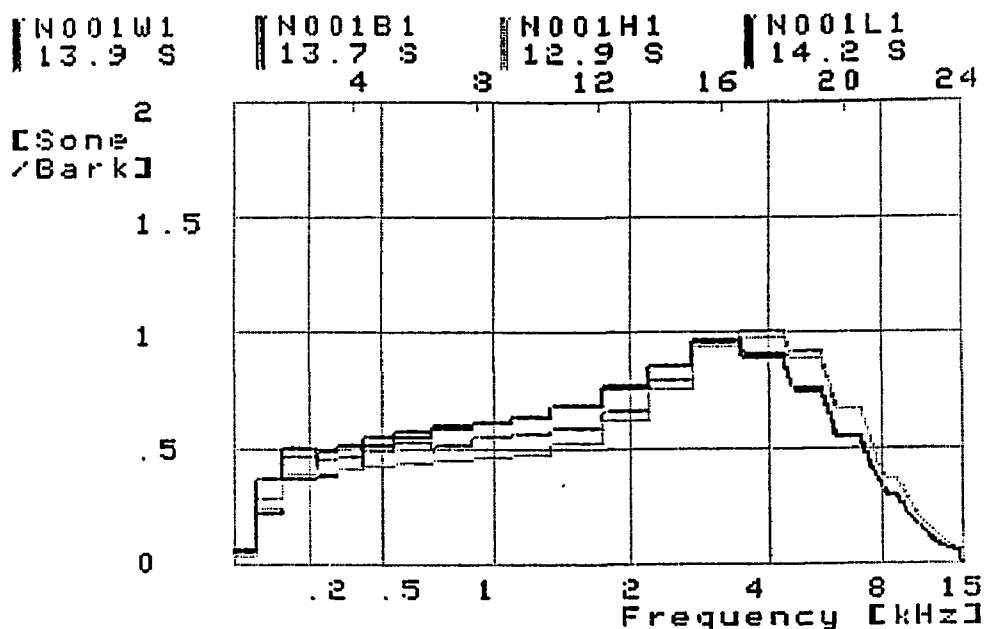


Figure 157. Loudness computations using the method of ISO 532B (1975) on the impulse noise test stimuli of experiment 2 with a duration of 1.5 msec, a repetition rate of 100 Hz. The spectral shapes of the steady background noises (at 10 dB peak-to-background ratio) are: l, low-pass filtered; b, band-pass filtered, h, high-pass filtered; and w, white.

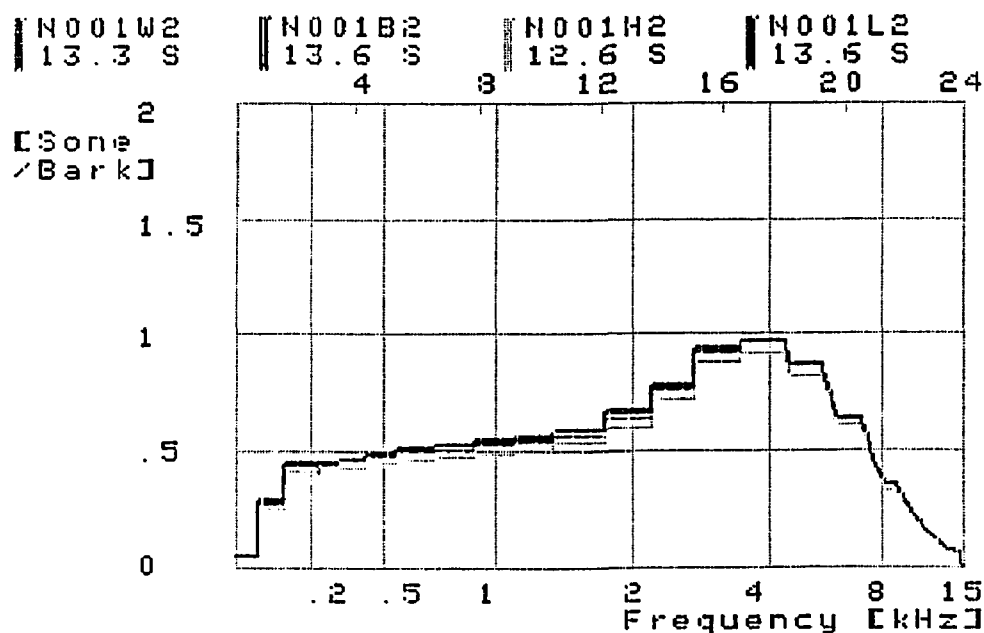


Figure 158. Loudness computations using the method of ISO 532B (1975) on the impulse noise test stimuli of experiment 2 with a duration of 1.5 msec, a repetition rate of 100 Hz. The spectral shapes of the steady background noises (at 20 dB peak-to-background ratio) are: l, low-pass filtered; b, band-pass filtered, h, high-pass filtered; and w, white.

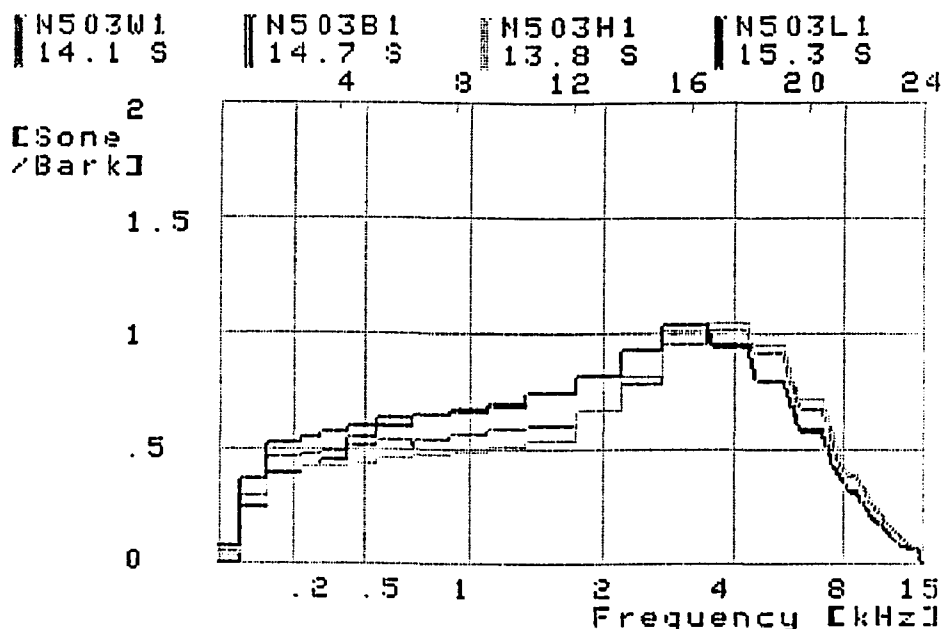


Figure 159. Loudness computations using the method of ISO 532B (1975) on the impulse noise test stimuli of experiment 2 with a duration of 3.5 msec, a repetition rate of 50 Hz. The spectral shapes of the steady background noises (at 10 dB peak-to-background ratio) are: l, low-pass filtered; b, band-pass filtered, h, high-pass filtered; and w, white.

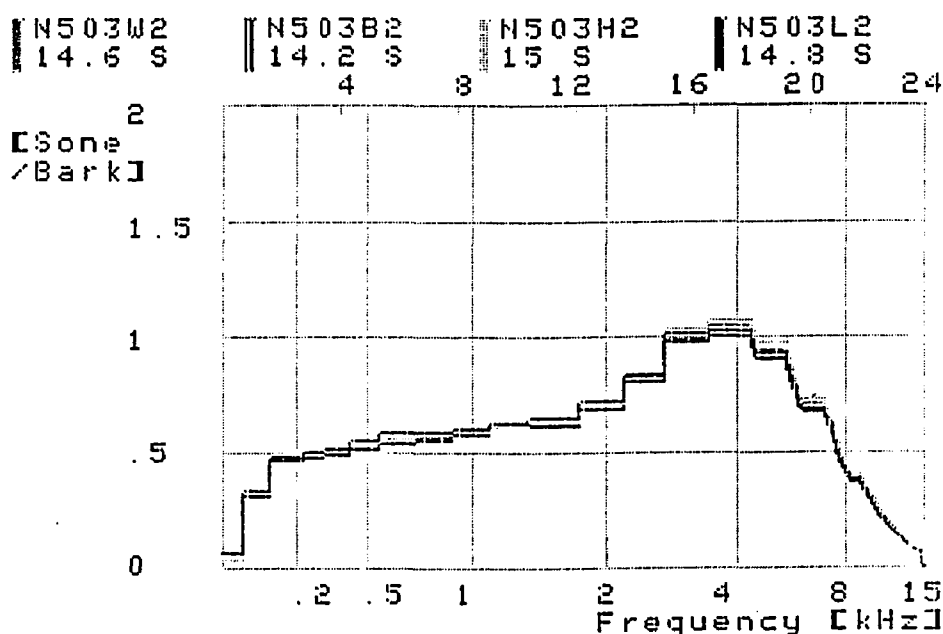


Figure 160. Loudness computations using the method of ISO 532B (1975) on the impulse noise test stimuli of experiment 2 with a duration of 3.5 msec, a repetition rate of 50 Hz. The spectral shapes of the steady background noises (at 20 dB peak-to-background ratio) are: l, low-pass filtered; b, band-pass filtered, h, high-pass filtered; and w, white.

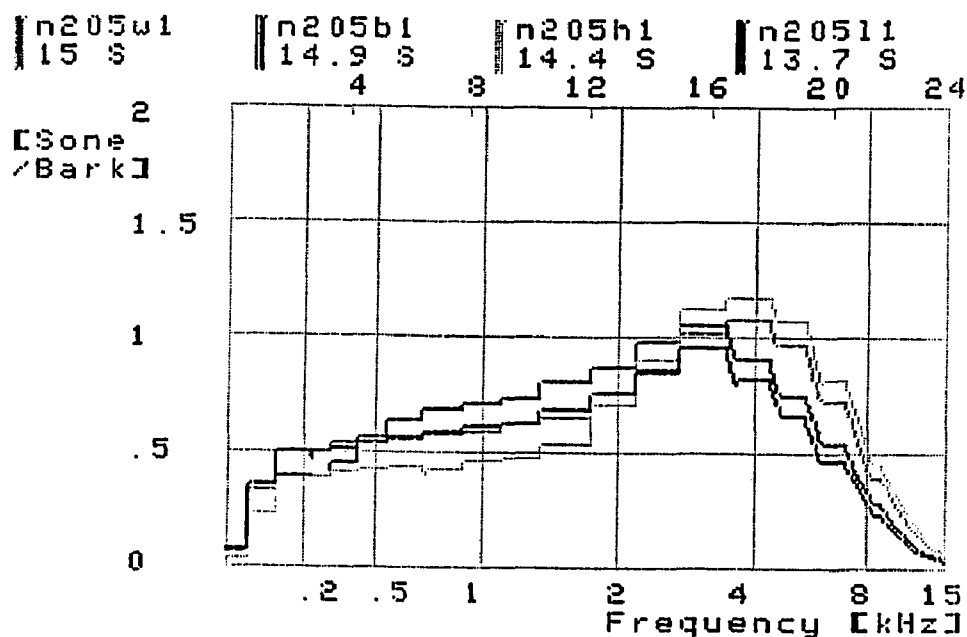


Figure 161. Loudness computations using the method of ISO 532B (1975) on the impulse noise test stimuli of experiment 2 with a duration of 5 msec, a repetition rate of 20 Hz. The spectral shapes of the steady background noises (at 10 dB peak-to-background ratio) are: l, low-pass filtered; b, band-pass filtered, h, high-pass filtered; and w, white.

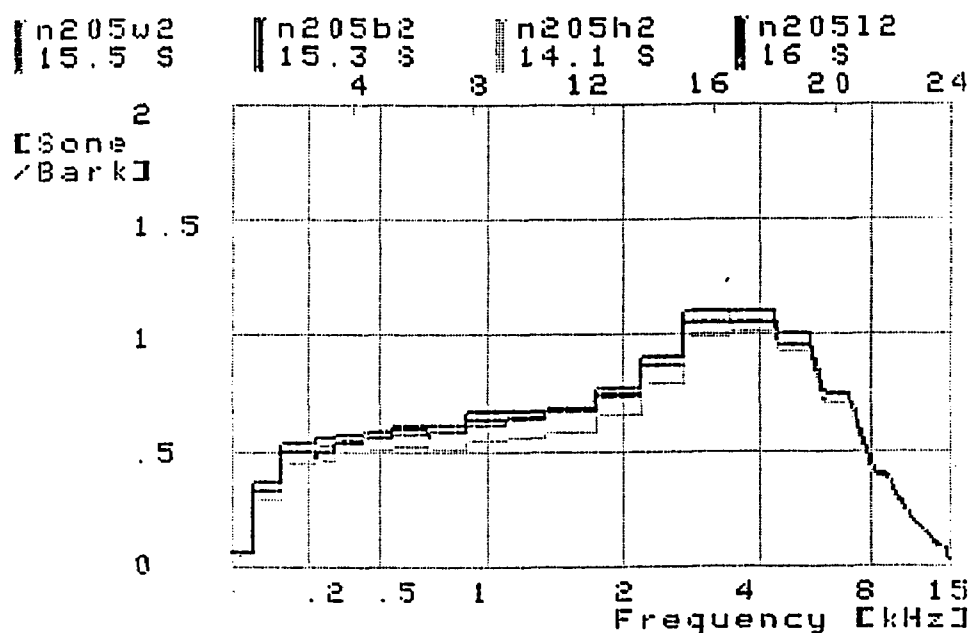


Figure 162. Loudness computations using the method of ISO 532B (1975) on the impulse noise test stimuli of experiment 2 with a duration of 5 msec, a repetition rate of 20 Hz. The spectral shapes of the steady background noises (at 20 dB peak-to-background ratio) are: l, low-pass filtered; b, band-pass filtered, h, high-pass filtered; and w, white.

