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An experimental study of the vortical structure of turbulent flows

Honkan, Anant Gangadhar, Ph.D.

City University of New York, 1994

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AN EXPERIMENTAL STUDY OF THE VORTICAL STRUCTURE OF TURBULENT FLOWS

by

Anant G. Honkan

A dissertation submitted to the Graduate Faculty in Engineering in partial fulfillment
of the requirements for the degree of Doctor of Philosophy, The City University of
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Abstract

AN EXPERIMENTAL STUDY OF THE VORTICAL STRUCTURE OF TURBULENT FLOWS

by

Anant G. Honkan**Advisor:** Professor Yiannis Andreopoulos

An attempt is made to explore the structures of a two-dimensional turbulent boundary layer flow and vortex flow over a 45° sweep delta wing by spatio-temporal measurements of velocity and vorticity vectors and vorticity flux at the boundaries. Two novel probes, with good spatial resolution, one to measure multi-point velocity vector and the other to measure vorticity flux have been designed and constructed. Tests results of the principal statistical properties computed from the measurements of instantaneous velocity and vorticity vectors in the turbulent boundary layers at $Re_\theta = 2244$ and $Re_\theta = 2790$ are extensively compared with existing datasets including those from direct numerical simulations at various Reynolds numbers and under different flow conditions. The conditionally sampled results of the inclination of vorticity vector at the position

closest to the wall suggest preferential orientation in the upper and lower quadrants. The turbulent structures identified by the conditional technique that are associated with streamwise vorticity seem to be of longer duration than those with the conditioned events of normal and spanwise vorticity. The probability of the orientation of vorticity vector as referred to the eigen vectors of the strain rate matrix closest to the wall, indicated this vector to be least likely to align with the most compressive eigen vector. The capabilities of the probe to measure the statistical quantities in both turbulent boundary layer flows with good accuracy were thus established and experimental data of time dependent three-dimensional vorticity field using this probe is collected for the first time in the region of strong vortices over a 45° sweep delta wing to investigate the complex structure of the leading edge vortices for a case without vortex breakdown. Flow visualization technique employing laser sheet is used to observe instantaneous "frozen" coherent structures in the flow in three different perspectives.

Affectionately dedicated to the memory of my mother

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TABLE OF CONTENTS

ABSTRACT	iii
LIST OF SYMBOLS	xi
LIST OF TABLES	xiv
LIST OF FIGURES	xv
1. INTRODUCTION	1
1.1. Vorticity and its significance:	1
1.2. Present understanding of the turbulent boundary layer flows:	6
1.3. Present understanding of flow over delta wing:	10
2. EXPERIMENTAL ARRANGEMENT, INSTRUMENTATION AND	
TECHNIQUES	21
2.1. Wind tunnel:	21
2.2 Flow Models:	22
2.2.1 Boundary Layer:	22
2.2.2. Delta Wing:	23
2.3 Vorticity Probe Design and Construction:	24

2.4. Vorticity Flux Module:	25
2.5. Traversing Mechanism:	26
2.6. Instrumentation:	28
2.7. Existing Techniques:	31
 3. FLOW VISUALIZATION TECHNIQUES	 47
3.1. Surface Flow Visualization:	47
3.2. Laser Light Sheet Technique:	48
 4. PRESENT APPROACH	 52
4.1. Theory of operation of vorticity probe:	52
4.1a. Analytical expression using King's law:	52
4.1b. Direct mapping through look up table:	59
4.2. Vorticity Computations For 3TOW Probe:	64
4.3. Calibration for velocity, yaw and pitch:	67
4.4. Kulite/Entran Modules:	68
4.5. Kulite/Entran Modules Calibrations:	69
 5. MEASUREMENTS	 89
5.1. Boundary layer flow: Preliminary Experiment	
Measurements By 3TOW Probe	89
5.2. Boundary layer flow : Concluding Experiment	
Simultaneous Measurements By 3TOW Probe & Entran module:	90

5.3. Flow over delta wing:	91
6. RESULTS & DISCUSSION	94
6.1. Resolution considerations:	94
6.2. Turbulent Boundary Layer : Preliminary Experiment	
3TOW Probe:	97
6.3. Turbulent Boundary Layer : Concluding Experiment	
3TOW Probe:	98
CONCLUSIONS:	123
6.4. DELTA WING :	
6.4.1 Flow Visualization:	126
6.4.2 3TOW probe:	127
CONCLUSIONS:	129
BIBLIOGRAPHY	228

LIST OF SYMBOLS

A	Mean velocity calibration line intercept
B	Mean velocity calibration line slope (King's law coefficient)
C	Chord length of delta wing model
c_f	Coefficient of skin friction
d	Hot-wire diameter
E	Anemometer (Hot-wire) voltage output
F	Discrete function representing yaw-pitch response of the hot-wire
f_s	Digitizing rate (Hz)
H	Shape factor δ^*/θ
h	Pitch coefficient for the hot-wire
k	Yaw coefficient for the hot-wire
l	Length of the hot-wire
l_s	Separation distance between two hot-wires of a triple sensor unit
l_p	Separation distance between two triple hot-wire units
p	Instantaneous pressure
p'	Fluctuating pressure
q	Heat flux
R	Overheat ratio
Re	Reynolds number
R_w	Resistance of the hot-wire at wire temperature T_w
R_{ref}	Resistance of the hot-wire at wire temperature T_{ref}

S	Semi-local span of delta wing model
T_w	Temperature of the hot-wire
T_{ref}	Reference temperature (ambient temperature)
$\bar{u}, \bar{v}, \bar{w}$	Mean velocity components along laboratory coordinates x, y and z respectively
u, v, w	Instantaneous velocity components along x, y and z directions
u', v', w'	R.m.s. of velocity components along x, y and z directions
X, Y, Z	Instantaneous velocity components in wire-fixed coordinates
V	Velocity vector
u_τ	Friction velocity $\sqrt{\frac{\tau_w}{\rho}}$

Greek Symbols:

α	Angle of attack
α_T	Temperature coefficient of resistivity per °C
γ	Pitch angle for hot-wire
δ	Yaw angle for hot-wire <u>OR</u> boundary layer thickness
δ^*	Displacement thickness
ϵ_{ijk}	Kroeneker delta
θ	Momentum thickness
μ	Fluid viscosity
ν	Kinematic viscosity μ/ρ
ρ	Fluid density
τ	Turbulent shear stress $\rho \overline{uv}$

τ_w	Wall shear stress
$\alpha_s, \beta_s, \gamma_s$	Eigen vectors of strain rate matrix.
$\Delta()$	Difference in $()$
ψ	Hot-wire inclination angle
Ω	Angular velocity
ω	Vorticity vector

Subscripts, superscripts and other symbols:

o	Values at the centroid of the 3TOW probe
1, 2, 3	Values of the voltage output of each sensor <u>OR</u> values at the center of the first, second and the third triple hot-wire respectively
0	Values at $\gamma=0$ and $\delta=0$
x, y, z	Values along x, y and z directions
n	King's law exponent
$+$	Non-dimensionalized values using appropriate factor/s for inner layer scaling
$()'$	root mean square value of $()$

LIST OF TABLES

Table 5.1.	Principal parameters of the turbulent boundary layers.	92
Table 5.2.	Locations of measurement points on the delta wing for 15° angle of attack for the 3TOW probe experiments.	93
Table 6.1.	Probe resolution in viscous units.	131
Table 6.2.	Probe resolution in microscale units.	132
Table 6.3.	Flow parameters of the existing datasets used in the comparison.	133

LIST OF FIGURES

Figure 1.1.	Flow pattern in the turbulent boundary layer.	16
Figure 1.2.	Flow field over a pitched delta wing.	17
Figure 1.3.	Leading edge vortex length scales. (Payne, 1987)	18
Figure 1.4.	Schematic of flow in the separated shear layer over a delta wing. (Squire,1961)	18
Figure 1.5.	Angle of attack at vortex breakdown as a function of sweep angle. (Polhamus,1971)	19
Figure 1.6.	Vortex breakdown location as a function of angle of attack. (Skow and Titiriga, 1978)	20
Figure 2.1.	Wind tunnel facility at CCNY.	34
Figure 2.2a.	Plot of friction coefficient c_f at 3 spanwise locations.	35
Figure 2.2b.	Plot of variation of skin-friction coefficient c_f with Reynolds number based on momentum thickness θ .	36
Figure 2.3.	Pitot tube traverse in the turbulent boundary layer.	37
Figure 2.4.	Sketch of the delta wing model used in the experiments.(not to scale).	38
Figure 2.5.	Support mechanism and installation of delta wing in the test section...	39
Figure 2.6.	Schematic of the 9 hot-wire vorticity (3TOW) probe.	40
Figure 2.7.	Enhanced photographs of the home-made 3TOW probe.	41
Figure 2.8.	Diagram of the vorticity flux (Kulite/Entran) module.	42
Figure 2.9.	3-d. traversing system with two independent rotations for yaw and pitch.	43

Figure 2.10.	Block diagram of the experimental arrangement for velocity and vorticity measurements.	44
Figure 2.11.	Block diagram of the experimental setup for simultaneous vorticity and wall pressure/vorticity flux measurements.	45
Figure 2.12.	Block diagram of stepper motor hardware.	46
Figure 3.1.	Schematic of the laser light sheet technique.	50
Figure 3.2.	Orientations of the laser light sheet for delta wing flow visualization.	51
Figure 4.1.	Velocity components, yaw and pitch angles definition.	70
Figure 4.2.	Orientations of each triple hot-wire in the 3TOW probe.	71
Figure 4.3.	Plots of sensitivity $\partial E/\partial U$, $\partial E/\partial \gamma$ and $\partial E/\partial \delta$.	72
Figure 4.4.	Domain of acceptability of velocity components by the three triple hot -wires of the 3TOW probe.	73
Figure 4.5.	Plot of discrete function F against yaw and pitch angles.	74
Figure 4.6.	Co-ordinate system for vorticity computation.	80
Figure 4.7.	Calibration plots of velocity for each triple hot-wire. Filled symbols : calibration at the beginning and open symbols : calibration at the end.	81
Figure 4.8.	Yaw and pitch response of each hot-wire.	83
Figure 6.1.	Mean velocity profile in the boundary layer as measured at the center of the probe.	134
Figure 6.2a.	Normalized r.m.s. axial velocity fluctuations u'	135
Figure 6.2b.	Normalized r.m.s. normal velocity fluctuations v'	136
Figure 6.2c.	Normalized r.m.s. spanwise velocity fluctuations w'	137

Figure 6.3.	Normalized Reynolds shear stress. $-\overline{uv}$	138
Figure 6.4a.	R.m.s. axial vorticity fluctuations ω'_x normalized by inner variables u_τ and ν .	139
Figure 6.4b.	R.m.s. normal vorticity fluctuations ω'_y normalized by inner variables u_τ and ν .	140
Figure 6.4c.	R.m.s. spanwise vorticity fluctuations ω'_z normalized by inner variables u_τ and ν .	141
Figure 6.3.1.	Measured r.m.s. of axial velocity fluctuations u' normalized by u_τ and δ .	142
Figure 6.3.2.	Measured r.m.s. of normal velocity fluctuations v' normalized by u_τ and δ .	142
Figure 6.3.3.	Measured r.m.s. of spanwise velocity fluctuations w' normalized by u_τ and δ .	143
Figure 6.3.4.	Measured distributions in the near wall region of axial velocity fluctuations u' normalized by u_τ and ν .	144
Figure 6.3.5.	Measured distributions in the near wall region of normal velocity fluctuations v' normalized by u_τ and ν .	144
Figure 6.3.6.	Measured distributions in the near wall region of spanwise velocity fluctuations w' normalized by u_τ and ν .	145
Figure 6.3.7.	Measured distributions in the near wall region of turbulent kinetic energy normalized by u_τ and ν .	146
Figure 6.3.8.	Measured distributions in the near wall region of r.m.s. flow angles θ_f and ϕ_f fluctuations.	147

Figure 6.3.9. Typical time series records of flow angles θ_f and ϕ_f .	148
Figure 6.3.10. Probability density function of flow angle θ_f measured at the center of probe 1.	149
Figure 6.3.11. Probability density function of flow angle ϕ_f measured at the center of probe 1.	150
Figure 6.3.12. Skewness factor of velocity component u and compared with other simulated and measured datasets.	151
Figure 6.3.13. Skewness factor of velocity component v and compared with other simulated and measured datasets.	151
Figure 6.3.14. Skewness factor of velocity component w and compared with other simulated and measured datasets.	152
Figure 6.3.15. Flatness factor of velocity component u and compared with other simulated and measured datasets.	153
Figure 6.3.16. Flatness factor of velocity component v and compared with other simulated and measured datasets.	153
Figure 6.3.17. Flatness factor of velocity component w and compared with other simulated and measured datasets.	154
Figure 6.3.18. Normalized Reynolds shear stress $-\overline{uv}$ across the boundary layer.	155
Figure 6.3.19. Normalized Reynolds shear stress $-\overline{uv}$ in the near wall region.	156
Figure 6.3.20. Measured correlation coefficient distribution across the boundary layer.	156
Figure 6.3.21. Computed turbulent kinetic energy production and dissipation rates normalized by wall variables u_τ and ν .	157

Figure 6.3.22.R.m.s.axial vorticity fluctuations ω'_x normalized by outer variables u_r and δ .	158
Figure 6.3.23.R.m.s. normal vorticity fluctuations ω'_y normalized by outer variables u_r and δ .	158
Figure 6.3.24.R.m.s. spanwise vorticity fluctuations ω'_z normalized by outer variables u_r and δ .	159
Figure 6.3.25.R.m.s. axial vorticity fluctuations ω'_x scaled by variables U_∞ and δ .	160
Figure 6.3.26.R.m.s. normal vorticity fluctuations ω'_y scaled by variables U_∞ and δ .	160
Figure 6.3.27.R.m.s. spanwise vorticity fluctuations ω'_z scaled by variables U_∞ and δ .	161
Figure 6.3.28.Near-wall axial vorticity fluctuations ω'_x normalized by inner variables u_r and ν .	162
Figure 6.3.29.Near-wall normal vorticity fluctuations ω'_y normalized by inner variables u_r and ν .	162
Figure 6.3.30.Near-wall spanwise vorticity fluctuations ω'_z normalized by inner variables u_r and ν .	163
Figure 6.3.31.Skewness factor of vorticity component ω_x and compared with other simulated and measured datasets.	164
Figure 6.3.32.Skewness factor of vorticity component ω_y and compared with other simulated and measured datasets.	164

Figure 6.3.33. Skewness factor of vorticity component ω_z and compared with other simulated and measured datasets.	165
Figure 6.3.34. Flatness factor of vorticity component ω_x and compared with other simulated and measured datasets.	66
Figure 6.3.35. Flatness factor of vorticity component ω_y and compared with other simulated and measured datasets.	166
Figure 6.3.36. Flatness factor of vorticity component ω_z and compared with other simulated and measured datasets.	167
Figure 6.3.37. Measured r.m.s. distributions of spatial derivatives of streamwise velocity component normalized by outer variables u_r and δ .	168
Figure 6.3.38. Measured r.m.s. distributions of spatial derivatives of normal velocity component scaled by outer variables u_r and δ .	168
Figure 6.3.39. Measured r.m.s. distributions of spatial derivatives of spanwise velocity component normalized by outer variables u_r and δ .	169
Figure 6.3.40. Near-wall r.m.s. distributions of spatial derivatives of streamwise velocity component normalized by inner variables u_r and ν .	170
Figure 6.3.41. Near-wall r.m.s. distributions of spatial derivatives of normal velocity component scaled by inner variables u_r and ν .	170
Figure 6.3.42. Near-wall r.m.s. distributions of spatial derivatives of spanwise velocity component normalized by inner variables u_r and ν .	171
Figure 6.3.43. Power spectral density of axial velocity component computed at $y^+ = 12.5$.	172

- Figure 6.3.44. Power spectral density of normal velocity component computed
at $y^+ = 12.5$ 172
- Figure 6.3.45. Power spectral density of spanwise velocity component computed
at $y^+ = 12.5$ 173
- Figure 6.3.46. One dimensional spectral density of fluctuating axial vorticity
component computed at $y^+ = 12.5$, normalized by wavenumber and
boundary layer thickness. 174
- Figure 6.3.47. One dimensional spectral density of fluctuating normal vorticity
component computed at $y^+ = 12.5$, normalized by wavenumber
and boundary layer thickness. 174
- Figure 6.3.48. One dimensional spectral density of fluctuating spanwise
vorticity component computed at $y^+ = 12.5$, normalized by
wavenumber k_x and boundary layer thickness δ 175
- Figure 6.3.49. Spectra of enstrophy and kinetic energy weighted by wavenumber
computed at $y^+ = 12.5$ 176
- Figure 6.3.50. Probability distribution function of axial component of fluctuating
velocity as measured at $y^+ = 12.5$ 177
- Figure 6.3.51. Probability distribution function of normal component of fluctuating
velocity as measured at $y^+ = 12.5$ 177
- Figure 6.3.52. Probability distribution function of spanwise component of
fluctuating velocity as measured at $y^+ = 12.5$ 178
- Figure 6.3.53. Probability distribution function of axial component of fluctuating
vorticity as measured at $y^+ = 12.5$ 179

- Figure 6.3.54. Probability distribution function of normal component of fluctuating vorticity as measured at $y^+ = 12.5$ 179
- Figure 6.3.55. Probability distribution function of spanwise component of fluctuating vorticity as measured at $y^+ = 12.5$ 180
- Figure 6.3.56a. Profiles of turbulent intensity ratios u'/v' and u'/w' in the inner layer. 181
- Figure 6.3.56b. Profiles of vorticity fluctuations ratios ω_x'/ω_y' and ω_x'/ω_z' in the inner layer. 182
- Figure 6.3.57. Log plot of powerspectra ratios of $\text{psd}(u)/\text{psd}(v)$ and $\text{psd}(u)/\text{psd}(w)$ vs. wavenumber normalized by δ computed at $y^+ = 12.5$ 182
- Figure 6.3.58. Log plot of powerspectra ratios of $\text{psd}(\omega_x)/\text{psd}(\omega_y)$ and $\text{psd}(\omega_x)/\text{psd}(\omega_z)$ vs. wavenumber normalized by δ at $y^+ = 12.5$ 182
- Figure 6.3.59. Probability distribution function of vorticity angle θ_v in x-z plane for threshold level 0, 50% and 100% of the r.m.s. of ω_z 183
- Figure 6.3.60. Probability distribution function of vorticity angle θ_v in x-z plane for threshold level 0, 50% and 100% of the r.m.s. when $\omega_y > 0$ 183
- Figure 6.3.61. Probability distribution function of vorticity angle θ_v in x-z plane for threshold level 0, 50% and 100% of the r.m.s. when $\omega_y < 0$ 184
- Figure 6.3.62. Probability of the alignment of the vorticity vector with each of the three eigen vectors α_s , β_s and γ_s associated with the strain rate matrix. 185

Figure 6.3.63. Relative amplitudes of the events associated with vorticity
conditioned on positive ω_x , threshold $k=2$ 186

Figure 6.3.64. Relative amplitudes of the events associated with velocity conditioned
on positive ω_x , threshold $k=2$ 186

Figure 6.3.65. Relative amplitudes of the events associated with vorticity conditioned
on negative ω_x , threshold $k=-2$ 187

Figure 6.3.66. Relative amplitudes of the events associated with velocity conditioned
on negative ω_x , threshold $k=-2$ 187

Figure 6.3.67. Relative amplitudes of the events associated with vorticity conditioned
on positive ω_y , threshold $k=2$ 188

Figure 6.3.68. Relative amplitudes of the events associated with velocity conditioned
on positive ω_y , threshold $k=2$ 188

Figure 6.3.69. Relative amplitudes of the events associated with vorticity conditioned
on negative ω_y , threshold $k=-2$ 189

Figure 6.3.70. Relative amplitudes of the events associated with velocity conditioned
on negative ω_y , threshold $k=-2$ 189

Figure 6.3.71. Relative amplitudes of the events associated with vorticity conditioned
on positive ω_z , threshold $k=2$ 190

Figure 6.3.72. Relative amplitudes of the events associated with velocity conditioned
on positive ω_z , threshold $k=2$ 190

Figure 6.3.73. Relative amplitudes of the events associated with vorticity conditioned
on negative ω_z , threshold $k=-2$ 191

Figure 6.3.74. Relative amplitudes of the events associated with velocity conditioned on negative ω_z , threshold $k=-2$.	191
Figure 6.3.75. Relative amplitudes of the events associated with vorticity flux / pressure conditioned on positive $\partial\omega_x/\partial y$, threshold $k=2$.	192
Figure 6.3.76. Relative amplitudes of the events associated with vorticity conditioned on positive $\partial\omega_x/\partial y$, threshold $k=2$	192
Figure 6.3.77. Relative amplitudes of the events associated with velocity conditioned on positive $\partial\omega_x/\partial y$, threshold $k=2$.	193
Figure 6.3.78. Relative amplitudes of the events associated with vorticity flux / pressure conditioned on positive $\partial\omega_x/\partial y$, threshold $k=1.5$.	194
Figure 6.3.79. Relative amplitudes of the events associated with vorticity conditioned on positive $\partial\omega_x/\partial y$, threshold $k=1.5$.	194
Figure 6.3.80. Relative amplitudes of the events associated with velocity conditioned on positive $\partial\omega_x/\partial y$, threshold $k=1.5$.	195
Figure 6.3.81. Relative amplitudes of the events associated with vorticity flux / pressure conditioned on negative $\partial\omega_x/\partial y$, threshold $k=-2$.	196
Figure 6.3.82. Relative amplitudes of the events associated with vorticity conditioned on negative $\partial\omega_x/\partial y$, threshold $k=-2$.	196
Figure 6.3.83. Relative amplitudes of the events associated with velocity conditioned on negative $\partial\omega_x/\partial y$, threshold $k=-2$.	197
Figure 6.3.84. Relative amplitudes of the events associated with vorticity flux / pressure conditioned on negative $\partial\omega_x/\partial y$, threshold $k=-1.5$.	198

- Figure 6.3.85. Relative amplitudes of the events associated with vorticity conditioned
on negative $\partial\omega_x/\partial y$, threshold $k=-1.5$ 198
- Figure 6.3.86. Relative amplitudes of the events associated with velocity conditioned
on negative $\partial\omega_x/\partial y$, threshold $k=-1.5$ 199
- Figure 6.3.87. Relative amplitudes of the events associated with vorticity flux /
pressure conditioned on positive $\partial\omega_z/\partial y$, threshold $k=2$ 200
- Figure 6.3.88. Relative amplitudes of the events associated with vorticity conditioned
on positive $\partial\omega_z/\partial y$, threshold $k=2$ 200
- Figure 6.3.89. Relative amplitudes of the events associated with velocity conditioned
on positive $\partial\omega_z/\partial y$, threshold $k=2$ 201
- Figure 6.3.90. Relative amplitudes of the events associated with vorticity flux /
pressure conditioned on positive $\partial\omega_z/\partial y$, threshold $k=1.5$ 202
- Figure 6.3.91. Relative amplitudes of the events associated with vorticity conditioned
on positive $\partial\omega_z/\partial y$, threshold $k=1.5$ 202
- Figure 6.3.92. Relative amplitudes of the events associated with velocity conditioned
on positive $\partial\omega_z/\partial y$, threshold $k=1.5$ 203
- Figure 6.3.93. Relative amplitudes of the events associated with vorticity flux /
pressure conditioned on negative $\partial\omega_z/\partial y$, threshold $k=-2$ 204
- Figure 6.3.94. Relative amplitudes of the events associated with vorticity conditioned
on negative $\partial\omega_z/\partial y$, threshold $k=-2$ 204
- Figure 6.3.95. Relative amplitudes of the events associated with velocity conditioned
on negative $\partial\omega_z/\partial y$, threshold $k=-2$ 205