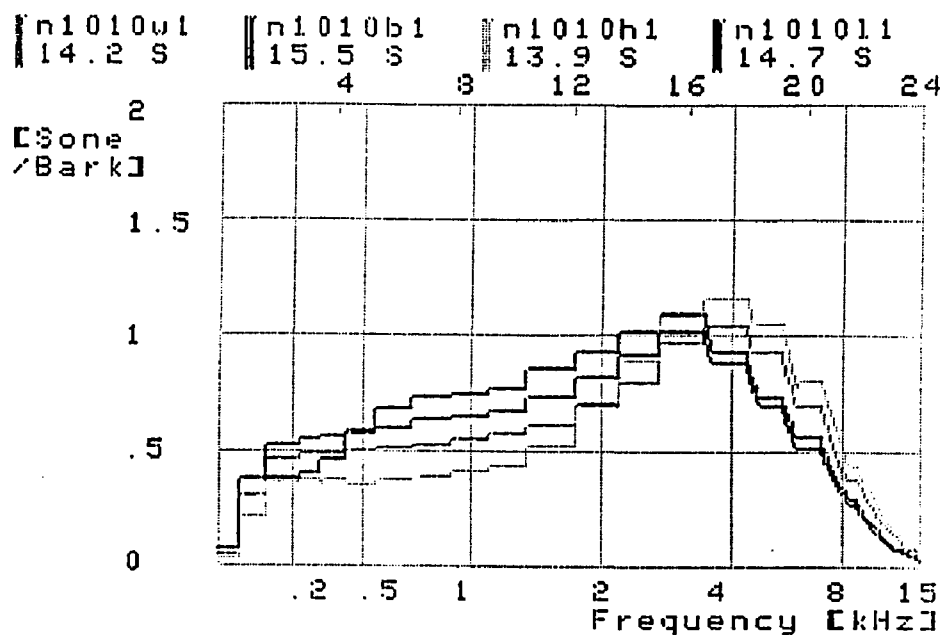


Figure 163. Loudness computations using the method of ISO 532B (1975) on the impulse noise test stimuli of experiment 2 with a duration of 10 msec, a repetition rate of 10 Hz. The spectral shapes of the steady background noises (at 10 dB peak-to-background ratio) are: l, low-pass filtered; b, band-pass filtered; h, high-pass filtered; and w, white.

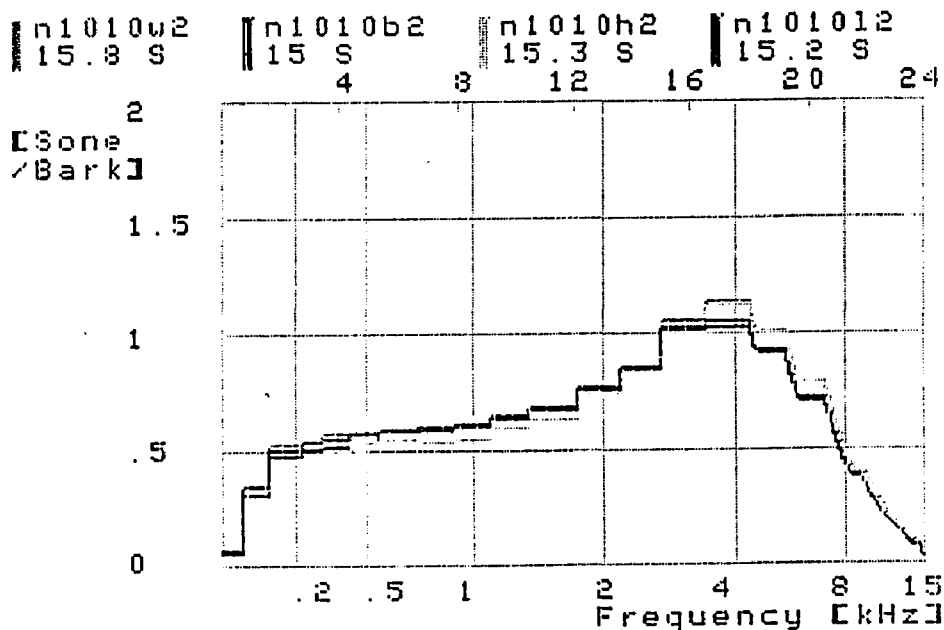


Figure 164. Loudness computations using the method of ISO 532B (1975) on the impulse noise test stimuli of experiment 2 with a duration of 10 msec, a repetition rate of 10 Hz. The spectral shapes of the steady background noises (at 20 dB peak-to-background ratio) are: l, low-pass filtered; b, band-pass filtered; h, high-pass filtered; and w, white.

APPENDIX D

C-LANGUAGE PROGRAM FOR PSYCHOACOUSTICAL TESTING

Note: Portions of this program and subroutines that were not written by the author have been deleted.

```

/*****
/*  DESCRIPTIVE NAME = Audio Application Programming Interface      */
/*                      Psychoacoustical Testing Program           */
/*                                                                */
/*  FUNCTION = Provides the following functions/tools:             */
/*                                                                */
/*                      Perform Psychoacoustical testing (2 AFC) with */
/*                      interleaved trials using the Audio API and ACPA. */
/*                                                                */
#include <math.h>                      /* Math Functions          */
#include <graph.h>                     /* Graphics functions      */
/*                                                                */
/*****CONSTANT DEFINITIONS*****/
/*
#define M_1 "Enter number of files to test ==> "
#define M_2 "Enter reference file name (no ext) and path ==> "
#define M_4 "Open failed, file already exists.\n"
#define M_5 "Open failed, file does not exist.\n"
#define M_14 "Enter reference level ==> "
#define M_15 "Enter number of reversals to quit ==> "
#define M_16 "\r Which was louder (1 or 2)? \n"
#define M_17 "Enter filename to store results ==> "
#define M_18 "Enter filename with test listings ==> "
#define M_19 "Enter subject name ==> "
#define M_20 "\nHit Enter to start testing.\n "
#define M_21 "Enter stimulus duration (msec) ==>"
#define M_22 "Enter interstimulus interval (msec) ==>"
/*
#define TOP 10
#define LEFT1 25
#define LEFT2 50
#define BOT 15
#define RIGHT1 35
#define RIGHT2 60
#define HEIGHT (BOT-TOP+1)
/*****RESIDENT FUNCTION DECLARATIONS*****/
STATIC VOID Sound(CHAR *, INT);      /* Play                      */
STATIC VOID Get_Dfile_Name(CHAR *);

```

```

/* FUNCTION NAME = Main */
/* FUNCTION = Main menu program for psychoacoustical testing with */
/*          ACPA. */
/* */
/* INPUT =      None - The user is prompted for the names of two files */
/*              that contain the stimulus and reference audio data. */
/* OUTPUT =     If successful */
/*              Audio file contents played in turn, levels adjusted */
/*              according to user response (transformed up/down). */
/*              Else error message written to screen */
/* */
/*****
*****CHAR
dosstr[] = "copy ";
main()
{
/* 010 Begin Function */
/* 010 */
/*****LOCAL VARIABLE DEFINITIONS*****/
INT dosres; /* DOS return code */
FILE *ifptr; /* Input file pointer */
FILE *ofptr; /* Output file pointer */
CHAR ofname[81]; /* Output file name */
CHAR ifname[81]; /* Input file name */
CHAR rpname[81]; /* Ref. file name and path */
CHAR spname[81]; /* Stim. file name and path */
CHAR rname[81]; /* Ref. name on vdisk */
CHAR sname[81]; /* Stim. name on vdisk */
CHAR subname[81]; /* Subject name */
CHAR *result; /* Return value of string cat. */
INT svola; /* Stimulus level-run a */
INT svolb; /* Stimulus level, run b */
INT rvol; /* Reference level */
LONG dur; /* Stimulus duration */
LONG isi; /* Interstimulus interval */
INT dsvola; /* Delta vol. run a */
INT dsvolb; /* Delta vol. run b */
INT rq; /* Reversals to quit (4-6) */
INT rna; /* Reversal number, trial A */
INT rnb; /* Reversal number, trial B */
CHAR ch; /* Keyb. in, 1('c') or 2('m') */
CHAR cha; /* Prev. keyb. in, run A */
CHAR chb; /* Prev. keyb. in, run B */
INT adata[20]; /* Result array, run A */
INT bdata[20]; /* Result array, run B */
INT index; /* index variable */
INT ndex; /* Another index */
INT num; /* Number of files to test */
time_t ltime; /* time variable */
DOUBLE avgb; /* Average delta L, run B */
DOUBLE avga; /* Average delta L, run A */
/*****
strcpy (rname,"d:ref.!au"); /* Define ref. name on vdisk */
strcpy (sname,"d:stim.!au"); /* and stim name on vdisk. */

```

```

cprintf(M_19); /* Ask for subject name. */
Get_Dfile_Name(subname); /* Get sub. name. */
cprintf(M_17); /* Ask for name of file to */
Get_Dfile_Name(ofname); /* Store results and get it. */
cprintf(M_18); /* Ask for name of file with */
Get_Dfile_Name(iframe); /* stim. file list., get it */
cprintf(M_2); /* Ask for ref. name and path.*/
Get_File_Name(rpname); /* Get it, and append ".*". */
cprintf (M_1); /* Ask for number of files to */
scanf("%d", &num); /* test and get it. */
/*cprintf (M_21); Ask for stim. duration in */
/*scanf("%ld",&dur); msec and get it. */
/*cprintf (M_22); Ask for interstimulus */
/*scanf("%ld",&isi); interval in msec, get it. */
cprintf(M_14); /* Ask for ref level */
scanf("%d", &rvol); /* Set ref level */
cprintf(M_15); /* Ask for no. reversals */
scanf("%d", &rq); /* Get no. to quit */
ifptr = fopen(iframe, "r"); /* Open input file for read. */
ofptr = fopen(ofname, "w"); /* Open output file for write.*/
fprintf(ofptr, /* Write subject name to out- */
"\rSubject name is %s. \n",subname) /* put file. */
fprintf(ofptr, /* Write input file name. */
"\rStimulus list file name is %s. \n",iframe);
fprintf(ofptr, /* Write ref. file name. */
"\rReference file is %s. \n", rpname);
fprintf(ofptr, /* Write reference level. */
"\rReference volume is %d. \n",rvol);
fprintf(ofptr, /* Write number of reversals. */
"\rNumber of reversals to quit is %d. \n",rq);
/*****
rna=rnb=0; /* Initialize num of reversals*/
avga=avgb=0; /* Initialize avarage delta Ls*/
FOR (index=1; index<(2*rq); index++)/* and data arrays. */
adata[index]=bdata[index]=0;
result = strcat(dosstr, rpname); /* Construct DOS string com- */
result = strcat(dosstr, " d:ref.*");/* mand string and copy ref. */
dosres = system (dosstr); /* files to vdisk as d:ref.* */
/*****
FOR (ndex=1; ndex<=num; ndex++) /* For each of NUM tests: */
{
skip: rna=rnb=0;
avga=avgb=0;
fgets(spname,81,ifptr); /* Read name of next stimulus */
fprintf(ofptr, /* file, and write it to */
"\rStimulus file is %s. \n",spname);/* output file. Then */
strcpy (dosstr, "copy "); /* construct DOS command */
result = strcat(dosstr, spname); /* string .... */
result = strcat(dosstr, " d:stim.*");
dosres = system (dosstr); /* copy stim. file to vdisk..*/

```

```

dosres = system("dir d:");          /* and check directory. */
time(&ltime);                      /* Use time to get a random */
svolb=svola=(rvol-6)+              /* number and use it to set */
    (12*(ltime%2));                /* start level to rvol+/-6dB.*/
dsvola=dsvolb=rq;                  /* Set initial step size in dB*/
/* to number of reversals. */

/*rewind(stdin);
cprintf(M_20);
WHILE (!kbhit());
input1: ch = getch();
IF ((ch != '\r') && (ch != 'q') && (ch != 's')) goto input1;
IF (ch == 'q') goto exit;
IF (ch == 's')
{
    ndex = ndex+1;
    goto skip;
}

/*****
WHILE ((rna <= rq) ||              /* Run while both reversal */
    (rnb <= rq))                  /* numbers are less than rq */
{                                  /* Beginning of main WHILE */
    time(&ltime);                 /* get time, to gen rand num */
    IF ((ltime%2) == 1)           /* Beginning presentation IF */
    {                             /* Play ref then stim (a) */
        _clearscreen(_GCLEARSCREEN);
        _settextwindow(TOP,LEFT1,BOT,RIGHT1);
        _settextcolor(17);
        _setbkcolor(2L);
        _outtext ("      1                      ")
        Sound(rname, rvol);          /* Play ref. */
        _settextcolor(1);
        _outtext ("      1                      ");
        _settextwindow(TOP, LEFT2, BOT, RIGHT2);
        _settextcolor (17);
        _outtext ("      2                      ");
        Sound(sname, svola);         /* Play stim. */
        /*rewind(stdin); not working    Clear keyboard buffer. */
        _settextcolor (1);
        _outtext ("      2                      ");
        _settextwindow(20, 30, 22, 70);
        _settextcolor(3);
        _setbkcolor(0L);
        _outtext("Which was louder (1/2)?  ");
        WHILE (!kbhit());
        input2: ch = getch();
        IF (ch == 'q') goto exit;
        IF (ch == 's')
        {
            ndex = ndex + 1;
            goto skip;
        }
    }
}

```

```

IF ((ch != 'c') && (ch != 'm')) goto input2;
_clearscreen(_GCLEARSCREEN);
_settextcolor(1);
IF (ch == 'c')
/* Begin stim IF */
{
/* IF reference is louder: */
IF (cha == 'm')
/* identify a reversal (min) */
{
/* Begin first reversal IF */
adata[rna]=svola;
/* save rev level */
rna=rna+1;
/* increment reversal count */
dsvola=rq-rna;
/* calculate volume increase */
IF (dsvola <= 0)
dsvola = 1;
}
/* End First reversal IF */
svola=svola+dsvola;
/* increase stim level */
cha=ch;
/* store input */
}
/* end Check-stim IF */
ELSE
/* if stim is louder */
{
/* begin check stim ELSE */
IF (cha == 'c')
/* identify reversal (max) */
{
/* Begin second reversal IF */
adata[rna]=svola;
/* save rev level */
rna=rna+1;
/* increment reversal count */
dsvola=rq-rna;
/* calculate volume decrease */
IF (dsvola <= 0)
dsvola = 1;
}
/* End second reversal IF */
svola=svola-dsvola;
/* Decrease stim level */
cha = ch;
/* store input */
}
/* End check stim ELSE */
}
/* End presentation IF */
ELSE
/* Else play stim then ref(b) */
{
/* Begin presentation ELSE */
_clearscreen(_GCLEARSCREEN);
_settextwindow(TOP,LEFT1,BOT,RIGHT1);
_settextcolor(17);
_setbkcolor(2L);
_outtext (" 1");
Sound(sname, svolb);
/* Play stim first, then */
_settextcolor(1);
_outtext (" 1");
_settextwindow(TOP, LEFT2, BOT, RIGHT2);
_settextcolor (17);
_outtext (" 2");
Sound(rname, rvol);
/* Play ref. */
/*rewind(stdin); not working Clear keyboard buffer */
_settextcolor (1);
_outtext (" 2");
_settextwindow(20, 30, 22, 70);
_settextcolor(3);
_setbkcolor(0L);
_outtext("Which was louder (1/2)? ");
WHILE (!kbhit());