Figure 6.3.96. Relative amplitudes of the events associated with vorticity flux / pressure conditioned on negative $\partial\omega_z/\partial y$, threshold $k=-1.5$.	206
Figure 6.3.97. Relative amplitudes of the events associated with vorticity conditioned on negative $\partial\omega_z/\partial y$, threshold $k=-1.5$.	206
Figure 6.3.98. Relative amplitudes of the events associated with velocity conditioned on negative $\partial\omega_z/\partial y$, threshold $k=-1.5$.	207
Figure 6.4.1 Imprint of delta wing surface flow for 20 degree angle of attack.	208
Figure 6.4.2 Imprint of delta wing surface flow for 40 degree angle of attack.	208
Figure 6.4.3 Filtered snap-shot of lateral laser sheet cross section, $\alpha = 10^\circ$ and $U_\infty = 3$ m/s	209
Figure 6.4.4 Filtered snap-shot of lateral laser sheet cross section, $\alpha = 15^\circ$ and $U_\infty = 3$ m/s	210
Figure 6.4.5 Filtered snap-shot of lateral laser sheet cross section, $\alpha = 5^\circ$ and $U_\infty = 3$ m/s	211
Figure 6.4.6 Filtered snap-shot of lateral laser sheet cross section, $\alpha = 15^\circ$ and $U_\infty = 3$ m/s (Inverted)	212
Figure 6.4.7 Filtered snap-shot of lateral laser sheet cross section at streamwise distance of half the chord, $\alpha = 15^\circ$ and $U_\infty = 3$ m/s....	213
Figure 6.4.8 Filtered frame of lateral laser sheet cross section, $\alpha = 5^\circ$ and $U_\infty = 3$ m/s	214
Figure 6.4.9 Filtered frame of longitudinal laser sheet cross section, $\alpha = 5^\circ$ and $U_\infty = 3$ m/s	215
Figure 6.4.11. Contours of constant mean axial vorticity in a cross-flow plane.	216

Figure 6.4.12.Iso-contours of mean axial velocity normalized by the freestream velocity.	216
Figure 6.4.13.Iso-contours of mean normal velocity normalized by the freestream velocity.	217
Figure 6.4.14.Iso-contours of mean spanwise velocity normalized by the freestream velocity.	217
Figure 6.4.15.Velocity vector plot in cross-flow plane.	218
Figure 6.4.16.Iso-contours of rms axial velocity.	219
Figure 6.4.17.Iso-contours of rms normal velocity.	219
Figure 6.4.18.Iso-contours of rms spanwise velocity.	220
Figure 6.4.19.Iso-contours of turbulent kinetic energy.	220
Figure 6.4.20.Iso-contours of normalized enstrophy.	221
Figure 6.4.21.3-d spline fitted surface plot of rms axial velocity.	222
Figure 6.4.22.3-d spline fitted surface plot of rms normal velocity.	223
Figure 6.4.23.3-d spline fitted surface plot of rms spanwise velocity.	223
Figure 6.4.24.3-d spline fitted surface plot of kinetic energy.	224
Figure 6.4.25.3-d spline fitted surface plot of rms of axial vorticity scaled by the semispan s and freestream velocity U .	224
Figure 6.4.26.3-d spline fitted surface plot of rms of normal vorticity scaled by the semispan s and freestream velocity U .	225
Figure 6.4.27.3-d spline fitted surface plot of rms of spanwise vorticity scaled by the semispan s and freestream velocity U .	225
Figure 6.4.28.3-d spline fitted surface plot of normalized enstrophy.	226

Figure 6.4.29. A sketch of the structure of vortex flow field deduced from the principal mean axial streamwise vorticity. 227

1. INTRODUCTION

1.1. Vorticity and its significance:

In fluid dynamics physical processes are described mathematically by differential equations either independent or coupled, representing conservation laws of mass, momentum and energy. Many properties are derived from these relations which mainly contain physically measurable quantities like pressure, temperature, velocity etc. One of the most important derived properties clearly is vorticity ω which is defined as the curl of the velocity vector V , thus

$$\vec{\omega} = \text{curl } \vec{V} \quad (1.1)$$

This relation yields following three components of the vorticity in Cartesian coordinates x, y, z corresponding to velocity components u, v, w respectively :

$$\omega_x = \left[\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right], \quad \omega_y = \left[\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right] \quad \text{and} \quad \omega_z = \left[\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right] \quad (1.2)$$

It can be shown that for solid body rotation the vorticity is

$$\vec{\omega} = \text{curl}(\vec{\Omega} \times \vec{r}) = 2\vec{\Omega} \quad (1.3)$$

where Ω is angular velocity. Since Ω does not depend on r , neither does vorticity ω and therefore it is constant in space. Thus, both, angular velocity and vorticity are constant for solid body rotation. It is however incorrect to equate vorticity with angular velocity of a fluid element assuming solid body rotation since deformation of the element also takes place in fluid flow as a result of viscosity.

By applying curl operator on the Navier-Stokes Equations, the dynamical

equation, also called the "vorticity transport equation" representing the above mentioned conservation feature in incompressible fluid flow, can be written as:

$$\frac{D\vec{\omega}}{Dt} = \vec{\omega} \cdot \nabla \vec{V} + \nu \nabla^2 \vec{\omega} \quad (1.4)$$

with the solenoidal condition

$$\nabla \cdot \vec{\omega} \equiv 0 \quad (1.5)$$

The first term on the right-hand side represents the action of velocity variations on vorticity of a fluid element (stretching/compression) while the last term as the transport of vorticity by viscous diffusion down a vorticity gradient analogous to momentum diffusion down a momentum gradient. Lighthill (1963) describes the physical meaning of all these quantities constituting the transport equation and finds its similarity to heat convection and conduction. A more recent discussion can be found in Panton(1984). The convection of vorticity has the characteristic that it is preserved on a particle path which implies that the vorticity can only be transferred to the neighboring fluid particle by diffusion i.e. by the effect of viscosity. The diffusion together with the convection results in the spread/decay of vorticity and thus plays vital role in the development of vortical flows.

Unlike Navier-Stokes Equation for momentum conservation, the pressure term does not appear explicitly in the vorticity transport equation and therefore enables simplification in the computation and interpretation of the theoretical models of more "complex" flows. Despite this fact however, it is important to note that pressure at the boundaries plays significant role as the vorticity is generated only at the boundaries of a fluid under the assumption that the fluid is homogeneous, barotropic and only

conservative forces are included. The concept of the "vorticity flux", which is the rate at which vorticity is produced at the boundary was first introduced by Lighthill (1963) in describing the significance of solid boundaries as distributed sources or sinks of vorticity. He defined the term for a two dimensional flow, analogous to the law of heat conduction as $-\nu \frac{\partial \omega}{\partial y}$ where ν is kinematic viscosity. Panton (1984) defines it by the following expression

$$\overline{\sigma}_i = -\nu \hat{n} \cdot (\nabla \overline{\omega}) \quad (1.6)$$

where $\hat{n}$ is unit vector normal to the surface and pointing away toward the fluid, and ν is kinematic viscosity which can now be applied to 3-dimensional flows. Lyman(1990) looked more carefully at the analogy to Fourier's law of heat conduction and proposed another definition of vorticity flux as

$$-\nu \hat{n} \times (\nabla \times \overline{\omega}) \quad (1.7)$$

This "vorticity flux" if calculated at a solid wall beneath a flow indicates the amount of vorticity entering into the flow, which otherwise cannot be obtained by considering the vorticity alone at the wall.

The momentum equation evaluated at the wall where the velocity vector is identically zero because of no slip conditions yields:

$$\frac{\partial p}{\partial x_i} = -\mu \varepsilon_{ijk} \frac{\partial \omega_k}{\partial x_j} \quad (1.8)$$

and

$$\frac{\partial p}{\partial x_i} = \rho \frac{\partial \tau_{ij}}{\partial x_j} \quad (1.9)$$

where τ_{ij} is the shear stress, p is the pressure and ρ is the density of fluid. Equation 1.7 indicates that the wall pressure gradient is generating a flux of vorticity into the fluid and shows that there is a strong coupling between pressure and vorticity. This relation is not apparent in the vorticity transport equation since the latter does not include any pressure term as mentioned earlier.

In a coordinate system on the wall, the vorticity components at the wall $y=0$ become

$$\omega_x = \frac{\partial w}{\partial y} \Big|_{y=0} \quad (1.10)$$

$$\omega_y = 0 \quad (1.11)$$

$$\omega_z = -\frac{\partial u}{\partial y} \Big|_{y=0} \quad (1.12)$$

All velocity gradients on the wall and along any direction parallel to the wall are zero.

Therefore equation 1.7 yields:

$$\frac{\partial p}{\partial x} = -\mu \frac{\partial \omega_z}{\partial y} \quad (1.13)$$

$$\frac{\partial p}{\partial z} = \mu \frac{\partial \omega_x}{\partial y} \quad (1.14)$$

Thus the vorticity flux vector parallel to the wall, σ_w written as

$$\vec{\sigma}_w = v \left[\left(\frac{\partial \omega_x}{\partial y} \right)_w \vec{i} + \left(\frac{\partial \omega_z}{\partial y} \right)_w \vec{k} \right] \quad (1.15)$$

where $\vec{i}$, $\vec{j}$ and $\vec{k}$ are unit vectors in x , y and z directions, can be evaluated by measuring instantaneously the pressure gradients.

Although most of the experimental research conducted so far aimed mainly at gathering information on velocity field in different types of flows, which enhanced our understanding of the underlying physics in these flows, the velocity field however is not quite well suited for defining and identifying organized coherent structures in time dependent vortical flows because of the fact that the streamlines and pathlines are completely different in two different inertial frames of reference. Vorticity field on the other hand, unlike velocity field, is invariant with regard to translational changes in the inertial frame (Galilean invariant) and therefore well suited for describing physical phenomena in vortical flows. Note however that vorticity is no longer invariant when a rotational frame of reference is required for flow description.

We can certainly understand the physics of flows further if ample information is available on the vorticity field. This need to obtain experimental data of temporally and spatially resolved instantaneous vorticity and thus help increase our understanding of turbulent flows motivated the present research project.

The objectives of the present research project therefore are:

- 1) To design and develop a new vorticity probe which is economical, reliable and based on techniques well established in the field.
- 2) Perform time-dependent measurements of velocity and vorticity vector field using this probe in the turbulent boundary layer and compare major statistical

properties including those of vorticity with the existing data and further understand the dynamic processes associated with turbulence in the flow near the wall region by applying conditional sampling techniques to the acquired data.

3) Perform similar measurements by using the probe in the vortex flow over delta wing to get first ever simultaneous measurements of the time dependent velocity and vorticity field.

4) Obtain estimates of the vorticity flux at the walls beneath a flow by time-dependent measurement of pressure gradients by special pressure module for the first time.

It is hoped that this modest attempt would provide more information on the dynamics of the near wall vortical structures and may help increase our understanding of the physical characteristics of the vortex flow over delta wing.