```

```

input3: ch = getch();          /* Check keyboard          */
IF (ch == 'q') goto exit;      /* Q to quit          */
IF (ch == 's')
{
    ndex = ndex+1;
    goto skip;
}
IF ((ch != 'c') && (ch != 'm')) /* If not 'c', 'm', or 'q', */
    goto input3;              /* check keyboard again.    */
_clearscreen(_GCLEARSCREEN);
_settextcolor(1);
    IF (ch == 'c')
    {
        /* Begin stim IF */
        /* If stim is louder */
        IF (chb == 'm')
        {
            /* identify a reversal (min) */
            /* Begin first reversal IF */
            bdata[rnb]=svolb;
            /* Save rev level */
            rnb=rnb+1;
            /* increment reversal count */
            dsvolb=rq-rnb;
            IF (dsvolb <= 0)
                dsvolb = 1;
        }
        /* End First reversal IF */
        svolb=svolb-dsvolb;
        /* decrease stim level */
        chb=ch;
        /* store input */
    }
    /* end Check-stim IF */
ELSE
    /* if stim is louder */
    {
        /* begin check stim ELSE */
        IF (chb == 'c')
        {
            /* identify reversal (max) */
            /* Begin second reversal IF */
            bdata[rnb]=svolb;
            /* save rev level */
            rnb=rnb+1;
            /* increment reversal count */
            dsvolb=rq-rnb;
            /* calculate volume increase */
            IF (dsvolb <= 0)
                dsvolb = 1;
        }
        /* End second reversal IF */
        svolb=svolb+dsvolb;
        /* Increase stim level */
        chb=ch;
        /* Save to check for rev */
    }
    /* End check stim ELSE */
}
/* End presentation ELSE */
}
/* End of main WHILE loop */
FOR (index=1; index<=rq; index++) /* FOR loop sums A rev levels */
{
    /* and prints them out. */
    avga=avga+adata[index];
    fprintf(ofptr,"\r Run A, Reversal %d was at %d. \n",
index,adata[index]);
}
FOR (index=1; index<=rq; index++) /* FOR loop sums B rev levels */
{
    /* and prints them out. */
    avgb=avgb+bdata[index];
    fprintf(ofptr,"\r Run B, Reversal %d was at %d. \n",
index,bdata[index]);
}
avga=(avga-adata[1])/(rq-1); /* calculate avg. delta L, A */

```


APPENDIX E
RAW DATA

TABLE 14
RAW DATA - CALIBRATION

	-12	-9	-6	-3	0	3	6	9	12
Subject Number 1									
	67.50	69.75	73.25	76.75	79.50	82.75	85.25	89.75	91.25
	64.75	68.75	70.75	76.00	79.00	79.25	84.50	87.25	90.75
	68.00	70.25	72.25	78.50	79.25	82.75	85.75	88.50	90.75
	65.75	67.75	72.75	72.50	79.25	82.25	83.75	86.25	91.25
Subject Number 2									
	67.75	69.50	74.25	77.25	79.25	82.75	83.75	88.25	89.50
	67.25	70.50	74.00	75.75	79.25	82.25	85.75	85.25	91.25
	69.00	69.25	74.25	76.25	77.50	81.75	85.25	87.25	91.75
	66.75	69.50	74.00	76.00	77.75	79.25	85.75	87.25	91.25
Subject Number 3									
	66.00	69.25	72.50	77.75	77.25	80.50	84.50	87.50	91.25
	66.75	73.00	72.75	73.50	81.25	81.75	85.75	88.75	89.75
	66.75	69.25	72.25	74.75	79.00	83.25	86.00	86.75	91.25
	67.25	68.50	73.00	77.50	79.00	84.25	84.25	87.75	89.75
Subject Number 4									
	66.25	70.25	71.75	75.75	78.75	81.25	84.25	85.25	92.25
	69.75	71.25	72.75	75.75	80.75	82.50	86.25	91.75	89.75
	67.25	68.75	71.25	76.25	77.75	80.00	83.50	86.25	90.50
	67.75	70.75	71.50	75.00	84.75	81.25	83.25	92.25	91.75

TABLE 14, cont.

	-12	-9	-6	-3	0	3	6	9	12
Subject Number 5									
65.50	69.00	72.75	74.25	76.75	81.00	82.00	87.00	88.50	
69.50	72.00	74.75	78.50	82.25	84.75	87.25	91.00	93.50	
68.00	67.50	71.75	76.00	78.25	81.25	82.75	84.75	88.00	
69.25	72.50	74.75	78.00	81.25	85.00	87.25	90.75	95.25	
Subject Number 6									
65.75	71.25	73.25	75.75	79.25	81.50	86.00	88.50	91.50	
67.00	69.75	72.25	75.00	79.25	82.00	86.25	87.25	91.25	
67.00	72.00	73.25	76.25	79.25	80.75	85.75	87.25	91.00	
66.75	67.25	72.25	76.25	78.75	81.25	83.25	87.50	91.25	
Subject Number 7									
66.25	69.25	71.50	74.75	79.25	81.50	85.50	87.25	89.00	
67.25	72.75	74.50	76.25	80.50	83.75	86.25	87.25	91.75	
67.25	70.25	73.50	75.50	78.75	82.00	84.25	87.50	90.50	
65.50	68.25	72.25	78.00	80.25	81.50	85.75	87.25	91.25	
Subject Number 8									
67.25	70.25	71.25	76.75	78.25	80.50	80.75	87.25	86.75	
67.75	70.75	75.75	76.50	80.75	82.75	87.50	90.75	92.75	
66.25	67.75	71.25	75.25	77.25	81.00	84.50	87.75	88.25	
69.75	72.25	75.75	75.75	78.75	81.75	83.75	88.75	92.75	
Subject Number 9									
66.25	69.25	73.50	76.50	78.75	82.75	83.25	88.25	91.75	
64.25	67.50	73.25	74.75	78.25	82.25	84.75	88.75	89.75	
66.25	70.50	71.50	77.25	79.25	81.75	85.75	87.50	90.75	
67.50	70.50	74.50	76.25	78.75	81.50	84.25	89.00	90.50	
Subject Number 10									
68.50	70.25	72.75	76.25	77.25	82.25	83.75	88.00	91.00	
64.25	69.25	72.50	75.25	79.25	80.25	84.75	87.75	89.00	
69.75	69.75	75.25	76.75	79.50	82.50	84.75	87.25	91.75	
61.00	69.25	71.50	75.00	78.50	81.75	82.75	88.50	90.25	

TABLE 15
RAW DATA - STEADY BACKGROUND NOISES

Subject Number 1

60.7500	58.7000	61.1500	61.0000
60.0000	57.2000	62.4000	57.7500
59.2500	58.9500	60.4000	60.7500
61.5000	59.7000	61.1500	59.7500

Subject Number 2

64.2500	61.7000	66.1500	62.2500
67.7500	61.9500	64.6500	60.2500
65.7500	60.4500	66.1500	59.7500
64.5000	60.9500	64.6500	60.7500

Subject Number 3

63.2500	62.7000	60.1500	59.2500
66.2500	62.9500	62.6500	60.5000
60.5000	61.4500	58.6500	59.2500
62.2500	65.4500	62.6500	60.7500

Subject Number 4

59.2500	60.2000	63.9000	60.2500
68.0000	66.4500	62.6500	62.5000
63.0000	62.4500	64.1500	60.0000
69.0000	63.2000	68.6500	61.0000

Subject Number 5

62.5000	56.4500	62.1500	57.2500
64.7500	57.7000	65.1500	64.2500
62.0000	56.4500	64.6500	58.7500
63.7500	59.4500	68.4000	62.7500

Subject Number 6

62.2500	60.4500	66.6500	59.5000
62.5000	61.4500	65.4000	59.2500
62.2500	59.4500	66.6500	60.7500
62.5000	61.2000	65.4000	60.7500

Subject Number 7

70.2500	63.4500	65.1500	60.5000
71.2500	65.2000	67.6500	62.0000
65.2500	61.7000	63.1500	60.7500
69.2500	62.9500	65.1500	61.5000

TABLE 15, cont.

Subject Number 8

63.5000	60.7000	62.6500	59.2500
65.7500	63.9500	66.4000	60.2500
64.2500	60.2000	65.6500	61.7500
67.2500	60.2000	67.6500	61.2500

Subject Number 9

73.2500	64.4500	64.1500	60.2500
75.2500	63.9500	66.1500	59.2500
70.2500	62.4500	65.6500	61.2500
71.2500	65.4500	69.1500	61.0000

Subject Number 10

69.2500	63.4500	65.1500	60.7500
67.2500	61.9500	65.9000	59.7500
67.5000	63.9500	64.4000	60.7500
68.2500	64.2000	65.9000	62.0000

TABLE 16
RAW DATA - EXPERIMENT 1

100-1.5 50-1.5 50-3.5 20-2 20-5 20-10 10-5 10-5 10-20 5-10 5-20 5-40

Subject Number 1, Sequence A, Replication 1

55.65 56.95 57.80 58.65 58.85 55.70 57.00 58.20 58.15 58.95 59.05 56.35
52.50 55.25 55.50 57.10 51.90 52.10 56.70 50.45 48.75 55.40 56.05 50.45
52.40 49.90 56.40 52.95 53.40 54.75 50.55 58.70 53.00 55.30 50.55 51.65

Sequence B, Replication 1

54.90 57.20 58.55 57.15 58.35 54.70 57.25 57.70 58.90 58.45 59.05 59.10
53.00 53.25 56.75 55.60 53.15 51.60 57.45 51.20 49.75 58.90 55.55 50.45
51.40 48.65 57.90 51.70 53.65 55.00 43.55 50.20 55.75 58.30 49.05 51.90

Sequence A, Replication 2

53.65 54.95 54.05 55.90 57.85 56.70 57.00 55.45 55.40 59.95 56.80 55.85
51.00 51.25 55.00 53.85 51.90 51.60 56.70 52.20 54.75 52.90 54.55 51.70
49.15 50.15 50.65 51.70 50.65 53.25 51.05 52.20 53.75 51.30 48.55 50.15

Sequence B, Replication 2

57.15 55.70 54.05 57.65 57.35 54.95 56.75 55.45 56.15 58.45 57.05 55.35
51.25 51.75 57.00 54.10 50.40 50.85 58.70 52.95 51.00 52.15 54.30 52.95
49.15 49.15 50.90 50.70 51.90 53.00 51.30 51.70 53.50 47.80 48.05 51.40

Subject Number 2, Sequence A, Replication 1

60.90 60.95 59.05 61.40 59.60 60.95 60.25 60.45 62.40 60.95 60.05 59.35
57.75 61.25 67.25 58.60 56.90 61.35 63.45 63.45 63.75 62.40 57.80 57.70
57.40 56.15 65.65 64.95 60.65 64.75 65.30 59.95 63.25 64.55 59.30 61.15

Sequence B, Replication 1

62.40 61.70 59.80 62.15 60.10 61.95 61.75 60.95 61.15 61.70 61.05 60.85
57.00 57.75 66.75 59.35 57.15 64.35 63.45 64.95 63.75 64.10 61.05 56.95
57.65 56.15 69.15 63.45 60.65 64.00 69.05 60.45 65.75 68.00 62.05 61.15

Sequence A, Replication 2

59.40 58.45 61.30 60.65 62.35 63.45 60.25 60.45 59.15 59.90 61.05 60.35
57.50 60.50 62.75 62.35 64.15 61.10 63.45 67.20 64.25 60.65 64.05 62.20
57.15 57.65 63.65 60.95 62.65 67.75 63.05 62.95 64.50 65.55 64.55 61.65

Sequence B, Replication 2

59.65 59.70 62.55 62.65 62.35 63.20 60.25 61.45 61.65 60.45 62.30 61.35
58.25 61.00 63.25 64.60 63.15 62.35 64.95 65.95 65.25 63.40 64.05 63.95
56.65 56.15 65.15 61.45 65.15 70.25 61.05 62.95 65.25 67.55 65.30 62.90

Subject Number 3, Sequence A, Replication 1

61.15 60.45 58.05 58.65 56.60 61.45 61.25 59.45 55.90 61.45 56.05 60.85
60.75 60.50 56.75 57.85 60.15 63.35 60.20 62.45 59.25 63.90 58.30 64.70
59.65 57.15 61.40 52.45 58.15 55.25 60.80 56.95 61.50 62.55 58.55 63.40

Sequence B, Replication 1

62.40 60.95 60.55 59.15 59.10 60.40 60.75 58.20 61.15 60.45 62.55 61.60
62.50 64.25 60.75 61.85 60.65 63.60 62.45 60.45 61.25 62.15 63.05 62.20
60.65 58.15 62.15 53.45 62.15 63.25 59.55 59.45 64.25 65.55 57.55 61.65

Sequence A, Replication 2

59.15 56.45 61.05 57.65 60.35 57.70 56.25 60.70 57.65 58.95 60.30 55.85
62.00 60.75 60.25 60.35 58.90 54.85 60.45 63.70 57.00 59.40 63.55 54.45
53.65 53.15 58.15 61.45 62.65 61.25 53.80 57.20 61.50 52.55 54.05 58.65

TABLE 16, cont.

100-1.5 50-1.5 50-3.5 20-2 20-5 20-10 10-5 10-5 10-20 5-10 5-20 5-40

Sequence B, Replication 2

61.15 59.45 62.55 60.65 61.35 62.20 59.25 61.95 59.65 59.45 61.05 58.60
 63.25 64.50 62.50 61.35 61.40 61.10 66.45 63.95 58.25 61.15 61.05 62.20
 55.65 60.15 60.90 66.70 63.65 63.75 63.05 63.95 64.25 54.55 53.80 59.15

Subject Number 4

Sequence A, Replication 1

59.15 59.45 59.55 59.65 60.85 62.95 60.75 57.95 61.15 61.95 58.80 58.10
 58.25 60.25 51.25 54.10 59.15 67.85 60.45 56.45 61.75 64.65 59.55 62.95
 52.15 52.40 62.15 54.70 51.90 55.25 51.55 53.20 56.25 58.80 64.55 55.90

Sequence B, Replication 1

54.15 60.45 57.05 62.65 62.10 63.20 56.75 61.95 59.90 62.20 58.55 59.35
 61.25 64.75 53.75 65.35 63.60 68.10 62.45 61.45 60.50 58.65 62.30 62.95
 49.15 57.15 59.90 63.45 55.90 59.75 63.05 58.20 54.00 64.30 60.05 56.15

Sequence A, Replication 2

58.65 58.70 57.80 58.15 62.85 64.45 57.50 58.20 61.65 61.70 62.05 60.35
 51.25 60.25 60.25 62.35 57.15 58.85 57.95 56.95 61.00 64.15 62.05 61.45
 56.15 52.40 55.65 56.70 57.15 59.00 54.80 56.95 57.25 57.80 56.55 57.15

Sequence B, Replication 2

58.65 61.45 58.55 63.15 61.35 64.95 60.75 58.20 62.65 64.45 60.30 60.10
 57.75 61.25 60.50 66.35 65.65 61.35 65.20 65.70 65.75 63.15 64.55 63.70
 56.65 57.15 57.40 65.45 64.90 61.00 63.05 60.70 60.25 58.55 59.05 57.65

Subject Number 5

Sequence A, Replication 1

56.15 57.95 56.55 56.65 59.10 58.70 58.25 57.20 58.90 59.95 58.55 57.85
 52.75 54.25 56.50 60.60 57.15 60.85 60.95 55.45 60.25 58.65 58.05 54.20
 54.65 53.40 56.40 59.70 56.15 57.00 56.55 57.95 60.50 63.80 56.05 62.40

Sequence B, Replication 1

58.65 59.45 59.05 60.65 61.85 61.45 62.25 61.20 62.15 61.95 60.55 60.60
 59.25 58.25 60.00 65.35 62.65 65.35 63.70 59.45 65.25 62.65 61.05 60.95
 58.40 59.90 59.15 64.20 59.65 63.25 63.05 63.70 63.75 67.05 63.05 65.90

Sequence A, Replication 2

57.15 55.95 56.05 56.65 57.85 56.45 58.25 58.45 57.40 58.95 58.55 57.10
 55.00 59.25 57.25 55.85 56.65 55.35 60.45 60.20 58.25 58.65 54.55 60.20
 50.65 52.65 55.15 61.45 55.65 54.50 56.55 57.45 56.00 58.55 53.05 55.65

Sequence B, Replication 2

58.90 60.45 59.30 61.65 60.85 60.70 60.75 61.20 59.90 61.20 63.05 60.60
 56.25 63.25 57.50 62.35 62.65 61.35 64.45 64.45 62.75 61.15 62.05 62.70
 55.90 56.90 60.15 67.70 59.15 57.25 62.55 61.95 61.50 64.05 61.55 59.65

Subject Number 6

Sequence A, Replication 1

60.15 62.70 60.55 62.40 60.35 61.25 61.25 60.20 62.15 60.45 60.05 62.10
 58.50 62.00 59.25 63.85 63.65 60.85 63.95 61.95 57.75 60.15 60.80 63.45
 64.65 56.15 56.65 66.45 62.65 59.00 66.55 61.95 57.25 61.80 68.55 64.90

TABLE 16, cont.

100-1.5	50-1.5	50-3.5	20-2	20-5	20-10	10-5	10-5	10-20	5-10	5-20	5-40
Sequence B, Replication 1											
59.15	61.95	61.05	60.65	61.85	61.45	61.25	52.95	62.15	59.20	61.05	63.85
58.75	64.50	61.25	63.60	61.40	60.85	61.95	62.20	61.25	60.40	59.55	61.95
66.15	63.65	57.90	64.95	65.15	62.00	64.30	61.70	58.00	60.05	66.80	61.65
Sequence A, Replication 2											
61.65	61.20	60.55	60.65	60.35	62.20	64.00	54.95	61.90	60.70	61.05	60.85
58.75	60.75	60.50	63.60	63.90	61.35	58.95	66.95	61.25	60.15	61.80	60.70
59.90	60.40	56.90	67.70	56.90	57.00	63.30	59.20	65.50	66.80	62.30	58.90
Sequence B, Replication 2											
60.65	59.70	61.05	59.40	61.85	62.95	59.75	59.70	60.65	60.20	62.05	60.60
60.25	61.00	60.75	62.85	62.65	61.85	61.95	64.20	64.50	60.40	62.80	62.20
63.15	61.15	60.65	68.70	62.40	57.50	67.05	61.95	64.00	66.80	64.30	57.65
Subject Number 7											
Sequence A, Replication 1											
60.40	60.45	58.80	61.15	62.35	56.95	62.75	62.95	61.90	62.45	61.05	60.35
58.75	59.25	64.25	63.85	60.90	63.85	63.95	60.45	55.50	62.65	61.80	53.45
61.65	59.65	63.40	66.95	62.65	61.75	65.55	63.20	59.00	59.30	63.05	59.65
Sequence B, Replication 1											
64.15	62.95	61.55	62.15	63.60	62.20	62.75	62.45	61.40	65.95	63.05	60.85
62.25	65.25	64.75	63.85	63.65	65.60	62.95	62.70	64.75	61.90	63.55	62.20
62.65	63.90	61.40	68.45	63.15	63.75	68.80	65.95	62.00	66.30	69.05	64.90
Sequence A, Replication 2											
61.15	61.45	61.05	60.40	60.35	60.45	60.75	60.95	61.15	60.45	61.05	60.35
65.00	65.00	59.00	59.85	65.90	60.85	62.45	64.45	62.25	63.15	61.55	64.45
63.15	64.15	61.15	66.95	65.65	62.25	67.05	64.20	62.50	65.05	64.80	61.90
Sequence B, Replication 2											
61.15	60.45	63.05	64.15	64.35	65.20	61.75	62.45	64.90	62.45	60.80	62.35
65.25	65.25	63.25	64.85	64.65	63.35	65.95	65.45	65.25	64.65	64.05	67.45
63.15	68.15	64.15	68.45	65.65	62.75	69.30	66.45	64.00	66.55	64.55	64.90
Subject Number 8											
Sequence A, Replication 1											
57.15	59.70	58.80	60.90	58.35	61.95	57.75	63.20	59.15	60.45	59.80	63.60
62.75	61.00	60.25	62.35	57.65	61.10	61.95	60.70	63.00	60.15	61.05	57.95
58.15	58.15	57.40	66.95	59.90	63.75	67.30	64.20	59.75	62.80	62.05	60.90
Sequence B, Replication 1											
61.15	63.45	59.05	59.15	60.85	61.20	62.25	62.70	62.65	62.95	61.05	62.35
59.50	67.00	64.00	63.85	62.40	62.60	64.70	66.20	65.00	64.15	68.05	63.70
58.90	66.90	61.65	70.45	68.65	59.25	69.05	68.70	61.00	69.55	65.05	64.90
Sequence A, Replication 2											
59.40	59.45	57.80	62.90	63.35	61.95	56.75	61.20	61.40	60.20	60.55	60.85
56.75	58.75	59.00	64.35	57.65	61.10	63.95	62.45	63.00	64.15	59.30	64.70
56.15	58.15	57.40	64.45	60.65	62.00	67.30	64.45	59.75	64.05	65.05	62.15
Sequence B, Replication 2											
63.90	64.45	65.05	63.65	62.85	61.20	63.00	63.45	61.15	59.95	61.05	62.35
58.50	64.25	64.25	63.85	62.40	62.60	63.45	61.95	65.00	64.15	59.55	63.95
61.65	65.65	61.65	69.95	62.15	59.75	69.05	63.45	61.00	71.05	67.80	65.40

TABLE 16, cont.

100-1.5 50-1.5 50-3.5 20-2 20-5 20-10 10-5 10-5 10-20 5-10 5-20 5-40

Subject Number 9

Sequence A, Replication 1

61.65 60.45 63.55 63.15 65.35 65.45 61.25 62.45 62.65 62.95 63.05 63.10
 65.50 64.00 63.25 68.60 69.90 65.35 64.95 67.95 71.25 65.15 66.30 67.20
 61.65 66.15 62.65 71.45 68.15 61.25 73.05 69.95 70.75 72.05 68.05 69.65

Sequence B, Replication 1

63.90 61.95 64.05 61.15 64.35 64.95 64.00 64.20 62.40 59.45 60.55 61.85
 63.50 65.00 61.25 68.85 72.65 65.60 66.95 67.70 68.75 65.65 67.05 64.95
 62.65 68.90 62.15 77.95 70.15 63.50 72.30 74.45 70.25 70.55 71.05 71.40

Sequence A, Replication 2

62.65 63.45 63.55 63.90 64.35 65.45 63.00 62.45 65.40 60.45 63.05 62.35
 63.25 64.75 62.25 67.85 68.65 69.35 67.45 67.45 70.25 65.65 65.55 67.20
 65.15 68.15 60.40 71.45 65.15 67.75 73.05 68.95 67.75 71.30 71.05 69.15

Sequence B, Replication 2

63.65 62.95 63.55 62.40 62.85 64.95 60.75 64.45 64.65 58.70 61.55 61.10
 62.75 69.25 66.75 69.60 68.65 67.60 67.70 68.45 68.75 65.40 64.80 67.95
 62.15 69.15 63.40 77.95 69.15 70.25 74.55 71.95 68.50 69.80 70.80 69.90

Subject Number 10

Sequence A, Replication 1

58.65 59.20 60.55 63.15 57.35 59.95 58.75 60.20 60.65 60.95 59.05 59.10
 61.75 61.25 60.50 63.60 62.90 63.85 64.45 62.45 60.50 61.40 63.30 62.20
 62.15 61.65 61.15 64.45 59.15 63.50 68.55 63.95 60.00 63.30 61.05 60.60

Sequence B, Replication 1

59.15 60.95 59.80 62.15 60.35 61.95 60.50 60.95 60.65 60.45 62.05 59.85
 62.25 62.25 61.25 66.60 63.90 62.85 64.95 61.70 60.75 63.65 63.55 64.45
 62.90 62.65 63.65 63.45 63.65 64.25 70.30 68.45 62.25 66.55 65.55 61.40

Sequence A, Replication 2

62.15 61.45 61.55 60.65 62.10 60.95 60.75 60.70 61.65 59.45 61.05 61.10
 61.75 60.50 61.50 61.35 63.65 62.85 61.45 62.45 63.25 64.15 62.05 63.70
 60.15 61.40 59.65 61.95 63.90 60.75 65.05 61.95 58.25 61.55 64.55 64.40

Sequence B, Replication 2

60.65 62.20 61.30 60.15 60.85 59.45 59.75 58.95 61.65 59.70 60.80 61.35
 61.75 59.75 61.00 61.85 63.65 63.35 62.95 60.45 62.00 64.15 62.55 61.95
 62.40 60.15 59.65 61.95 64.40 61.75 64.80 64.45 59.75 64.05 64.55 62.65

TABLE 17
RAW DATA - EXPERIMENT 2

White Band-pass Low-pass High-pass

Subject Number 1

Sequence A, Replication 1

55.6500	55.0500	53.1500	55.4000	100 Hz	1.5 msec	10 dB
52.5000	48.4500	49.4000	48.4000	100 Hz	1.5 msec	20 dB
57.8000	55.3500	54.5500	58.0500	50 Hz	3.5 msec	10 dB
55.5000	52.9000	52.5500	51.1500	50 Hz	3.5 msec	20 dB
58.8500	56.3500	55.1500	57.3000	20 Hz	5 msec	10 dB
51.9000	53.7500	52.4500	53.1500	20 Hz	5 msec	20 dB
58.2000	57.7500	55.4000	54.9500	10 Hz	10 msec	10 dB
50.4500	56.0500	53.2500	54.7500	10 Hz	10 msec	20 dB

Sequence B, Replication 1

54.9000	52.5500	53.1500	56.1500
53.0000	49.9500	46.4000	45.1500
58.3000	57.3500	56.0500	56.5500
56.7500	52.4000	51.3000	53.9000
58.3500	57.3500	55.6500	56.3000
53.1500	54.7500	52.2000	51.6500
57.7000	58.7500	54.6500	54.7000
51.2000	52.5500	49.2500	53.2500

Sequence A, Replication 2

53.6500	55.0500	51.6500	53.6500
51.0000	48.4500	46.6500	48.4000
54.0500	55.3500	53.0500	55.0500
55.0000	50.6500	49.5500	54.4000
57.8500	53.8500	54.1500	56.8000
51.9000	50.2500	47.4500	51.4000
55.4500	56.2500	53.6500	54.2000
52.2000	47.5500	46.7500	48.2500

Sequence B, Replication 2

75.2500	71.0000	70.7500	71.7500
69.2500	66.2500	65.5000	63.2500
72.2500	73.2500	71.2500	74.7500
75.0000	65.5000	68.7500	71.2500
75.7500	71.5000	72.2500	71.7500
69.0000	68.0500	65.2500	70.7500
73.7500	75.0000	71.2500	73.7500
71.2500	69.7500	70.7500	71.0000

Subject Number 2

60.9000	60.0500	56.4000	61.4000
57.7500	60.2000	57.6500	64.6500
59.0500	61.1000	60.0500	63.0500
67.2500	61.6500	63.5500	64.1500
59.6000	62.1000	65.4000	62.5500
56.9000	66.7500	59.4500	60.1500
60.4500	65.7500	62.1500	62.4500
63.4500	62.0500	63.7500	62.0000

TABLE 17, cont.