1.2. Present understanding of the turbulent boundary layer flows:

The majority of fluid flows with practical applications are flows adjacent to a solid boundary and are inevitably turbulent. Boundary layer flows being of vital importance, particularly in the field of aerodynamics, were and still are at the center of many scientific investigations by fluid dynamicists with primary objective of studying the complex processes of turbulence production, mixing and dissipation. Figure 1.1 shows a simplified sketch of a fully developed, zero pressure gradient turbulent boundary layer in which low free-stream turbulence and two dimensional mean flow are assumed. Enormous amount of research work, laboratory as well as simulations in "numerical wind tunnels" can be found in the literature for such turbulent boundary layer flows although

large proportion is found to be concentrated on the canonical flat plate boundary layer and small proportion on two dimensional channel flows. Many structural features uncovered through experimental evidence are not only confirmed by the numerical simulations but additional information about these coherent structures that is difficult to measure in the laboratories, e.g. low pressure regions in the cores of vortices, has been added by this effort. Kline and Robinson (1988), Robinson, Kline and Spalart (1988) and Robinson (1991) in their comprehensive survey of various research efforts in the investigation of turbulent boundary layer flows have classified various quasi-coherent structures into eight major categories which will be revisited briefly below.

Low speed streaks in the viscous sublayer ($0 < y^+ \leq 10$):

These are the regions where streamwise velocity is less than the local mean value. Smith and Metzler (1983), Elder (1960) and Kline and Meyer (1961) have shown that these regions have a mean spanwise dimension of $100 \nu/u_\tau$ and are visible up to $y^+ \approx 40$. They have also concluded that the low speed streaks spacing is not Reynolds number dependent for a moderately high range. Schraub and Kline (1965) reported that this spanwise spacing is same for adverse or favorable pressure gradients. The reasons however for such a spacing are not yet known. The streaks by themselves do not imply vortex structures but are just regions of low speed motion having a streamwise velocity of about half the local mean speed and are observed to extend long axial distances.

Ejections of low speed fluid outward from the wall:

The low speed fluid as it travels downstream is found to move away from the wall ("lifting") and then suddenly found to undergo rapid oscillations when the region starts to breakdown into motions with much smaller scales. The works of Kline and Runstadler (1959), Kline *et al.* (1967), Willmarth and Lu (1972), Corino and Brodkey (1969), Smith and Metzler (1983) and Tiederman *et al.* (1985) demonstrate such lifting and ejections of low speed fluid away from the wall. The combination of all events leading up to and including the breakup is commonly referred in the literature as "bursting". The results of probability distribution of these ejection motions by Runstadler *et al.* (1963) suggest the possibility of interaction between fluid in the low speed region and that in the log and wake regions for $Re_\theta = 1400$. Robinson and Kline (1988) suggest that low speed streaks are mainly in the sublayer and are passive in terms of their role in the turbulence production but ejected streaks since observed in the region $10 < y^+ < 40$ are of significant importance in the turbulence production process.

Rashidi and Banerjee (1990) in their experiments in the turbulent open channel flows with sheared gas liquid interface, found that the effect of boundary conditions (slip or free slip) is much less than the rate of shear in the formation of the low-speed streaks. They also observed interaction between the ejections at the wall and the free surface. Lee *et al.* (1987) have shown the significance of rate of shear on the streaks. The numerical simulations of channel flow by Lam and Banerjee (1992) do show formation of streaks near a free slip surface under shear.

Sweeps of high speed fluid toward the wall:

Fluid from the regions where the streamwise velocity is higher than the local mean speed is suggested to sweep towards the wall in order to fill the voids generated by the low speed ejections. The existence of these high speed sweeps however are not clearly verified but using the continuity principle Corino and Brodkey (1969), Grass (1971) and others have hypothesized the events. Further, Willmarth and Lu (1972), Brodkey *et al.* (1974) and Willmarth and Bogar (1977) have concluded that these sweeps are important in the Reynolds shear stress production near the wall.

Vortex structures of various forms:

The majority of the investigations on the boundary layer structure is focussed on identifying and examining vortex structures and their relationship with other coherent motions. Several valid reasons are cited by Robinson (1991) for such an effort: that the vortices are "carriers" of mass and momentum across the cross stream velocity gradient except those with wall normal orientation, that the vortices tend to have a longer life span apart from being recognized as the most coherent and most basic among all complex three dimensional turbulent motions. Most importantly low pressure cores of strong vortices can generate pressure waves and induce pressure gradients in the neighboring regions.

Several different shapes have been associated with the vortices observed. Theodoresen (1952) called these as "horseshoe-shaped" and Runstadler *et al.* (1963) suggested these same vortices to be "arch like" while Head and Bandyopadhyay (1981) saw these as hair pin like structures. Chu and Falco (1986) found the shape of these

structures to be "ring like" and formed as a consequence of vorticity redistribution. Regardless of different terminology used to describe these structures, their existence is clearly demonstrated using two point correlations of the hot-wire data by Blackwelder and Eckelmann (1979) and employing novel statistical tool of proper orthogonal decomposition (POD) by Bakewell and Lumley (1967). On the other hand, laboratory experiments of Smith and Lu (1989), Foss and Wallace (1989) demonstrated several characteristics of the vortical structures.

Internal near-wall shear layers:

These are the regions where the local shear rate is much higher than the local mean. Blackwelder and Haritonidis (1983), Alfredsson and Johansson (1984), Jimenez *et al.* (1988) among others have observed these internal shear layers through their measurements and Tiederman (1986, 1987) found these layers to be upstream of a vortex structure, suggesting the formation of vortices by the possible roll up of the shear layers. Although it is difficult to differentiate between sharp small scale shear layers and large jumps in the axial velocity which are entirely different category of coherent motions, Blackwelder and Kaplan (1976) using VITA detection techniques characterized the near-wall shear layers.

Near wall "Pockets" :

Falco (1980) and Smith (1983) reported observing regions where the marked fluid particles were totally absent. These pockets seen in the inner region are found to have far less significance in the dynamics of the over all flow.

Large, δ scale discontinuities in the outer region:

These are large scale shear layers found to exist throughout the boundary layer as reported by Eckelmann *et al.* (1977) and Brodkey *et al.* (1984). Since these shear layers are inclined at 12° to 25° to the wall they are referred to as "backs" by some and "fronts" by others. Brown and Thomas (1977) ascribe importance to these discontinuities in the turbulence generation due to high correlation found between turbulence producing events and the passage of these "backs". They also illustrate a high vorticity value, as is to be expected in these shear layers using conditional velocity data.

Large scale motions in the outer region:

Large scale motions at the interface between the turbulent fluid inside the boundary layer and the outer potential flow were reported by Kovasznay *et al.* (1970). Corsin and Kistler (1954) observed a sharp interface in the outer region which is now considered as instantaneous edge of the boundary layer.

1.3. Present understanding of flow over a delta wing:

When a flow approaches a delta wing pitched at certain angle of attack, two spiralling vortices are formed as the flow separates into a pair of shear layers at the leading edges. These vortices increase in size as they are convected downstream by the streamwise velocity of the outer flow. The schematic of the flow field showing various regions with unique features, as used by Anderson (1991) in discussing the aerodynamics of the delta wing, is shown in figure 1.2. The flow from high pressure region, as it negotiates the sharp leading edge, separates and curls into a primary vortex which

reattaches along the primary attachment line on the low pressure surface before further separating to form a secondary vortex which in turn reattaches along a secondary attachment line. There thus appears to be a number of smaller and smaller vortices inboard of each leading edge which either decay by dissipation or are swept away downstream by the main flow. The primary vortices formed are strong and stable having cores with low static pressure while the most of the central surface of the wing having fairly constant pressure as pointed out by the surface pressure measurements of Fink and Taylor (1967). The streamlines on the upper surface form complex curvature producing suction which suggests that the lifting of the delta wing is mainly governed by the strong vortical flow. Because of the enhanced lift stalling of the delta wing is delayed for larger angles of attack which are beyond stall for conventional wing forms. The dimensions of the primary leading edge vortices are of the order of half the wing span while those of secondary vortices scale with the thickness of the separating shear layers. The normal force was first resolved by Polhamus (1966) into two components, potential component (based on the potential flow of lifting surfaces) and vortex component (recognized as Leading Edge Suction Analogy LESA). LESA is used to successfully predict the lift force until a critical value for the angle of attack is reached. The inability to estimate the normal force beyond this value is solely due to a sudden and complex transformation in the vortices, a phenomenon well known as "bursting" or "vortex breakdown".

The potential and vortical components of the normal force and its chordwise distribution are experimentally obtained by Er-El and Yitzhak (1988) through surface pressure measurements and invoking the linearized potential flow theory for sweep angles of 75° and 60° . They found that the results for low aspect ratio and 0 to 20° angle of

incidence agree with those predicted by LESA while greatly differ for high aspect ratio wings. Zohar and Er-El (1987) with similar experimental study showed that suction increases with angle of attack in the absence of breakdown while opposite effect was observed for wings with high aspect ratio. Rizzi and Purcell (1987) simulated separation and roll up of leading edge transonic flow for small angle of attack by using Euler equations.

The stability of the leading edge vortices was tested by Shih, Lee and Ho (1987) by imposing unsteady large perturbations in the free-stream flow. Their investigations show the flow to be more sensitive to the disturbance at the apex than any other location along the leading edge based on their observation of changes in the vorticity generation along the leading edge being transmitted in what they call one turn over time which is maximum at the trailing edge and decreases towards the apex. Their results using laser induced fluorescence also show that the lift generated follow the variation of the time derivative of the free-stream velocity. Ayoub and McLachlan (1987) from flow visualization studies have identified the following five flow regimes of delta wing flows.

a) Regimes of stable pair of leading edge vortices for angle of attack in the range 25° to 35° where vortices are in stable equilibrium with relatively high axial velocity with continuous convection of vorticity in the downstream direction, b) regimes of independent vortex breakdowns in the range 35° to 40° brought about essentially by the increase in the pressure at the trailing edge and increase in swirl components of velocity. Axial symmetry is still not affected however, c) regimes of interaction between vortex asymmetry and breakdown in the range 40° to 55° due to two shear layers competing for space on the suction side, d) regimes of apex vortex aligned with the main stream

observed in the range 60° to 70° as a consequence of inability of shear layers to roll up independently close to the surface and e) regimes dominated by near wake bubble with relatively small scale vortices due to instability of its boundaries observed in the range 80° to 90° .

Visualization measurements to obtain vortex core position, shape, strength and magnitude of the local velocity by Lowson (1990) at low Reynolds numbers from 3000 to 30,000 are surprisingly consistent with the theoretical models established for high Reynolds number flows.

Mehta and Cantwell (1987) performed experiments to investigate a single vortex generated by half delta wing placed at small angle of attack using cross hot-wire probe. Their streamwise vorticity contour results suggest that the vortex reaches equilibrium state at streamwise distance of about one and half times the span.

Payne (1987) conducted extensive study on a family of delta wings with sweep angles ranging from 70° to 85° and at angles of attack from 10° to 40° , in the structure of leading edge vortices especially on the factors contributing to their breakdown. He demonstrated many features of these vortices by using five hole probe combined with laser Doppler anemometry and obtained mean and r.m.s. velocity measurements of axial and swirl components at the breakdown locations along the chord and in the wake region. He also estimated the relative length scales in the primary vortex (figure 1.3) based on the previous investigations by Erickson (1980) and Maskel (1962), who defined the leading edge vortex into three regions viz. shear layer, rotational core and viscous subcore distinguished by the magnitude of the spacing between successive turns of the spiral (d) and diffusion scale $\left(\frac{v x}{U_\infty}\right)^{1/2}$. Squire(1961) from his oil flow visualization

experiments suggested that streamwise vortices may be embedded in the separated vortex sheet (figure 1.4) and attributed the phenomenon to instability in this type of strongly three dimensional flows. Erickson(1980) and Maskel (1962) stated and explained why the strength and the location of the bound vortex to be insensitive to the changes in the Reynolds number.

The breakdown phenomena is associated with sudden expansion in the size of the vortices, sharp increase in the dynamic pressure and marked decrease in the axial velocity. The location on the upper surface where bursting occurs depends on major factors like angle of attack, sweep angle of the leading edges, aspect ratio, side slip velocity among others. In order to investigate the basic spatio-temporal behavior of the vortices, in the absence of breakdown, it was essential to design an experiment where additional phenomena like vortex breakdown are not likely to be present. The results of Polhamus (1971), shown in figure 1.5 and Skow and Titiriga (1978), shown in figure 1.6, and those of Gad-el-Hak and Blackwelder (1987) revealed that for a sweep angle of 45° no breakdown would occur on the wing surface. For the present study therefore a 45° sweep angle geometry for the delta wing model was chosen.

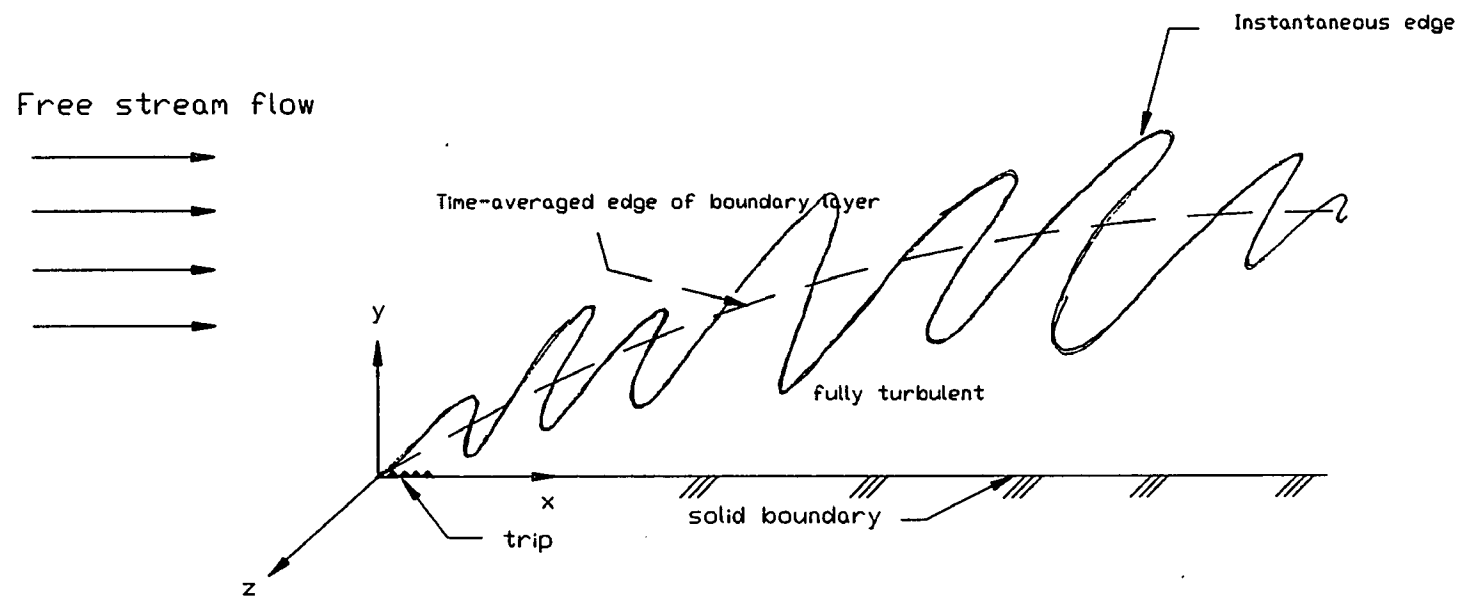


Figure 1.1. Flow pattern in the turbulent boundary layer.

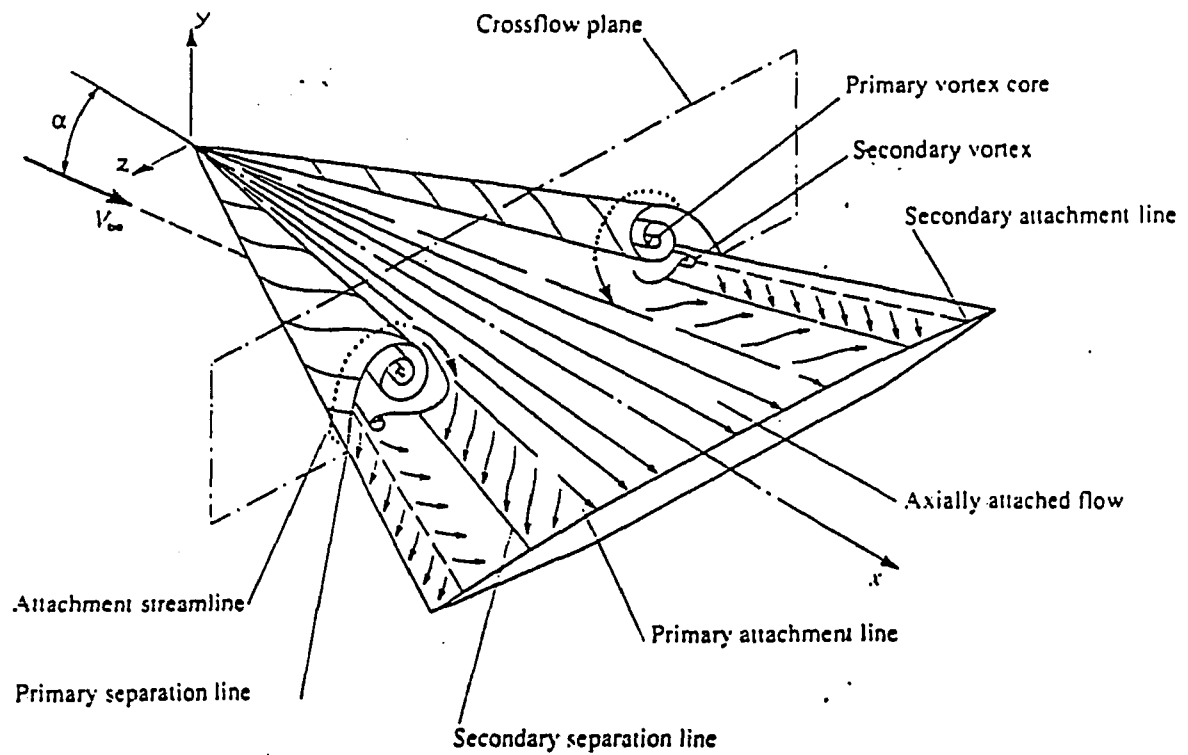


Figure 1.2. Flow field over a pitched delta wing.

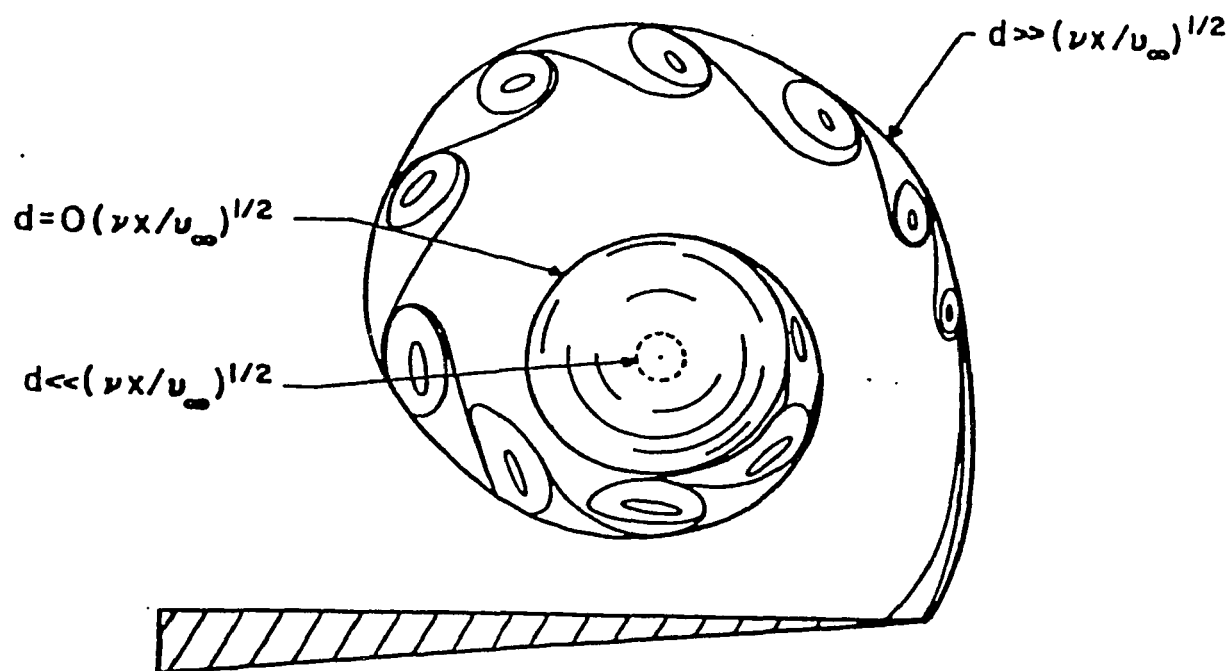


Figure 1.3. Leading edge vortex length scales. (Payne, 1987)

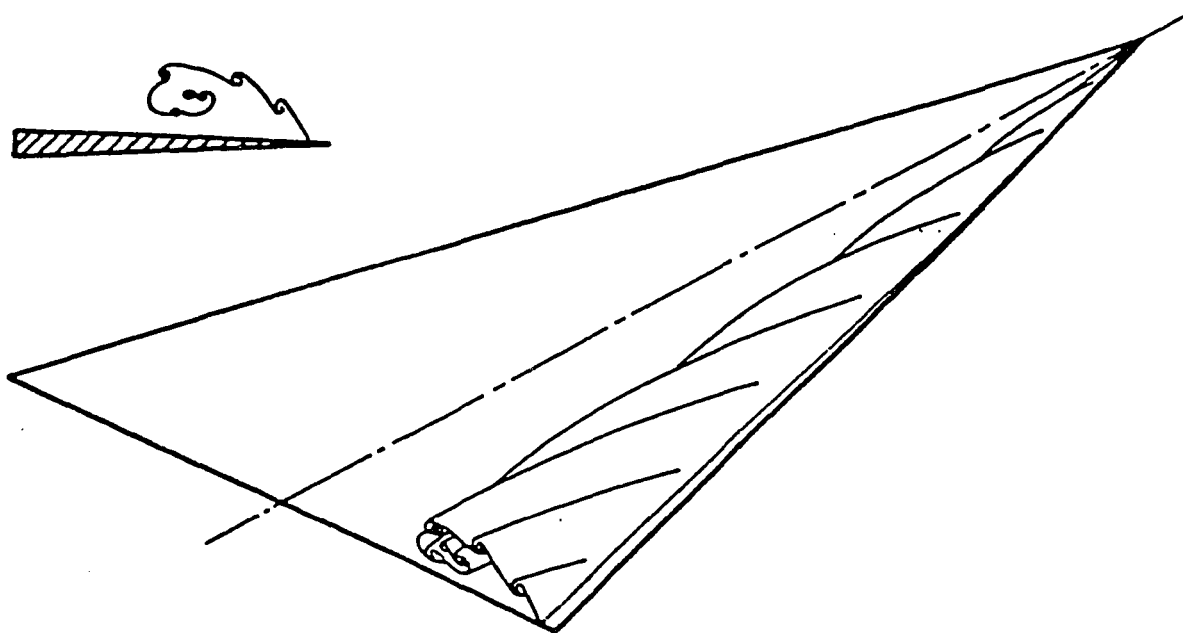


Figure 1.4. Schematic of flow in the separated shear layer over a delta wing.