62.4000	61.5500	56.6500	62.6500
57.0000	62.7000	57.6500	61.4000
59.8000	63.6000	60.8000	65.0500
66.7500	61.6500	64.5500	65.1500
60.1000	63.3500	64.1500	62.0500
57.1500	63.5000	61.7000	61.4000
60.9500	65.7500	61.1500	64.4500
64.9500	63.0500	68.5000	62.5000

59.4000	59.0500	59.6500	57.1500
57.5000	58.7000	58.6500	57.9000
61.3000	57.6000	60.0500	58.5500
62.7500	60.9000	64.0500	59.6500
62.3500	60.8500	60.1500	57.0500
64.1500	61.2500	63.4500	62.6500
50.4500	61.5000	60.6500	61.7000
67.2000	62.0500	62.7500	60.7500

77.7500	78.7500	79.2500	76.2500
76.2500	81.7500	78.7500	77.2500
80.7500	79.2500	79.5000	75.2500
81.2500	80.2500	80.7500	79.2500
80.7500	80.2500	80.0000	76.5000
81.7500	79.2500	81.2500	84.2500
79.7500	77.7500	79.2500	80.5000
84.2500	81.2500	82.2500	79.2500

Subject Number 3

61.1500	58.3000	57.6500	59.6500
60.7500	59.9500	58.1500	60.6500
58.0500	58.3500	56.5500	60.0500
56.7500	60.1500	58.5500	58.6500
56.6000	57.1000	61.6500	57.5500
60.1500	59.7500	58.9500	60.1500
59.4500	61.2500	60.1500	57.9500
62.4500	58.0500	62.5000	55.7500

62.4000	58.3000	60.1500	61.1500
62.5000	61.4500	59.1500	62.1500
60.5500	61.3500	62.0500	62.3000
60.7500	61.1500	58.3000	62.6500
59.1000	59.3500	63.1500	59.0500
60.6500	60.0000	60.4500	60.4000
58.2000	64.7500	62.4000	61.2000
60.4500	60.5500	64.2500	57.2500

TABLE 17, cont.

59.1500	60.0500	59.9000	59.6500
62.0000	58.9500	58.6500	60.9000
61.0500	58.8500	59.8000	59.8000
60.2500	58.6500	59.8000	57.6500
60.3500	58.3500	60.6500	57.3000
58.9000	59.0000	61.7000	64.9000
60.7000	59.2500	61.1500	55.9500
63.7000	59.3000	60.7500	59.0000

79.2500	79.2500	80.7500	78.7500
81.2500	80.2500	82.2500	79.2500
80.7500	79.2500	82.2500	78.2500
80.5000	79.7500	77.7500	79.2500
79.7500	78.5000	80.7500	79.2500
80.0000	80.7500	81.7500	84.7500
80.2500	78.7500	81.5000	77.2500
82.2500	79.7500	80.2500	80.7500

Subject Number 4

59.1500	56.3000	58.6500	56.1500
58.2500	53.9500	54.6500	56.6500
59.5500	61.3500	58.5500	63.0500
51.2500	57.9000	57.5500	55.4000
60.8500	60.1000	59.9000	58.8000
59.1500	56.2500	58.9500	58.1500
57.9500	63.0000	56.6500	57.9500
56.4500	64.5500	57.2500	61.2500

54.1500	63.5500	62.6500	61.1500
61.2500	57.7000	58.9000	58.1500
57.0500	64.8500	58.8000	63.8000
53.7500	64.6500	62.5500	63.4000
62.1000	63.8500	59.6500	63.5500
63.6500	64.7500	67.4500	64.9000
61.9500	65.2500	59.6500	58.4500
61.4500	65.5500	63.2500	62.2500

58.6500	58.8000	50.6500	60.1500
51.2500	54.2000	53.1500	59.1500
57.8000	57.3500	53.0500	58.5500
60.2500	56.9000	56.0500	54.4000
62.8500	63.3500	62.1500	60.3000
57.1500	56.2500	56.4500	62.1500
58.2000	60.5000	59.6500	62.7000
56.9500	57.3000	59.0000	56.7500

TABLE 17, cont.

76.7500	83.7500	83.2500	82.2500
75.7500	79.5000	80.2500	78.2500
76.7500	81.0000	79.5000	80.5000
78.5000	80.2500	75.7500	79.7500
79.7500	83.7500	83.2500	79.5000
84.2500	79.2500	81.2500	81.7500
76.5000	83.5000	81.2500	81.2500
84.0000	80.5000	80.2500	81.5000

Subject Number 5

56.1500	54.5500	52.4000	57.1500
52.7500	53.7000	53.9000	54.9000
56.5500	54.8500	55.5500	56.5500
56.5000	52.4000	59.5500	56.9000
59.1000	57.3500	54.6500	55.0500
57.1500	55.2500	54.9500	56.1500
57.2000	56.7500	56.6500	56.2000
55.4500	57.0500	58.2500	56.7500

58.6500	56.5500	56.1500	60.6500
59.2500	55.9500	56.6500	59.1500
59.5500	57.3500	58.8000	60.3000
60.2500	57.1500	64.5500	59.1500
61.8500	58.8500	57.6500	58.5500
62.6500	60.7500	57.9500	60.4000
61.2000	59.2500	57.4000	57.9500
59.2000	58.5500	60.7500	61.0000

57.1500	55.5500	57.1500	57.1500
55.0000	54.9500	55.4000	55.4000
56.0500	58.8500	53.3000	57.0500
57.2500	56.1500	56.5500	53.4000
57.8500	57.3500	58.4000	55.8000
56.6500	56.7500	54.9500	60.6500
58.4500	59.5000	56.1500	56.4500
60.2000	58.3000	55.7500	56.7500

77.0000	76.2500	75.2500	78.2500
74.2500	77.2500	76.5000	78.7500
78.7500	80.0000	75.2500	76.7500
75.5000	75.2500	76.7500	74.7500
79.2500	76.5000	77.7500	75.7500
81.2500	76.7500	76.2500	82.2500
79.5000	80.2500	77.0000	77.0000
82.7500	78.2500	76.5000	78.7500

TABLE 17, cont.

Subject Number 6

60.1500	61.5500	59.6500	61.9000
58.5000	61.7000	60.6500	59.6500
60.5500	62.8500	63.0500	66.0500
59.2500	60.6500	63.0500	59.6500
60.3500	66.6000	61.6500	60.0500
63.6500	61.2500	57.7000	63.1500
60.2000	66.2500	60.1500	63.7000
61.9500	59.5500	59.7500	65.2500

59.1500	64.0500	60.6500	60.4000
58.7500	63.9500	59.4000	59.9000
61.0500	65.1000	62.3000	65.5500
61.2500	60.1500	61.5500	63.1500
61.8500	66.1000	62.1500	64.5500
61.4000	62.2500	57.4500	64.6500
52.9500	64.2500	60.9000	64.2000
62.2000	64.3000	61.2500	65.0000

61.6500	62.0500	62.6500	61.6500
58.7500	62.2000	61.9000	62.6500
60.5500	61.6000	63.0500	61.5500
60.5000	63.9000	63.5500	63.1500
60.3500	61.8500	61.6500	60.3000
63.9000	63.0000	61.9500	63.6500
55.2000	61.2500	60.6500	61.4500
66.9500	62.3000	61.5000	63.7500

78.7500	79.2500	79.2500	79.0000
78.2500	81.2500	80.7500	82.0000
79.2500	79.0000	81.0000	78.7500
78.7500	80.2500	80.7500	80.0000
80.2500	78.2500	79.0000	79.5000
81.2500	81.2500	80.7500	81.0000
78.0000	79.2500	78.7500	80.0000
82.5000	80.7500	80.2500	82.2500

Subject Number 7

60.4000	61.5500	60.4000	60.6500
58.7500	62.2000	62.4000	62.9000
58.8000	61.3500	59.3000	62.0500
64.2500	65.6500	64.0500	63.1500
62.3500	63.3500	64.1500	64.5500
60.9000	64.7500	63.9500	61.6500
62.9500	64.2500	62.1500	61.7000
60.4500	61.3000	63.2500	61.0000

TABLE 17, cont.

64.1500	63.0500	63.6500	62.1500
62.2500	64.4500	63.1500	64.4000
61.5500	61.8500	62.3000	64.3000
64.7500	65.6500	64.0500	65.9000
63.6000	64.3500	65.1500	63.5500
63.6500	66.7500	64.4500	64.1500
62.4500	65.0000	63.6500	61.9500
62.7000	63.0500	64.2500	61.2500

61.1500	61.0500	62.6500	61.4000
65.0000	63.4500	62.6500	64.4000
61.0500	61.3500	62.5500	61.5500
59.0000	63.1500	63.0500	62.1500
60.3500	61.6000	63.9000	59.0500
65.9000	62.7500	63.4500	63.1500
60.9500	62.0000	63.1500	62.7000
64.4500	60.3000	63.7500	64.7500

79.2500	80.2500	81.7500	81.7500
83.2500	83.7500	83.0000	83.2500
81.2500	80.7500	83.7500	80.2500
81.2500	80.7500	80.7500	81.2500
82.7500	80.7500	83.2500	78.7500
83.2500	81.5000	81.2500	80.7500
80.2500	79.7500	83.0000	80.2500
83.7500	80.5000	84.0000	83.5000

Subject Number 8

57.1500	62.0500	54.9000	58.6500
62.7500	57.2000	60.4000	58.1500
58.8000	60.1000	58.0500	64.3000
60.2500	61.6500	57.5500	61.6500
58.3500	65.8500	59.6500	61.8000
57.6500	68.2500	56.9500	62.1500
63.2000	61.2500	60.9000	63.7000
58.9500	59.0500	62.0000	62.7500

61.1500	61.0500	63.1500	63.1500
59.5000	61.9500	59.6500	66.1500
59.0500	68.1000	61.5500	63.5500
64.0000	64.4000	61.3000	65.4000
60.8500	69.8500	61.1500	63.0500
62.4000	62.2500	58.4500	66.6500
62.7000	67.7500	61.4000	64.2000
62.4500	63.0500	63.5000	63.7500

TABLE 17, cont.

59.4000	58.5500	59.6500	59.6500
56.7500	61.9500	60.4000	57.6500
57.8000	60.3500	63.0500	61.0500
59.0000	58.6500	65.0500	64.6500
63.3500	55.8500	59.6500	58.5500
57.6500	60.0000	57.9500	62.4000
61.2000	59.2500	61.1500	63.9500
61.2000	61.0500	62.2500	60.5000

82.0000	76.0000	76.7500	79.7500
76.5000	84.7500	81.2500	76.2500
83.2500	79.2500	80.5000	79.7500
82.2500	76.7500	82.2500	85.2500
81.2500	77.0000	78.0000	80.5000
81.0000	81.2500	81.2500	83.5000
81.7500	78.0000	77.2500	85.2500
79.2500	81.0000	81.7500	79.7500

Subject Number 9

61.6500	58.5500	60.6500	60.6500
65.5000	60.9500	57.6500	61.1500
63.5500	64.1000	58.5500	64.0500
63.2500	62.6500	64.8000	63.1500
65.3500	63.8500	62.1500	65.3000
69.9000	63.2500	62.9500	63.9000
62.4500	66.2500	63.1500	64.4500
67.9500	65.5500	66.2500	63.0000

63.9000	62.0500	61.1500	63.1500
63.5000	63.4500	58.9000	64.1500
64.0500	64.3500	64.0500	63.3000
61.2500	64.1500	65.3000	66.9000
64.3500	65.8500	67.9000	68.0500
72.6500	64.7500	65.4500	64.6500
64.2000	69.2500	67.6500	64.7000
67.7000	68.5500	68.2500	67.2500

62.6500	60.0500	60.4000	63.1500
63.2500	62.9500	60.1500	59.4000
63.5500	62.3500	64.0500	62.5500
62.2500	60.6500	66.5500	62.1500
64.3500	62.6000	62.1500	60.8000
68.6500	65.5000	64.9500	65.9000
62.4500	64.5000	63.4000	64.9500
67.4500	67.0500	65.5000	65.2500

TABLE 17, cont.

81.7500	81.7500	83.2500	82.2500
80.7500	83.2500	80.0000	81.0000
81.7500	83.2500	82.5000	80.5000
84.7500	84.0000	85.5000	81.7500
81.2500	81.7500	81.2500	81.2500
87.2500	84.2500	85.2500	85.7500
82.7500	84.0000	84.7500	83.2500
86.7500	84.2500	87.5000	86.2500

Subject Number 10

58.6500	63.0500	60.4000	62.1500
61.7500	61.4500	60.9000	62.1500
60.5500	62.8500	60.0500	61.5500
60.5000	61.6500	64.0500	60.6500
57.3500	62.3500	60.4000	62.8000
62.9000	63.2500	63.9500	61.6500
60.2000	62.7500	61.1500	61.2000
62.4500	62.5500	62.0000	62.2500

59.1500	62.5500	60.6500	62.1500
62.2500	60.9500	60.4000	63.1500
59.8000	61.6000	60.8000	63.0500
61.2500	61.6500	63.5500	61.6500
60.3500	64.3500	61.6500	64.5500
63.9000	63.2500	63.7000	63.4000
60.9500	62.5000	60.6500	62.9500
61.7000	63.0500	62.0000	62.7500

62.1500	60.5500	60.6500	61.1500
61.7500	60.9500	60.1500	63.1500
61.5500	62.1000	60.0500	62.5500
61.5000	62.1500	61.5500	61.1500
62.1000	64.1000	62.9000	61.5500
63.6500	64.5000	60.9500	63.1500
60.7000	61.0000	64.1500	61.9500
62.4500	62.8000	63.2500	62.0000

78.7500	79.0000	78.7500	79.5000
79.7500	79.2500	78.2500	81.5000
79.5000	79.5000	78.2500	80.5000
79.0000	78.7500	81.2500	79.5000
79.2500	82.0000	81.0000	79.7500
82.2500	82.2500	80.2500	81.2500
77.2500	79.7500	82.7500	79.2500
78.7500	81.7500	80.0000	81.5000

TABLE 18
RAW DATA - PILOT STUDY

42	48	54	60	66
Subject Number 1				
56.6500	53.1500	53.6500	55.6500	57.1500
70.0000	63.7500	53.7500	52.5000	42.0000
53.3000	54.0500	55.0500	57.8000	55.0500
55.0000	53.2500	51.5000	55.5000	48.0000
51.3500	54.8500	51.6000	58.8500	55.3500
48.1500	48.1500	48.1500	51.9000	50.1500
52.9500	53.9500	53.7000	58.2000	55.4500
51.2000	48.4500	46.7000	50.4500	50.4500
53.0500	54.0500	53.0500	59.0500	57.8000
51.5500	49.5500	49.0500	56.0500	51.8000
55.6500	53.4000	54.6500	54.9000	55.9000
51.2500	52.5000	48.2500	53.0000	48.7500
52.3000	54.5500	53.8000	57.5500	56.0500
52.7500	52.7500	49.0000	56.7500	49.2500
56.1000	56.6000	54.3500	58.3500	55.8500
50.6500	53.1500	49.1500	53.1500	49.9000
54.4500	55.4500	55.9500	57.7000	55.2000
51.4500	47.4500	45.9500	51.2000	51.7000
54.5500	55.0500	57.5500	59.0500	57.3000
50.5500	49.8000	48.8000	55.5500	52.5500
55.4000	55.6500	53.4000	53.6500	54.9000
53.0000	52.0000	47.0000	51.0000	48.0000
53.3000	54.0500	53.0500	55.0500	56.5500
55.0000	49.7500	46.7500	55.0000	52.7500
54.6000	53.8500	53.8500	57.8500	54.3500
50.6500	47.6500	46.9000	51.9000	47.1500
52.9500	52.2000	54.7000	55.4500	54.2000
51.7000	50.9500	52.4500	52.2000	53.2000
56.0500	61.0500	56.5500	56.8000	56.0500
53.5500	48.0500	50.3000	54.5500	50.8000
51.9000	54.1500	52.9000	57.1500	55.6500
51.7500	49.5000	54.5000	51.2500	50.7500
52.3000	54.0500	55.0500	54.0500	58.5500
52.7500	49.0000	50.7500	57.0000	52.7500
53.3500	53.1000	52.1000	57.3500	56.8500
53.6500	49.6500	48.9000	50.4000	49.1500
54.4500	53.4500	52.4500	55.4500	55.9500
49.9500	47.2000	48.4500	52.9500	55.9500
56.0500	57.0500	57.5500	57.0500	57.0500
51.8000	46.8000	49.5500	54.3000	53.5500

TABLE 18, cont.

Subject Number 2

61.4000	59.6500	59.9000	61.1500	61.6500
60.7500	61.2500	58.2500	60.7500	61.2500
60.0500	59.5500	59.3000	58.5500	61.3000
59.2500	59.2500	59.7500	56.7500	61.5000
59.8500	60.8500	58.8500	56.6000	60.8500
60.4000	56.9000	58.6500	60.1500	63.1500
59.4500	58.7000	59.2000	59.4500	60.7000
57.4500	59.9500	60.7000	62.4500	62.4500
60.0500	59.0500	57.5500	56.0500	59.5500
57.8000	57.5500	59.5500	58.3000	61.5500
61.1500	60.1500	61.1500	62.4000	63.1500
60.7500	59.7500	58.7500	62.5000	62.7500
60.5500	60.5500	61.0500	60.5500	60.5500
59.7500	60.5000	56.5000	60.7500	62.2500
60.3500	60.6000	60.3500	59.1000	61.1000
60.1500	59.9000	60.9000	60.6500	63.6500
60.7000	59.9500	60.4500	58.2000	60.9500
56.7000	60.4500	60.9500	60.4500	62.4500
60.5500	59.5500	67.5500	62.5500	58.3000
59.5500	58.3000	60.8000	63.0500	62.5500
60.1500	59.1500	60.1500	59.1500	59.4000
61.7500	58.7500	59.0000	62.0000	60.7500
58.5500	60.5500	59.5500	61.0500	60.5500
59.2500	60.7500	59.5000	60.2500	58.7500
59.1000	60.6000	60.6000	60.3500	57.3500
60.9000	58.6500	59.6500	58.9000	62.6500
59.7000	60.9500	63.2000	60.7000	60.2000
56.9500	61.2000	61.4500	63.7000	60.2000
59.0500	58.5500	59.0500	60.3000	60.3000
64.5500	61.8000	62.5500	63.5500	61.5500
61.4000	62.1500	61.1500	61.1500	62.6500
62.2500	59.7500	58.7500	63.2500	62.5000
57.8000	59.8000	61.0500	62.5500	60.5500
63.2500	61.0000	60.5000	62.5000	59.0000
60.8500	61.3500	61.6000	61.3500	61.8500
60.4000	61.6500	58.9000	61.4000	63.1500
59.9500	59.7000	61.2000	61.9500	59.2000
56.4500	61.4500	61.9500	63.9500	61.9500
60.0500	59.5500	60.3000	61.0500	60.0500
59.8000	61.5500	63.3000	61.0500	61.0500

TABLE 18, cont.

Subject Number 3

58.6500	57.6500	57.1500	59.1500	59.6500
55.7500	53.7500	52.5000	58.2500	53.2500
55.5500	58.5500	58.3000	59.0500	60.5500
53.7500	53.0000	58.2500	51.2500	57.0000
57.6000	62.1000	60.3500	60.8500	60.3500
53.6500	55.4000	56.6500	59.1500	58.4000
58.4500	60.9500	60.4500	57.9500	58.9500
52.7000	51.9500	50.7000	56.4500	64.9500
60.8000	58.0500	59.0500	58.8000	60.8000
63.0500	58.3000	59.5500	59.5500	57.5500
57.4000	59.9000	58.6500	54.6500	62.4000
60.5000	60.0000	57.2500	61.2500	60.0000
55.0500	61.0500	62.5500	57.0500	59.3000
56.0000	55.0000	61.2500	53.7500	64.7500
59.3500	58.8500	60.6000	62.1000	61.3500
57.1500	58.6500	60.6500	63.6500	64.4000
60.9500	62.7000	62.7000	61.9500	61.7000
55.9500	57.7000	64.4500	61.4500	65.7000
60.5500	59.5500	58.5500	58.5500	59.8000
59.5500	60.0500	63.8000	62.3000	61.5500
60.6500	57.1500	57.6500	58.6500	56.1500
57.0000	57.5000	57.2500	51.2500	51.7500
60.0500	57.3000	57.5500	57.8000	56.3000
53.7500	57.7500	53.5000	60.2500	55.7500
56.3500	61.1000	57.8500	62.8500	59.3500
58.4000	52.4000	55.9000	57.1500	60.9000
62.9500	58.7000	62.4500	58.2000	59.7000
55.9500	55.7000	53.4500	56.9500	59.9500
59.3000	61.0500	59.5500	62.0500	57.0500
59.0500	58.8000	57.0500	62.0500	60.0500
61.4000	57.9000	63.9000	58.6500	56.9000
58.2500	60.2500	60.5000	57.7500	61.2500
59.8000	59.5500	62.0500	58.5500	60.5500
55.5000	61.7500	62.7500	60.5000	63.7500
60.3500	63.3500	60.3500	61.3500	61.8500
63.6500	55.1500	61.6500	65.6500	67.6500
62.9500	65.7000	58.4500	58.2000	63.9500
55.7000	62.9500	58.4500	65.7000	68.9500
60.3000	61.5500	60.0500	60.3000	62.0500
61.3000	61.0500	60.8000	64.5500	64.5500

TABLE 18, cont.

Subject Number 4

56.6500	58.6500	55.6500	56.1500	57.6500
56.2500	57.0000	53.7500	52.7500	54.5000
57.3000	58.5500	55.5500	56.5500	57.3000
56.2500	56.7500	55.5000	56.5000	56.2500
53.8500	56.8500	56.8500	59.1000	58.3500
53.6500	57.4000	55.4000	57.1500	60.1500
56.4500	56.7000	57.9500	57.2000	58.7000
54.4500	53.9500	60.2000	55.4500	59.4500
59.0500	59.0500	58.0500	58.5500	57.5500
57.0500	59.5500	58.5500	58.0500	60.5500
57.4000	59.1500	56.9000	58.6500	59.6500
57.7500	57.2500	54.0000	59.2500	58.7500
58.3000	59.3000	57.0500	59.0500	58.8000
57.0000	58.5000	56.5000	60.0000	59.7500
57.3500	59.8500	59.8500	61.8500	61.1000
54.4000	60.1000	58.1500	62.6500	60.6500
57.2000	59.9500	58.9500	61.2000	59.7000
55.2000	57.2000	59.4500	59.4500	63.9500
59.0500	61.0500	59.8000	60.5500	61.0500
56.5500	60.3000	61.0500	61.0500	62.8000
57.1500	54.9000	56.9000	57.1500	54.9000
53.5000	54.2500	53.7500	55.0000	51.5000
58.3000	56.0500	55.0500	56.0500	53.0500
55.2500	55.5000	58.0000	57.2500	53.5000
52.6000	56.3500	54.8500	57.8500	58.8500
54.4000	56.4000	56.6500	56.6500	58.6500
54.7000	56.7000	56.9500	58.4500	58.4500
49.2000	55.2000	52.7000	60.2000	52.7000
58.5500	56.0500	57.0500	58.5500	57.5500
53.5500	57.0500	56.5500	54.5500	58.0500
56.9000	55.6500	59.1500	58.9000	55.1500
56.7500	55.2500	53.2500	56.2500	54.2500
58.0500	57.3000	56.3000	59.3000	57.8000
57.2500	56.0000	58.0000	57.5000	55.2500
54.3500	57.3500	55.3500	60.8500	60.1000
54.4000	58.6500	56.9000	62.6500	62.1500
56.9500	58.9500	60.2000	61.2000	59.2000
50.9500	54.9500	55.4500	64.4500	56.4500
59.8000	57.3000	60.8000	63.0500	61.5500
54.8000	59.0500	63.3000	62.0500	59.3000

TABLE 18, cont.

Subject Number 5

60.6500	60.6500	61.9000	60.4000	60.6500
61.2500	60.2500	61.5000	58.7500	60.5000
61.3000	59.3000	60.0500	58.8000	63.0500
64.7500	61.2500	61.7500	64.2500	60.5000
63.3500	60.8500	63.1000	62.3500	60.8500
61.6500	63.4000	63.1500	60.9000	63.1500
61.4500	62.4500	62.4500	62.9500	61.9500
60.7000	61.4500	62.7000	60.4500	60.9500
58.5500	60.5500	61.0500	61.0500	59.5500
60.5500	62.8000	63.0500	61.8000	64.0500

60.6500	60.4000	62.9000	64.1500	62.4000
60.7500	60.7500	62.7500	62.2500	64.7500
59.8000	61.0500	61.3000	61.5500	64.0500
63.2500	61.5000	62.2500	64.7500	64.5000
64.6000	61.6000	62.8500	63.6000	63.1000
62.6500	63.6500	62.6500	63.6500	66.9000
60.9500	62.9500	62.9500	62.4500	62.4500
60.4500	65.9500	63.9500	62.7000	63.9500
61.5500	60.5500	62.0500	63.0500	61.5500
62.0500	62.0500	64.0500	64.5500	65.5500

58.1500	58.6500	61.1500	61.1500	61.1500
60.5000	60.7500	59.2500	65.0000	63.7500
60.5500	60.5500	60.8000	61.0500	61.3000
59.7500	60.2500	64.0000	59.0000	61.0000
60.3500	62.3500	61.3500	60.3500	61.8500
62.4000	63.1500	63.9000	65.9000	62.4000
61.2000	63.2000	59.2000	60.9500	61.9500
62.2000	61.4500	63.4500	64.4500	62.7000
60.5500	61.3000	61.0500	61.0500	60.8000
61.3000	63.3000	61.5500	61.5500	61.8000

61.1500	60.6500	61.4000	61.1500	64.4000
61.0000	61.2500	62.2500	65.2500	66.5000
61.0500	60.5500	62.0500	63.0500	62.3000
61.2500	62.7500	64.2500	63.2500	66.2500
61.8500	61.8500	62.8500	64.3500	63.8500
61.6500	62.1500	65.1500	64.6500	65.1500
61.2000	64.2000	63.4500	61.9500	62.9500
64.2000	63.2000	64.4500	65.4500	65.9500
60.5500	61.5500	63.5500	60.8000	62.5500
63.5500	61.0500	64.5500	61.5500	63.5500

TABLE 18, cont.

Subject Number 6

60.4000	60.6500	61.4000	58.6500	60.6500
61.2500	60.2500	61.5000	58.7500	60.5000
61.3000	59.3000	60.0500	58.8000	63.0500
64.7500	61.2500	61.7500	64.2500	60.5000
63.3500	60.8500	63.1000	62.3500	60.8500
61.6500	63.4000	63.1500	60.9000	63.1500
61.4500	61.9500	62.4500	62.9500	61.9500
60.7000	61.4500	62.7000	60.4500	60.9500
58.5500	60.5500	61.0500	61.0500	59.5500
60.5500	62.8000	63.0500	61.8000	64.0500

61.4000	60.6500	60.6500	59.1500	61.1500
60.7500	60.7500	62.7500	62.2500	64.7500
59.8000	61.0500	61.3000	61.5500	64.0500
63.2500	61.5000	62.2500	64.7500	64.5000
64.6000	61.6000	62.8500	63.6000	63.1000
62.6500	63.6500	62.6500	63.6500	66.9000
60.9500	62.9500	62.9500	62.4500	62.4500
60.4500	65.9500	63.9500	62.7000	63.9500
61.5500	60.5500	62.0500	63.0500	61.5500
62.0500	64.0500	64.0500	64.5500	65.5500

61.6500	60.6500	58.6500	62.1500	60.6500
60.5000	60.7500	59.2500	65.0000	73.7500
60.5500	60.5500	60.8000	61.0500	61.3000
59.7500	60.2500	64.0000	59.0000	61.0000
60.3500	62.3500	61.3500	60.3500	61.8500
62.4000	63.1500	63.9000	65.9000	62.4000
61.2000	63.2000	59.2000	60.9500	61.9500
62.2000	61.4500	63.4500	64.4500	62.7000
60.5500	61.3000	61.0500	61.0500	60.8000
61.3000	63.3000	61.5500	61.5500	61.8000

60.9000	62.4000	60.1500	60.6500	61.1500
61.0000	61.2500	62.2500	65.2500	66.5000
61.0500	60.5500	62.0500	63.0500	62.3000
61.2500	62.7500	64.2500	63.2500	66.2500
61.8500	61.8500	62.8500	64.3500	63.8500
61.6500	62.1500	65.1500	64.6500	65.1500
61.2000	64.2000	63.4500	61.9500	62.9500
63.9500	63.2000	64.4500	65.4500	65.9500
60.5500	61.5500	63.5500	60.8000	62.5500
63.5500	61.0500	64.5500	61.5500	63.5500

SELECTED BIBLIOGRAPHY

- Akay, A. 1978. A review of impact noise. J. Acoust. Soc. Am. 64:977-987.
- Amadasi, S.M. 1990. Classification of noise sources of textile machines with analysis technique based on short Leq measurements on TWF time signal. In Proceedings of Inter-Noise 90:1045-1047.
- American National Standards Institute. 1970. Specifications for audiometers. ANSI S3.6-1969.
- American National Standards Institute. 1971. Methods for the measurement of sound pressure levels. ANSI S1.13-1971.
- American National Standards Institute. 1978. Specification for personal noise dosimeters. ANSI S1.25-1978.
- American National Standards Institute. 1983. Specification for sound level meters. ANSI S1.4-1983. (Revision of ANSI S1.4-1971).
- American National Standards Institute. 1986. Method for the measurement of impulse noise. ANSI S12.7-1986.
- American National Standards Institute. 1988. Quantities and procedures for description and measurement of environmental sound. ANSI S12.9-1988.
- Arai, K., and H. Miura. 1977. An analysis of impulsive sounds generated from construction equipments by the Wigner distribution with a Gaussian window. J. Acoust. Soc. Jpn. (E) 8:271-276.
- Banner, D.L., K.S Nordby, and B.L. Wible. 1976. Loudness balance for steady and impulsive noise. IBM Technical Report TR 01.2020.
- Berglund, B., U. Berglund, and S. Lindberg. 1986. Loudness of impulsive sound from different weapons. In Proceedings of Inter-Noise 86:815-820.
- Berry, B.F. 1985. Evaluation of impulsive environmental noise: I. Laboratory studies of annoyance reactions. In Proceedings of Inter-Noise 85:921-924.
- _____. 1987. The Evaluation of Impulsive Noise. National Physical Laboratory, Middlesex UK. Acoustics Report AC 111 (September).