(Squire, 1961)

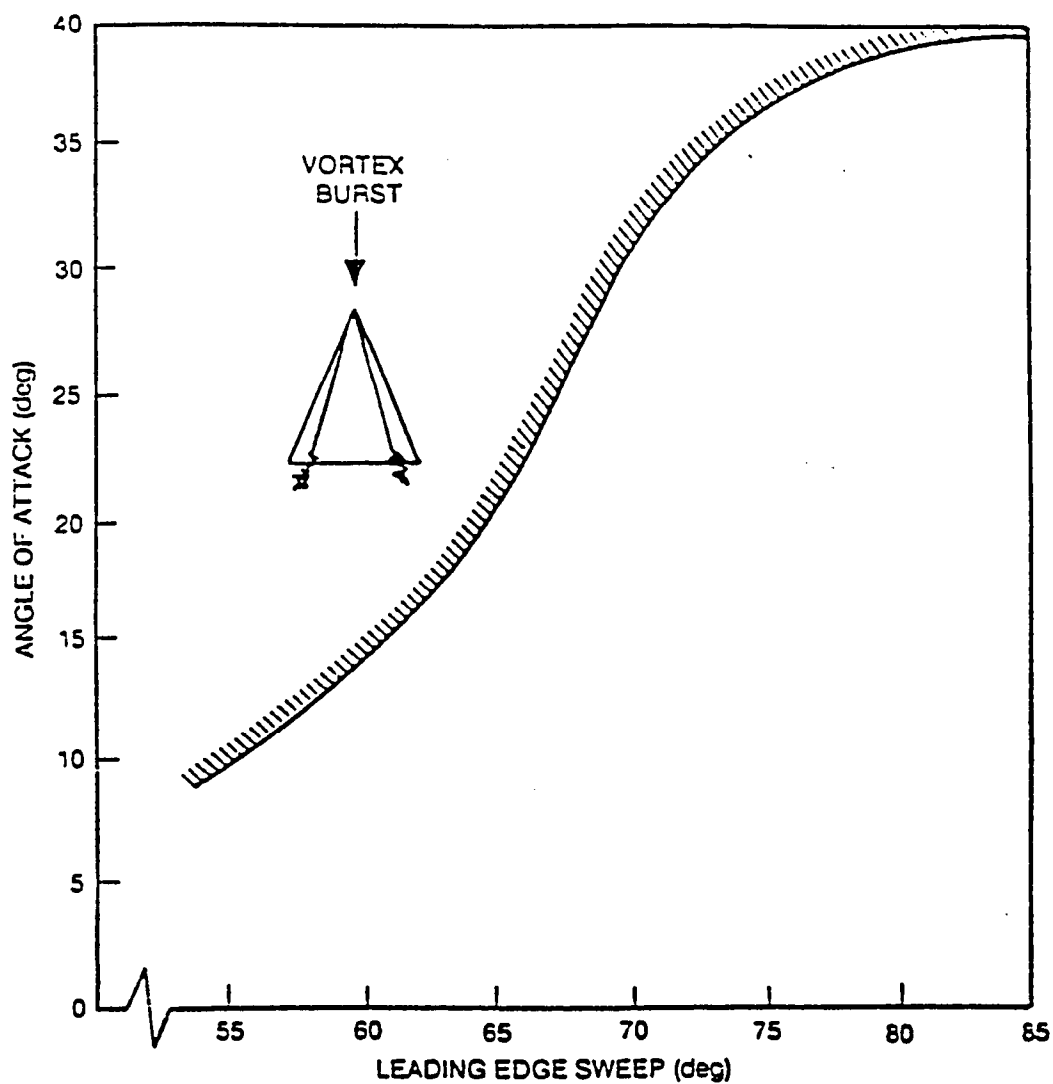


Figure 1.5. Angle of attack at vortex breakdown as a function of sweep angle. (Polhamus, (1971))

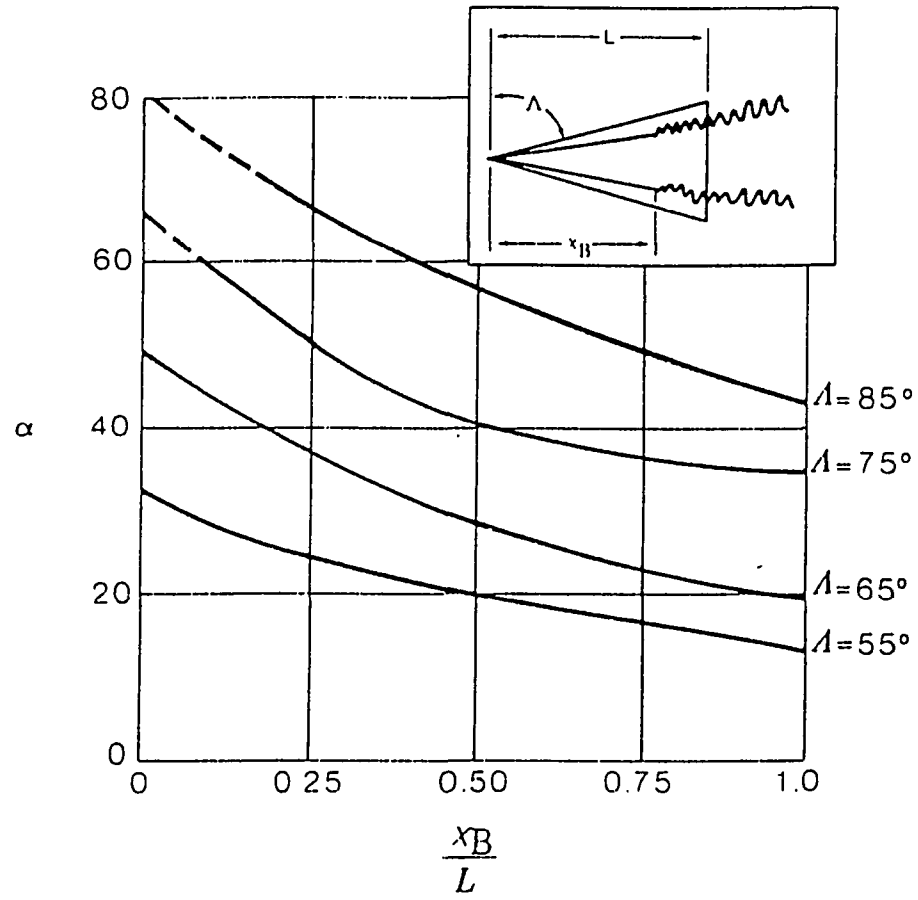


Figure 1.6. Vortex breakdown location as a function of angle of attack. (Skow and Titiriga, (1978))

2. EXPERIMENTAL ARRANGEMENT, INSTRUMENTATION AND TECHNIQUES

2.1. Wind tunnel:

All the experimental investigations in this research have been carried out in the wind tunnel of Mechanical Engineering Department, CCNY (figure 2.1). It is open ended suction type, with 4ft x 4ft cross section and has 28 ft. long working area. It is powered by a 20hp, 460V, 3 phase frequency controlled AC motor, driving axial fan with 7 blades rotating at a maximum rpm of 1750 delivering 32000 cubic ft/min. capacity providing a maximum speed of 11.5 m/s in the working section. The flow velocity can be controlled by varying frequency from 0 to 100 % in 5% increments. The motor and fan assembly which is housed in a sound absorbing diffuser allowing low noise operation of the facility and low levels of acoustical noise transmitted in the working section. It is also mounted on a frame which rests on eight springs to minimize vibration and isolates the motor and fan assembly from the working section. Three sides, top, bottom and one wall of the working section are of 1 inch plywood while the other wall has four plexiglass windows also of 1 inch thickness for observation. The inside of the working section is painted black to aid in flow visualization studies. The inlet of the contraction section is fitted with honeycomb followed by three layers of fine steel screen to obtain uniform flow of turbulence intensity less than 0.1 % for the maximum speed in the working section. This contraction section is 12 ft x 12 ft at one end narrowing down to 4ft x 4ft resulting in 9:1 contraction ratio.

2.2 Flow Models

2.2.1 Boundary Layer:

The boundary layer under investigation is developed on the floor of the wind tunnel and transition to a stable turbulent flow is triggered by a 1 inch wide strip of medium grit sand paper which is glued on the floor across the entire span upstream at the entrance of the working section to obtain fully developed turbulent boundary layer at the measuring location 15 ft. downstream for the test velocity of 3 m/s. The spanwise uniformity of the flow was checked by Preston tube traverse 12 inches on either side of the measuring location. The friction coefficient c_f , computed from these tests is plotted as a function of free-stream velocity and is shown in figure 2.2a, which also agreed with the values obtained from Clauser charts. The coefficient of skin friction c_f , a crucial parameter was evaluated at several Reynolds numbers in the old working section and a plot of these values against the Reynolds number based on the momentum thickness θ is shown in figure 2.2b. On this plot the data of Coles (1962), Schewe (1983) and that of Spalart (1988) are also shown for comparison. The present values of c_f in the worst case, are about 4% higher than that from the analysis by Coles of Weighard's data. The flow in the new working section behaves better as indicated by the close agreement of c_f with Coles' results. The flow in both the working sections of the wind tunnel therefore was comparable with that in other facilities. The mean velocity profile as measured at the center of the tunnel width by the Pitot tube is shown in figure 2.3 which indicated a well developed turbulent boundary layer flow for the investigations.

The final experiment was carried out in a similar boundary layer flow but further downstream from the above at a distance of approximately 22 ft. from the leading edge

in the new working section. The flow was tripped to obtain stable transition to turbulence. The flow qualifying tests by the pitot tube traverse at the new location were satisfactory and the value of skin-friction coefficient obtained by the Clauser chart at the test Reynolds number compared well with those obtained by other experimentalists as mentioned above.

2.2.2. Delta Wing:

The 45 degree sweep delta wing model is fabricated from 9.5 mm (3/8") aluminum stock (ASTM-A36) and has a root chord of 305 mm (12") and span 610 mm (24") thus giving an aspect ratio of 4:1. The leading edges were bevelled at 30° while the trailing edge was square (figure 2.4). Two grooves from apex to trailing edge at angle of approximately 27° on either side of the center-line, were machined and two 3.2 mm (1/8") diameter copper tubes were embedded for feeding the smoke at the apex for flow visualization studies. The suction surface of the wing was painted black. Two holes of 44.45 mm (1-3/4") and 50.8 (2") mm diameter were drilled and replaced with two round aluminum plates of the same thickness for inserting high frequency pressure transducers. Five holes for mounting the transducers were then drilled along the diameter of both the plates. The plates could be rotated in place allowing the pressure transducers to be located at different spanwise position with ease. The model is suspended in the center of the working section of the wind tunnel with the help of supporting mechanism which consisted of two aluminum struts hinged on the bracket fitted on the top of the wind tunnel. A cross member across the two struts made the model stay rigid in the flow and also allowed for a lead screw to be mounted inside in such a way to enable the wing

to be pitched at any desired angle of attack between 0° and 45° . The model was installed inverted in the tunnel as shown in the figure 2.5. The blockage effect of the model to the flow in the wind tunnel was less than 5%.