- _____. 1989. Recent advances in the measurement and rating of impulse noise. In Proceedings of the Thirteenth International Congress on Acoustics:147-50.
- Berry, B.F., H.C. Fuller, A.J. John, and D.W. Robinson. 1979. The Rating of Helicopter Noise: Development of a Proposed Impulse Correction. NPL Acoustics Report AC 93.
- Berry, B.F., A.D. Wallis, and A. Rozwadowski. 1989. The use of short-term L_{Aeq} in the assessment of impulsive noise. Presentation at the Institute of Acoustics 1989 Autumn Conference on Industrial Noise.
- Berry, B.F., and E. Zwicker. 1986. Comparison of subjective evaluations of impulsive noise with objective measurements of the loudness-time function given by loudness meter. In Proceedings of Inter-Noise 86:821-823.
- Bisping, R. 1989. Steady versus impulsive noises: spectral parameters and subjective ratings. In Proceedings of the Thirteenth International Congress on Acoustics:143-46.
- Boone, M.M. 1973. Loudness measurements on pure tone and broad band impulsive sounds. Acustica 29:198-204.
- Brambilla, G., and M.R. Caretti. 1989. Assessment of annoyance and impulsivity of environmental noises. In Proceedings of the Thirteenth International Congress on Acoustics:139-142.
- Brambilla, G., M.R. Caretti, and S. Santoboni. 1988. Laboratory subjective evaluation of environmental impulse sounds. In Proceedings of NOISE 88 3:159-164.
- Bruel, P.V. 1976. Do we measure damaging noise correctly. Bruel and Kjaer Technical Review Number 1.
- _____. 1977. Do we measure damaging noise correctly? Noise Control Eng. J. 8:52-60.
- _____. 1980. The influence of high crest factor noise on hearing damage. Scand. Audiol. Suppl. 12:25-31.
- _____. 1985. Impulsive noise in industry. In Proceedings of Inter-Noise 85:1045-1048.
- _____. 1987a. Measurement of impulsive noises which apparently sound continuous. In Proceedings of Inter-Noise 87:1335-1338.
- _____. 1987b. Measurement of impulsive signals. In Proceedings of Inter-Noise 87:1339-1342.
- Carter, N.L. 1972. Effect of rise time and repetition rate on the loudness of triangular transients. J. Sound Vib. 21:227-239.

- Committee on Hearing, Bioacoustics, and Biomechanics 1968. Proposed Damage-Risk Criterion for Impulse Noise (Gunfire). Report of Working Group 57, NAS-NRC. Washington, D.C.
- Cluff, G.L. 1980. Exposure considerations for impulse and continuous noise. Sound and Vibration 14:26-27.
- Cohen, A., B. Kylin, and P.J. Labenz. 1966. Temporary threshold shifts in hearing from exposure to combined impact/steady-state noise conditions. J. Acoust. Soc. Am. 40:1371-1380.
- Coles, R.R.A., G.R. Garinther, D.C. Hodge, and C.G. Rice. 1967. Criterion for Assessing Hearing Damage Risk from Impulse Noise Exposure. US Army Human Engineering Laboratories, Aberdeen Proving Ground, Maryland. Technical Memorandum No. 13-67
- Coles, R.R.A., G.R. Garinther, D.C. Hodge, and C.G. Rice. 1968. Hazardous exposure to impulse noise. J. Acoust. Soc. Am. 43: 336-343.
- Coles, R.R.A., and C.G. Rice. (1967) Hazards from impulse noise. Ann. Occ. Hyg. 10:381-388.
- Coles, R.R.A., and C.G. Rice. 1970. Towards a criterion for impulse noise in industry. Ann. Occ. Hyg. 13:43.
- Coles, R.R.A. and C.G. Rice. 1971. Assessment of risk of hearing loss due to impulse noise. In Occupational Hearing Loss, ed. D.W. Robinson, 1-77. London and New York: Academic Press.
- Commings, D.E., M. Sidhamed, A. Fournol, and F. Laville. 1985. CEC Joint Project on Impulse Noise: Physical characterization and detection. In Proceedings of Inter-Noise 85:897-900.
- Commings, D.E., and J-P. Sirieys. 1981. A digital sound level meter with a programmable integration time and internal storage capability. In Proceedings of Inter-Noise 81: 857-862.
- Dym, C.L. 1977. Sources of industrial Impact/impulsive noise. Noise Control Eng. J. 8:81-87.
- Earshen, J.J. 1980. On overestimation of noise dose in the presence of impulsive noise. In Proceedings of Inter-Noise 80: 1007-1010.
- Engen, T. 1971. Psychophysics. In Woodworth and Schlosberg's Experimental Psychology. ed. J. W. Kling and L.A. Riggs. New York: Holt, Rinehart, and Winston.
- Engstrom, J.R., and K.S. Nordby. 1979. Noisiness of impulsive vs steady noise. In Proceedings of Noise-Con 79:207-212.

- Environmental Protection Agency, Office of Noise Abatement and Control. 1974. Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety. Report 550/9-74-004.
- Erbes, A. 1986. Impact matrix printer noise control. In Proceedings of Inter-Noise 86:1439-1442.
- Erdreich, J. 1986. A distribution-based definition of impulse noise. J. Acoust. Soc. Am. 79:990-998.
- Erlandsson, B., H. Hakanson, A. Ivarsson, E., Karlsson, and P. Nilsson. 1980. Estimation of impulse noise from cumulative time distributions with a sound pressure analyzer. Scand. Audiol. Suppl. 12:33-39.
- Fidell, S., K. Pearsons, M. Grignetti, and D.M. Green. 1970. The noisiness of impulsive sounds. J. Acoust. Soc. Am. 48:1304-1310.
- Flindell, I.H., C.G. Rice, and C.G. Swift. 1989. Human response to impulse noise - Impulsivity and annoyance. In Proceedings of the Thirteenth International Congress on Acoustics: 155-58, 1989.
- Fosbroke, J. 1831. Practical observations on the pathology and treatment of deafness. Lancet 19:645-648.
- Garner, W.R. 1949. The loudness and loudness matching of short tones. J. Acoust. Soc. Am. 21:398-401.
- Garner, W.R., and G.A. Miller. 1947. The masked threshold of pure tones as a function of duration. J. Exp. Psychol. 37:293-303.
- Gelfand, S.A. 1981. Hearing, An Introduction to Psychological and Physiological Acoustics. New York:Marcel Dekker.
- Green, D.M., T.G. Birdsall, and W.P. Tanner. 1957. Signal detection as a function of signal intensity and duration. J. Acoust. Soc. Am. 29:523-531.
- Guignard, J.C. 1973. A Basis for Limiting Noise for Hearing Conservation. NTIS Report No. AD-767 274, (AMRL-TR-73-90, EPA-550/9-73-001-A). Prepared for Aerospace Medical Research Laboratory, Wright Patterson AFB, Ohio, at the University of Dayton Research Institute, Dayton, Ohio.
- Gustafson, B. 1974. The loudness of transient sounds as a function of some physical parameters. J. Sound Vib. 37:389-398.
- Hamernik, R.P., D. Henderson, J.J. Crossley, and R. Salvi. 1974. Interaction of continuous and impulse noise: audiometric and histological effects. J. Acoust. Soc. Am. 55:117-121.

- Hashimoto, T., S. Namba, and C.G. Rice. 1984. The loudness of decaying impulsive sounds. In Proceedings of Inter-Noise 84:793-798.
- Hassel, J.R., and K. Zaveri. 1978. Application of Bruel and Kjaer Equipment to Acoustic Noise Measurements. Bruel and Kjaer, Inc.
- Henderson, D., and R.P. Hamernik. 1982. Asymptotic threshold shift from impulse noise. In New Perspectives on Noise Induced Hearing Loss. Eds. R.P. Hamernik, D. Henderson, and R. Salvi. New York: Raven Press.
- Henderson, D., and Hamernik, R.P. 1986. Impulse noise: Critical review. J. Acoust. Soc. Am. **80**:569-584.
- Hetu, R., S. Belzile, A-M. Forget, and E. Tetu. 1984. Exposure limits to impact noise: The relation between the peak level and the number of long duration impact noises. In Proceedings of Inter-Noise 84:859-862.
- Hewlett Packard Corporation. 1985. The Fundamentals of Signal Analysis. Application Note 243.
- Hiramatsu, K., K. Takagai, and T. Yamamoto. 1990. Permissible criteria for impulse noise recommended by Japan Association of Industrial Health. In Proceedings of Inter-Noise 90:1227-1230.
- Hodge, D.C., and G.R. Price. 1978. Hearing damage risk criteria. In Noise and audiology. Ed., D. M. Lipscomb. Chicago: University Park Press.
- Holt, E.E. 1882. Boilermaker's deafness and hearing in noise," Trans. Am. Otol. Soc. **3**:34-44.
- International Electrotechnical Commission. 1965. Sound level meters. IEC Publication 123.
- International Electrotechnical Commission. 1973. Precision sound level meter. IEC Publication 179.
- International Electrotechnical Commission. 1973. Additional characteristics for the measurement of impulsive sound. IEC Publication 179A.
- International Electrotechnical Commission. 1979. Sound level meters. IEC Publication 651.
- International Electrotechnical Commission. 1985. Integrating-averaging sound level meters. IEC Publication 804.
- Institute of Electrical and Electronics Engineers 1969. Technical Committee Report on Recommended Practices for Burst Measurements in the Time Domain. IEEE No. 265.

- International Standards Organization. 1975. Acoustics - Method for calculating loudness level. ISO 532-1975.
- International Standards Organization. 1982. Acoustics - Description and measurement of environmental quantities - Part 1. Basic quantities and procedures. ISO 1996/1-1982(E).
- International Standards Organization. 1979. Acoustics - Guide to international standards on the measurement of airborne acoustical noise and evaluation of its effects on human beings. ISO 2204-1979 (E).
- International Standards Organization. 1988. Acoustics - Measurement of airborne noise emitted by computer and business equipment. ISO 7779-1988 (E).
- Ishizaki, S., and H. Tachibana. 1985. Loudness sensation for isolated impulsive sounds. In Proceedings of Inter-Noise 85:933-936.
- Japanese Industrial Standard. 1988. Precision sound level meters. JIS C-1505.
- Johnson, D.R., and D.W. Robinson. 1969. Procedure for calculating the loudness of sonic bangs. Acustica 21:307-318.
- Jussil, P., S. Jukkal, and Y. Jukka. 1987. Effect of ear protectors on high impulse sound levels. In Proceedings of Inter-Noise 87:1363-1404.
- Kamperman, G.W. 1980. The measurement of impulse noise. Editorial, Sound and Vibration 12:5.
- _____. 1980. Dosimeter response to impulsive noise. in Proceedings of Inter-Noise 80:1011-1014.
- Katz, J. ed. 1985. Handbook of Clinical Audiology, Third edition. 1985. Baltimore: Williams and Wilkins.
- Kay, S.M., and S.L. Marple, Jr. 1981. Spectrum analysis - A modern perspective. In Proceedings of the IEEE 69:1380-1419.
- Kryter, K.D. 1970. The Effects of Noise on Man. New York: Academic Press.
- Kumagai, M., M. Ebata, and T. Sone. 1981. Effect of some physical parameters of impact sound on its loudness (A study on the loudness of impact sound. I). J. Acoust. Soc. Jpn. (E) 2:15-26.
- Kumagai, M., M. Ebata, and T. Sone. 1982. Comparison of loudness of impact sounds with and without steady duration (A study on the loudness of impact sound. II). J. Acoust. Soc. Jpn. (E) 3:33-40.

- Kumagai, M., M. Ebata, and T. Sone. 1982. Loudness of impact sound with wide band spectrum (A study on the loudness of impact sound III). J. Acoust. Soc. Jpn. (E). 3:111-118.
- Kumagai, M., Y. Suzuki, T. and Sone, T. 1982. The loudness of repeated impact sound (A study on the loudness of impact sound (IV)). J. Acoust. Soc. Jpn. (E). 3:231-238.
- Kumagai, M., Y. Suzuki, and T. Sone. 1984. A study on the time constant for an impulsive sound level meter (A study on the loudness of impact sound. V). J. Acoust. Soc. Jpn. (E). 5:31-36.
- Kundert, W.R. 1974. The impulsive sound level meter - What's it all about?. Sound and Vibration 8:50-53.
- _____. 1977. Sound level meters: The state of the art. Noise Control Eng. J. 9:120-130.
- _____. 1982. Dosimeters, impulsive noise, and the OSHA hearing conservation amendment. Noise Control Eng. J. 19:74-79.
- Kuwano, S., S. Namba, and T. Kato. 1978. The loudness of impulsive sound. J. Acoust. Soc. Jpn. 34:316-317.
- Kuwano, S., S. Namba, H. Miura, and H. Tachibana. 1984. Evaluation of the loudness of impulsive sounds using sound exposure level (LAE) based on the results of a round-robin test in Japan. In Proceedings of Inter-Noise 84:809-814.
- Kuwano, S., S. Namba, H. Miura, and H. Tachibana. 1987. Evaluation of the loudness of impulsive sounds using sound exposure level based on the results of a round-robin test in Japan. J. Acoust. Soc. Jpn. (E). 8:241-247.
- Lahti, T., and J. Starck. 1980. Industrial impulse noise measurements. Scand. Audiol. Suppl. 12:63-69.
- Laroche, C., and R. Hetu. 1990. The influence of the spectral content and the decay time of impulse noise on asymptotic threshold shift. Acustica 70:29-44.
- Laville, F., A. Fournol, and D.E. Commins. 1986. Impulse Noise Quantification Using Very Short-Term Log Time Series. Commins-BBN Report 120.
- Levitt, H. 1970. Transformed up-down methods in Psychoacoustics. J. Acoust. Soc. Am. 49:467-477.
- Levitt, H. 1978. Adaptive testing in audiology. In Sensorineural Hearing Impairment and Hearing Aids, ed. G. Ludweisen and J. Barfod, Scand. Audiol. Suppl. 6:241-291.

- Lim, D.J., D.E. Dunn, J. A. Ferraro, and B.L. Lempert. 1982. Anatomical changes found in cochleas of animals exposed to typical industrial noise. In New Perspectives on Noise Induced Hearing Loss, ed. R.P. Hamernik, D. Henderson, and R. Salvi. New York: Raven Press.
- Little, J.W., and J.E. Mabry. 1969. Sound duration and its effect on judged annoyance. J. Sound Vib. 9:247-262.
- Luz, G.A., and D.C. Hodge. 1971. Recovery from impulse-noise induced TTS in monkeys and men: A descriptive model. J. Acoust. Soc. Am. 49:1770-1777.
- Martin, A.M. 1976. The Equal Energy Concept Applied to Impulse Noise. Institute of Sound and Vibration Technical Report No. 77. University of Southampton, UK. (also published in Effects of Noise on Hearing, ed. D. Henderson, et al. New York: Raven Press.
- Martin, R. 1976. The impulse sound level meter and proposals for its use in Germany. In Proceedings of Inter-Noise 76:117-122.
- Melnick, W. 1978. Temporary and permanent threshold shift. In Noise and audiology. Ed., D. M. Lipscomb. Chicago: University Park Press.
- Miller, G.A. 1948. The perception of short bursts of noise. J. Acoust. Soc. Am. 20:160-170.
- Miller, G.A. and W.G. Taylor. 1948. The perception of repeated bursts of noise. J. Acoust. Soc. Am. 20:171-182.
- Moore, B.C.J. 1982. An Introduction to the Psychology of Hearing, Second Edition. New York: Academic Press.
- Munson, W.A. 1947. Growth of auditory sensation. J. Acoust. Soc. Am. 19:584-591.
- Nabelek, I.V. 1982. Advances in noise measurement schemes. In New Perspectives on Noise Induced Hearing Loss, Ed. R.P. Hamernik, D. Henderson, and R. Salvi. New York: Raven Press.
- Nakamura, T., Y. Nakajima, and S. Namba. 1984. The relation of loudness and noisiness to measurement time interval in exposure to impulsive noise trains. Proceedings of Inter-Noise 84:871-874.
- Namba, S. 1987. On the psychological measurement of loudness, noisiness, and annoyance: A review. J. Acoust. Soc. Jpn(E). 8: 211-222.
- Namba, S., T. Hashimoto, and C.G. Rice. 1987. The loudness of decaying impulsive sounds. J. Sound Vib. 116:491-507.
- Niedzwicki, A. and H.S. Ribner. 1978a. Subjective loudness of N-wave sonic booms. J. Acoust. Soc. Am. 64:1617-1621.

- Niedzwicki, A. and H.S. Ribner. 1978b. Subjective loudness of "minimized" sonic boom waveforms. J. Acoust. Soc. Am. **64**:1622-1627.
- Niese, H. 1956. Vershlag fuer die Definition und messung der Deutlichkeit nach Subjektiven Grundlagen," Hochfrequenztech. und Elektroak. **65**:4-30.
- Niese, H. 1958. Untersuchung der Lautstarkeempfindung von rythmischen Gerauschen. Hochfrequenztech. und Elektroakoust. **66**:115.
- _____. 1959. Die Tragheit der Lautstarkeempfindung und ihre Nachbildung bei objektiven Lautstaerkmessern. In Proceedings of the Third International Congress on Acoustics:129.
- _____. 1960. Das ubliche und notwendige dynamische Verhalten objektiver Lautstarkmessgerate. Hochfrequenztech. und Elektroakoust. **69**:17.
- _____. 1961. Die messtechnische Ermittlung der Lautstarke von biebungen Gerauschen unter Beruchsichtigung der Einflusse des Zeitblaufes und der Spektrumtransform. Acustica **11**:70.
- _____. 1965. Beitrag zur relation zwischen lautstarke und lastigkeit von gerauschen. Acustica **15**:236-243.
- Oldrich, K. 1990. Impulse noise of forming machines and its abatement. In Proceedings of Inter-Noise **90**:733-736.
- Parmentier, G., and K. Buck. 1980. Methods for measuring impulse noise. Scand. Audiol. Suppl. **12**:77-83.
- Passchier-Vermeer, W., R. van den Berg, and R. Leeuw. 1980. Measurement of impulse noise at workplaces: Relation between oscillographic measurements with an ordinary precision sound level meter. Scand. Audiol. Suppl. **12**:87-97.
- Pedersen, O.J., P.E. Lyregaard, and T. Poulsen. 1977. The Round Robin Test on Evaluation of Loudness of Impulsive Noise. Report of the Acoustics Laboratory of the Technical University of Denmark, Lyngby, Denmark.
- Pekkarinen, J., and J. Starck. 1983. Impulse noise in a shipyard. In Proceedings of the Eleventh International Congress on Acoustics: 195-198.
- Peterson, A.P.G. 1980. Handbook of Noise Measurement Concord: General Radio Corporation.
- Pfander, F., H. Bongartz, H. Brinkamnn, and H. Kietz. 1980. Danger of auditory impairment from impulse noise: A comparative study of the CHABA damage-risk criteria and those of the Federal Republic of Germany. J. Acoust. Soc. Am. **67**:628-633.

- Plomp, R., and M.A. Bouman. 1959. Relation between hearing threshold and duration for tone pulses. J. Acoust. Soc. Am. **31**:749.
- Pollack, I. 1969. Periodicity pitch for interrupted white noise - Fact or artifact? J. Acoust. Soc. Am. **45**:237-238.
- Port, E. 1959. Die Lautstärke von Tonimpulsen verschiedener Dauer. Frequenz: 242.
- _____. 1963a. Über die Lautstärke einzelner kurzer Schallimpulse. Acustica **13**:212-223.
- _____. 1963b. Zur Lautstärkeempfindung und Lautstärkemessung von pulsierenden Geräuschen. Acustica **13**:224-233.
- Poulsen, T. 1981. Loudness of tone pulses in a free field. J. Acoust. Soc. Am. **69**:1786-1790.
- Price, G.R. 1986. Hazard from intense low-frequency acoustic impulses. J. Acoust. Soc. Am. **80**:1076-1086.
- Ramazini, B. 1713. De Morbis Artificum Padua. In Disease of Workers (New York:Hafner 1964).
- Reichardt, W. 1965. Zur Tragheit der Lautstärkedildung. Acustica **15**: 345-354.
- _____. 1969. Subjective and objective measurement of the loudness level of single and repeated impulses. J. Acoust. Soc. Am. **47**: 1557-1562.
- Reichardt, W., and Muller, M. 1965. Einfluss der Messmethode und der Versuchspersonen auf der Beurteilung der Lautstärke von Einzelimpulsen. Hochfrequenztech. und Elektroak. **74**:135-139.
- Reichardt, W., and H. Niese. 1970. Choice of sound duration and silent intervals for test and comparison signals in the subjective measurement of loudness level. J. Acoust. Soc. Am. **47**:1083-1090.
- Rice, C.G. 1989. Human response to impulse noise - CEC studies review of 1987/89 Research Programme. In Proceedings of the Thirteenth International Congress on Acoustics:135-38.
- Ritterstaedt, U., and J. Kastka. 1985. CEC Joint project on impulse noise: A new definition of impulsiveness of environmental noise. In Proceedings of Inter-Noise 85:917-920.
- Roberto, M., W.A. Ahroon, R.I. Davis, and R.P. Hamernik. 1987. The interaction of impulse and continuous noise: Energy and spectral considerations in the production of hearing loss. J. Acoust. Soc. Am. **81** Suppl. 1:S76.

- Rosenheck, A.J., and R.F. Hoffman. 1977. Weapon noise measurements for community exposure ratings using dB(A) impulse compared with dB(A) fast. In Proceedings of Inter-Noise 77:B358.
- Sakai, T. 1986. Loudness and annoyance of construction noise. In Proceedings of Inter-Noise 86:751-756.
- Sapega, A.E. 1959. Characteristics of typewriter noise. J. Acoust. Soc. Am. **31**:849.
- Saunders, J.C., S.P. Dear, and M.E. Schneider. 1985. The anatomical consequences of acoustic injury: A review and tutorial. J. Acoust. Soc. Am. **78**:833-860.
- Sheely, E.C., and R.C. Bilger. 1964. Temporal integration as a function of frequency. J. Acoust. Soc. Am. **36**:1850-1857.
- Sidhamed, M., and Commins, O. 1983. Measurement and Analysis of Various Impulse Noise Sources Using Very Short-Term Leq Time-Series. Commins-BBN Report No. 64.
- Sirieys, J.P., and D.E. Commins. 1980. Short term equivalent level series: An efficient tool for environmental assessment. In Proceedings of Inter-Noise 80:985-990.
- Small, A.M., J. F. Brandt, and P.G. Cox. 1962. Loudness as a function of signal duration. J. Acoust. Soc. Am. **34**:513.
- Smootenburg, G.F. 1982. Damage risk criteria for impulse noise. In New Perspectives on Noise Induced Hearing Loss, ed. R.P. Hamernik, D. Henderson, and R. Salvi. New York: Raven Press.
- Sone, T., Y. Ogura, and Y. Suzuki. 1989. Loudness evaluation of impulsive noise. In Proceedings of Inter-Noise 89:821-826.
- Sone, T., et al. 1987. Loudness and noisiness of a repeated impact sound: Results of round robin tests in Japan (II). J. Acoust. Soc. Jpn(E). **8**:249-261.
- Stephens, S.G.D. 1974. Methodological factors influencing loudness of short-duration sounds. J. Sound Vib. **37**:235-246.
- Stevens, S.S. 1971. Perceived level of noise by Mark VII and decibels (E). J. Acoust. Soc. Am. **51**:575-593.
- Stevin, G.O. 1982. Spectral analysis of impulse noise for hearing conservation purposes. J. Acoust. Soc. Am. **72**:1845-1854.
- Suzuki, Y., M. Kumagai, T. Takahashi, and T. Sone. 1984. Loudness of impact sounds: results of round robin tests in Japan. In Proceedings of Inter-Noise 84:827-832.
- Svensson, J. 1980. Rating of impulse noise through level distribution. Scand. Audiol. Suppl. **12**:105-106.

- Tachibana, H., S. Ishizaki, and K. Yoshihisa. 1987. A method of evaluating the loudness of impulsive sounds with narrow frequency-components. J. Acoust. Soc. Jpn. 8:29-38.
- Tachibana, H., K. Yoshihisa, and S. Ishizaki. 1984. Equal loudness relation for impulsive sounds. In Proceedings of Inter-Noise 84: 799-802.
- Terhardt, E. 1974. On the perception of periodic sound fluctuations (roughness). Acustica 30:201-213.
- Theopold, H-M. 1975. Degenerative alterations in the central cochlear nucleus of the guinea pig after impulse noise exposure - A preliminary light and electron microscopic study," Arch. Oto Rhino Laryngol. 209:247-262.
- Thiery, L. 1987. Characterization of industrial impulse noises by discriminant analysis. J. Sound Vib. 113:404-406.
- Thiery, L. and C. Meyer-Bisch. 1988. Hearing loss due to partly impulsive industrial noise exposure at levels between 87 and 90 dB. J. Acoust. Soc. Am. 84:651-659.
- Thiessen, G.J. and K. Subbarao. 1962. Effect of reverberation on the assessment of repetitive impulse noise. J. Acoust. Soc. Am. 34: 1761-1763.
- Vos, J. 1990. On the level-dependent penalty for impulse sound. J. Acoust. Soc. Am. 88:883-893.
- Vos, J., and F.W.M. Geurtson. 1987. L_{eq} as a measure of annoyance caused by gunfire consisting of impulses with various proportions of higher and lower sound levels. J. Acoust. Soc. Am. 82:1201-1206.
- Vos, J., and G.F. Smoorenburg. 1985. Penalty for impulse noise derived from annoyance ratings for impulse and road-traffic sounds. J. Acoust. Soc. Am. 77:193-201.
- Walker, J.G. 1972. Temporary threshold shift caused by combined steady-state and impulse noises. J. Sound Vib. 24:493-504.
- Wallis, A.D., and B.F. Berry. 1989. Using short L_{eq} in the measurement and rating of impulsive noise. In Proceedings of Inter-Noise 89:951-954.
- Wallis, A.D., and J.M. Holding. 1984. A method of generating short L_{eq} . In Proceedings of Inter-Noise 84:1039-1041.
- Wilkerson, R.B. 1975. Sound level meter and dosimeter response to unsteady noise levels. Noise Control Eng. J. 4:68-75.
- Winer, B.J. 1962. Statistical Principles in Experimental Design. New York: McGraw Hill.

- Yano, H., A. Kobayashi, and K. Izumi. 1989. Noisiness of repeated impulse sounds: effects of background to peak level and duration. In Proceedings of Inter-Noise 89:833-836.
- Yano, H. and A. Kobayashi. 1990. Disturbance caused by impulsive, fluctuating, and combined noises. In Proceedings of Inter-Noise 90:1189-1191.
- Zepler, E.E., and J.R.P. Harel. 1965. The loudness of sonic booms and other impulsive sounds. J. Sound Vib. 2:249-256.
- Zwicker, E. 1960. Ein Verfahren zur Berechnung der Lautstärke. Acustica 10:304-308.
- _____. 1961. Der gegenwaertige Stand der Objektiven Lautstaerkemessung. Teil 1, ATM V55-6.
- _____. 1966. Ein Beitrag zur Lautstarkmessung impulshaltiger Schalle. Acustica 17:11-22.
- _____. 1977. Procedure for calculating loudness of temporally variable sounds. J. Acoust. Soc. Am. 62:675-682.
- _____. 1984. BASIC-Program for calculating the loudness of sounds from their 1/3-oct band spectra according to ISO 532 B. Acustica 55:63-67.
- _____. 1987. Meaningful noise measurement and effective noise reduction. Noise Control Eng. J. 29:66-76.
- Zwislocki, J. 1960. Theory of temporal auditory summation. J. Acoust. Soc. Am. 32:1046-1060.