2.3 Vorticity Probe Design and Construction:

The probe is made up of a set of three triple hot-wire sensors with each sensor of the triple wire being mutually orthogonal to the other, thus oriented at approximately 54.7 degrees to the mean flow. The centers of the three triple hot-wires formed three vertices of an equilateral triangle of side approximately 2.46 mm. The sensor length is 0.8 mm and the distance between the centers of any two sensors is about 1.23 mm. The probe had to be fabricated locally since no such configuration of triple wires is available commercially. A 1.23 mm diameter 50 mm long cylindrical rod of ceramic with two holes separated by approximately 0.8 mm is used to make one component of the 9 wire probe. Two 0.254 mm diameter, 100 mm long stainless steel prongs are first sanded down to approximately 0.24 mm then tapered uniformly at one end to a point by electrolytic reduction in a solution of aqua regia. The prongs are then inserted in the ceramic rod and glued at one end while the other end extending out approximately 10 mm and by using a specially machined jig two tips are made simultaneously flat for mounting the sensor at the required nominal angle of 54.7 degrees. This process is repeated for eight other components of the probe. A second jig is then made and used to manipulate and hold three ceramic components simultaneously in place. Using this jig the three components were positioned such that planes containing the prongs were at 120° to one another. The three components were then glued together to form the body

of a single mutually and nominally orthogonal triple sensor probe. Two other such units were then fabricated in the same way and using a third jig (similar to the second one) to assist in manipulation, all 3 units were held in place and then glued together to form the final geometry, a schematic of which is shown in figure 2.6 with relevant dimensions. The unit is then inserted and glued in a thin walled brass tube with the body extending out approximately 25.4 mm (1"). Miniature size gold connectors are then soldered to the rear end of prongs by using special flux and shielded wires are then soldered to these connectors. The brass tube is then placed inside a hollow aluminum cylindrical enclosure specially machined to form one smooth streamlined body of the probe. All 18 wires connecting the prongs are then soldered to a 25 pin mini female connector so that 25 pin mini male connector carrying 9 miniature, shielded, low noise BNC cables, could be plugged into it.

2.5 μm platinum plated tungsten sensors were then welded on each pair of prongs using a specially fabricated mounting/holding jacket and Dantec welding generator, micromanipulator model 55A12 and 55A13 respectively and a stereo microscope.

Two posterized photographs of this vorticity probe consisting of 3 Triple Orthogonal hot-Wires which will be referred to as 3TOW probe in the present work, are shown in figure 2.7.

2.4. Vorticity Flux Module:

For instantaneous four point pressure measurement on the delta wing surface, 4 high frequency/sensitivity ultra-miniature pressure transducers model XCS-062 supplied by Kulite Semiconductor Products Inc. each with a sensing diameter of 0.028 inch were

epoxied together to form a module as shown in figure 2.8. The separation distance between any two transducers was 1.6 mm. This module was then placed inside a bolt with one edge machined flat so that the bolt could be securely threaded in place in the boundary layer or inside the two aluminum plates which snug fit in the two openings in the delta wing. This module will henceforth be referred to as Kulite module for simplicity.

For boundary layer flow a similar module was fabricated using 4 ultra miniature pressure transducers with sensing diameter of 0.5 mm and 2 psi pressure range and having a resonant frequency of 100 Khz. This module will be referred to as Entran module. A study to compare the performance of the two vorticity flux modules in boundary layer flows has also been carried out. The results will be reported later.

2.5. Traversing Mechanism:

Traversing mechanism consisted of two units. One provided rectilinear motion along the three axis x-y-z while the other provided two independent rotations, one for pitch (rotation about z axis) and one for yaw (rotation about y axis). The unit is shown in figure 2.9. It consisted of two rails 0.2 m (78") long, mounted one each on two 15.24 cm wide, 5.08 cm high and 182.88 cm long (6" x 2" x 72") steel box beams . These beams were placed 60.96 cm (24") apart by two cross members bolted at either end forming the base. A flat aluminum plate 60.96 cm (24") long, 1.143 m (45") wide and 19.05 mm (3/4") thick, carrying 4 linear bearing blocks was then mounted on the above two railings. This provided translation in the x (streamwise) direction. On this flat plate another set of rails perpendicular to the bottom ones were mounted and carried another

rectangular aluminum flat plate 19.05 mm (3/4") thick, 60.96 cm (24") long and 38.1 cm (15") wide fitted with 4 adjustable linear bearing blocks. This arrangement provided translation in the z (spanwise) direction. For translation in the y direction (normal) Thompson unit model DSRA-8 was bolted on the second flat plate and an anti-backlash nut was fitted on the carriage. stainless steel lead screw of 5 mm pitch was then mounted between two thrust bearings. The cumulative lead error over the entire length of 0.914 m (36") was between 25 to 50 μm . The bottom end carried a miter gear which meshed with another miter gear fitted on the shaft of the stepper motor. The ratio of the two gears was 1:1 thus one rotation of the stepper motor driving shaft resulted in one rotation of the lead screw and subsequently 5mm of translation of the carriage riding on the rails of the Thompson unit. The stepper motor was fixed on an aluminum frame which was bolted to the flat plate. This frame also was fitted with a flat dial and a vernier for angular measurement of the partial rotation of the shaft. This mechanism required 72 degrees of stepper motor shaft rotation for every mm of vertical travel of the carriage.

The second unit is attached to the carriage of the first unit by an L shaped aluminum bracket. Second stepper motor is fitted on this bracket by four screws and aligning spacers and carried a sprocket gear on its shaft. A 1.2m (48") long stainless steel tube of 25.4mm (1") outside diameter was then held inside a ball bearing by two set screws to enable the tube to rotate freely. The ball bearing was press fitted inside a brass bushing so that the tube could be mounted vertically on the bracket. A ring gear was then fitted on a bushing and fixed at proper position on the tube to enable a steel impregnated nylon timing chain to pass over the gear and the sprocket gear on the stepper motor shaft. The timing chain provided no slip, positive drive for the mechanism.

A linear rotary bearing fitted in a 35.5cm (14") long aluminum arm was used as a second support for the tube. The arm was then clamped on the vertical frame of the Thompson unit. The steel tube now provided independent rotation in xz plane (yaw).

A solid steel rod of 9.52mm (3/8") diameter was then placed inside the 25.4mm (1") steel tube by two aluminum blocks, held on either end of the tube and each carried a ball bearing. A third stepper motor was bolted on a rectangular aluminum frame by four screws and spacing washers and the frame with the stepper motor was bolted to the cylindrical aluminum block at the bottom end of the tube. An adjustable sleeve coupling connected the shaft of the motor to the steel shaft which carried a double start right handed worm at its top end. A frame fabricated from 9.52mm (3/8") thick stock of aluminum was pivot positioned on a shaft inside a block fitted with two ball bearings. This shaft also carried a gear which meshed with the worm on the top end of the steel rod and provided worm and gear engagement. Thus rotary motion of the stepper motor shaft was transformed into oscillatory motion of the frame about the axis of the shaft. A 12.7mm (0.5") diameter, 762mm (30") long hollow steel tube of was fitted on one side of this frame and carried a mounting bracket for the probe. The rear end of the frame was fitted with an adjustable counter weight so that the frame could be balanced for the weight of the probe and the cable and damp any oscillations.

The rotational motion provided the angular motion in the x-y plane (pitch).

2.6. Instrumentation:

The hot-wire sensors of the vorticity probe were operated by 9 channel Constant Temperature Anemometers (CTA) model 56CO1/C17 manufactured by Dantec

Electronics Inc.

For the preliminary experiment in the boundary layer and in the investigation of the delta wing flow, two channel analog filters, model 7356 made by ITHACO, and model 3302 and 3323, manufactured by Krohn-hite were utilized to low pass filter the anemometer output voltage signals and minimize the electronic noise mainly from the frequency control unit of the wind tunnel fan. The filters also provided amplification of these signals by 20 dB before acquisition. Tests on both ITHACO and Krohn-hite filters for possible frequencies in the flows, showed negligible phase shift.

One multi-channel analog oscilloscope made by Tektronix and two dual channel digital scopes made by IWATSU were used to monitor all 9 hot-wire signals during the experiments.

MKS Baratron model 223B pressure transducer with full scale output of $\pm 5V$ for maximum pressure difference across its diaphragm of 12.7 mm ($\frac{1}{2}$ ") of water, was connected to a Pitot tube to measure mean axial velocity in the working section. This transducer had digital readout unit which supplied the necessary 15 volts DC power to the transducer. A miniature thermocouple was placed alongside with the pitot tube and was connected to a digital read out for monitoring ambient temperature.

All four pressure transducers of Kulite module were powered by a 9 volt battery instead of the rated 15 volts power supply. The transducers of Entran module required 5.4V dc power. This helped to reduce the electronic noise contamination of the signal. Four EG & G PARC low noise differential preamplifiers model 113 were needed to obtain single voltage output from differential output by each of the four transducers.

Data acquisition hardware used for the preliminary experiment in the boundary

layer and the investigation of the delta wing flow, consisted mainly of 12 bit (1 part in 4096) resolution high performance analog and digital interface board model DAS-20 manufactured by Metrabyte. This board has an a/d conversion rate of 100,000 samples per second. Three simultaneous sample and hold boards model SSH-4, each with 4 channel capacity also manufactured by Metrabyte were daisy-chained to the a/d board to allow simultaneous acquisition of 9 channels of data. The acquisition time was less than 10 μ S with under 40 nS aperture uncertainty between channel. Each sample and hold unit had 9 independently selectable input ranges which enabled to get flexible resolution of the signals. The data acquisition during velocity, yaw and pitch calibration stage of all the experiments was performed by a program written in BASIC language, while a company supplied software called STREAMER was used for instantaneous data acquisition. This software utilized the DMA capability to transfer data continuously at high speeds directly to a hard drive over long periods of time. However sampling rates upto only 60,000 were sustained as a result. The experimental setup in the form of a block diagram is shown in figure 2.10.

For the final experiment in the turbulent boundary layer, signals of nine hot-wires and three Entran pressure transducers were sampled **simultaneously** using the instrumentation setup, (figure 2.11) which consisted of two ADC units of eight channels capacity each with sample and hold circuitry on board with 16 bit resolution a/d converter and 100 kHz maximum sampling rate (model ADC488/8S) manufactured by IOtech Inc. The converter has acquisition time of 1.8 μ S with under 0.25 nS aperture uncertainty between the channels with memory expansion of 128 Kbytes provided maximum of 200 kbytes/second throughput to IEEE bus. Two units of low pass analog

filters again each with eight channels capacity and programmable control of cutoff frequency and input amplification, model Filter 488/8 made by IOtech Inc, were utilized.

The linear travel along x, y and z direction was achieved manually with the positioning uncertainty being 0.25 mm in measurement along x and z directions while it was much less in the y direction because of the stepper motor control.

Yaw and pitch rotations were computer-controlled by PC-Motion Interface board supplied by Rogers Lab model ESH-080, driver board model ESH 083, and power supply of 28V dc supplied by Cyber Research for 3 Vexta stepper motors, 4.2 amps 2 phase, model Ph296E4-2B manufactured by Oriental Motors. Basic and assembly language subroutines of the motion control hardware were modified for coordinating with the data acquisition process on Gateway-2000, an IBM compatible 80-386 microcomputer and Zeos 80-486 microcomputer. For reliable operation of the stepper motors dropping resistors of required ratings were installed in the circuit. The motor step size was 1.8° and with a setting of 5 microsteps per full step, one revolution of the motor shaft required 400 pulses. Figure 2.12 shows a block diagram of the hardware arrangement for stepper motors.

2.7. Existing Techniques of vorticity measurements:

In spite of several attempts to measure one or more components of time dependent spatially resolved vorticity in turbulent flows, there exists very small amount of experimental data of the vorticity fields in basic vortical flows like turbulent boundary layer or vortex flows over a delta wing. The significance and the need to measure vorticity in fluid flows is stressed in all of these attempts. Existing experimental methods

to measure this quantity can be categorized into three types: 1) Those which measure velocity components at different locations closely spaced to estimate vorticity either by using the relation

$$\Gamma = \int_C \vec{V} \cdot d\vec{S} = \int_A \vec{\omega} \cdot \hat{n} dA \quad (2.1)$$

between circulation about a small area and vorticity or by computing velocity gradients about a point by finite difference, 2) methods that use properties of systems that are able to sense the velocity gradients and 3) methods that sense the rotation itself of a fluid element either directly or indirectly. A comprehensive survey of these methods by Wallace (1986) and Foss and Wallace (1989) not only describe these methods in some details but also emphasize their limitations and the need for a reliable experimental means to accurately measure vorticity in flows with wide range of flow characteristics. The majority of the methods in the first category utilize the hot-wire/film anemometry and estimate one or at the most two components. Very recently Balint *et al.* (1991) demonstrated successfully by their experiments in a turbulent boundary layer that all the three components of vorticity can be measured simultaneously. Their probe consists of 9 hot-wire sensors mounted on 12 prongs with one common prong for each of the three arrays and inclined at 45 degrees to the mean flow. The wires were operated at low over heat ratio of 1.22. They used a common prong for each set of triple wires which required zero current at any time under a variety of dynamical conditions. Thus the uncertainty in the magnitude of the effects of cross talk in the sensitive electronic circuitry and the complexity in the interpretation of anemometer output voltage to velocity components by their technique provided impetus to make such measurements by improvement in the

probe. It is essential that a data base of instantaneous velocity and vorticity vector fields be available in order to investigate truly turbulent nature of any real flow. The need for such data base and the fact that the hot-wire anemometry being economical and reliable techniques to measure time dependent velocities were strong motivations for the design and implementation of the new multi-sensor probe.

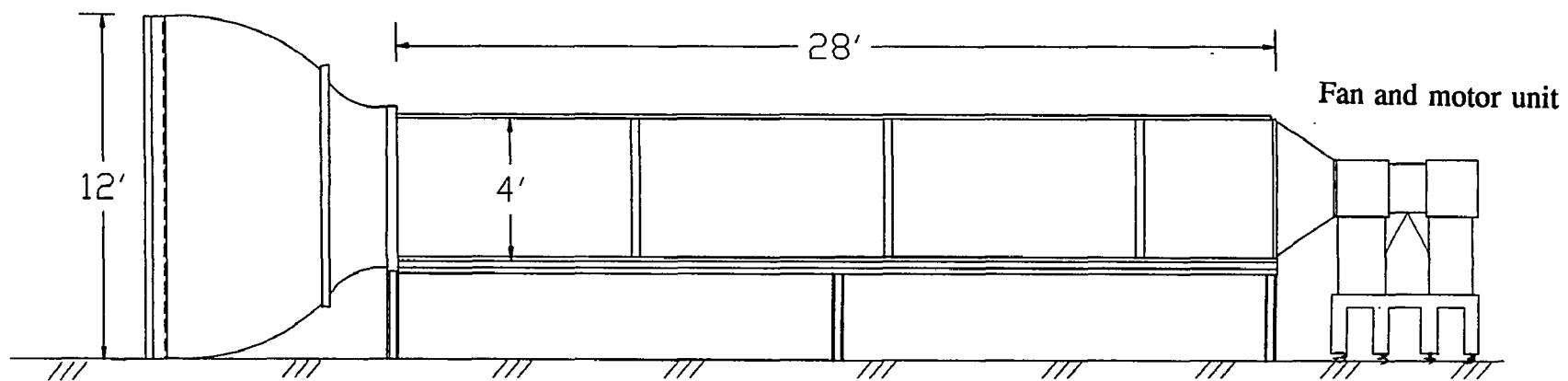


Figure 2.1. Wind tunnel facility at CCNY.

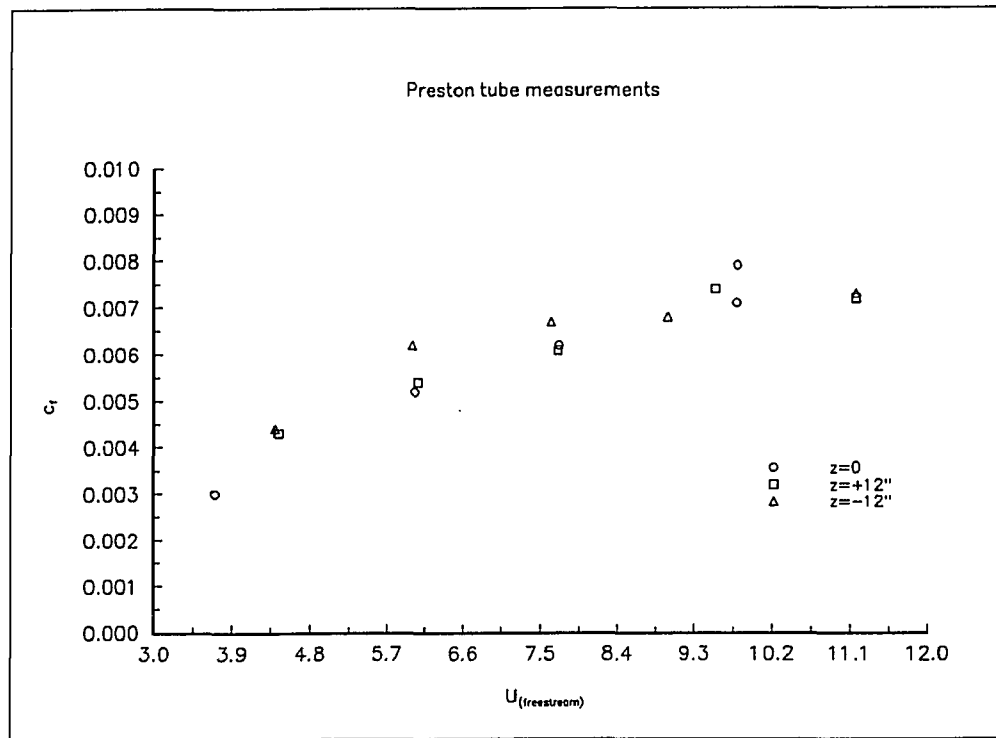


Figure 2.2a. Plot of variation of skin-friction coefficient c_f at three spanwise locations.

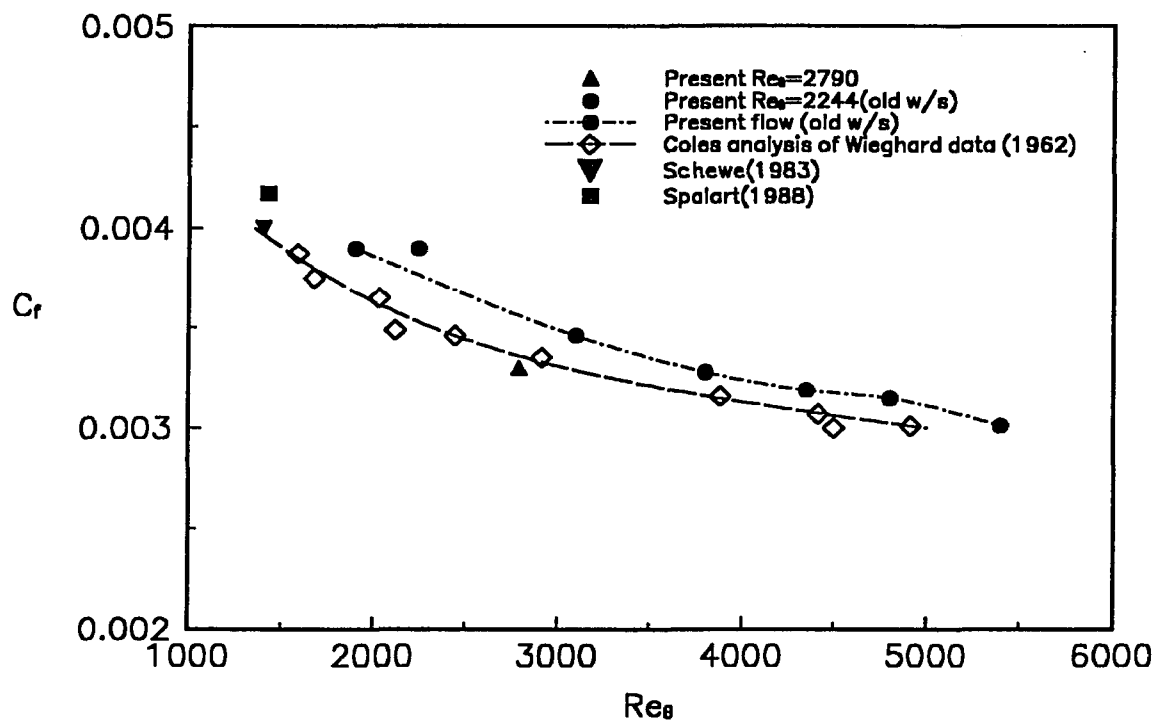


Figure 2.2b. Plot of variation of skin-friction coefficient c_f with Reynolds number based on momentum thickness θ .

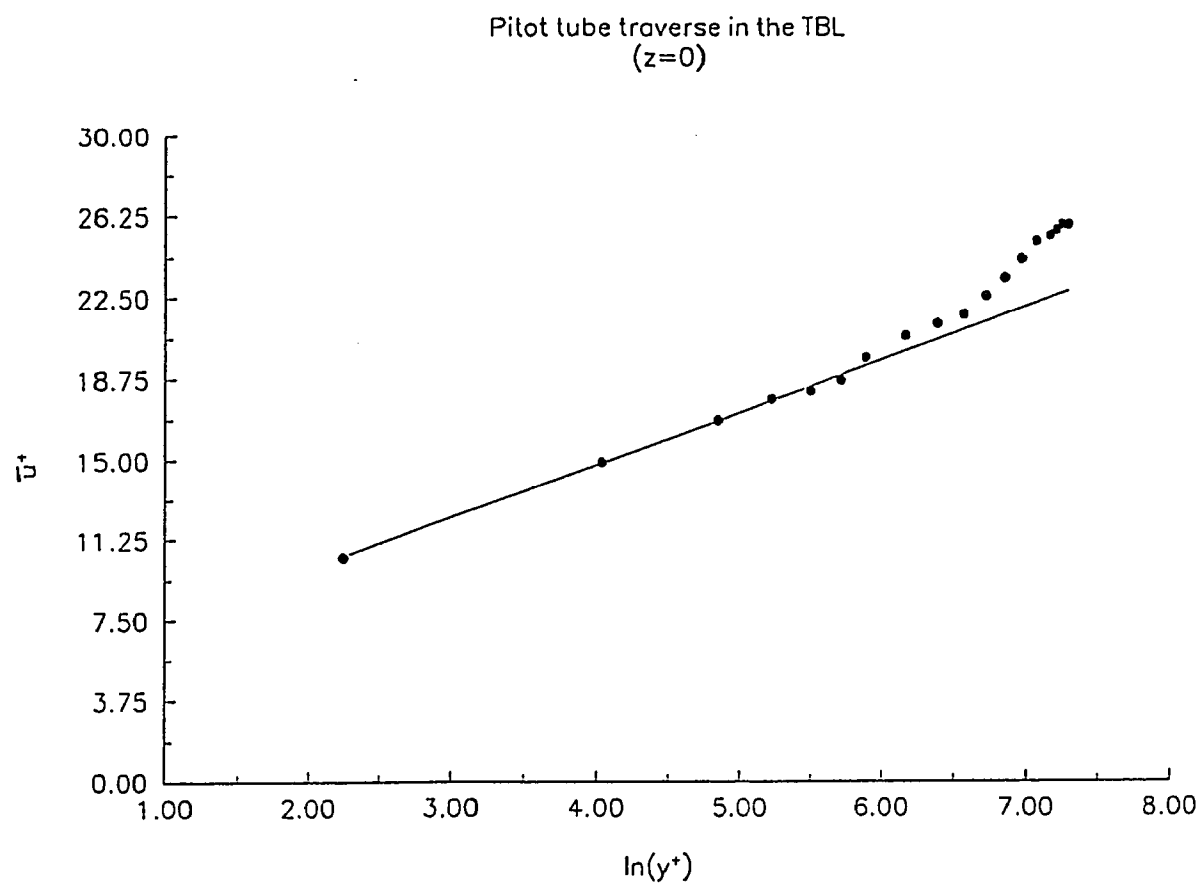


Figure 2.3. Pitot tube traverse in the turbulent boundary layer.

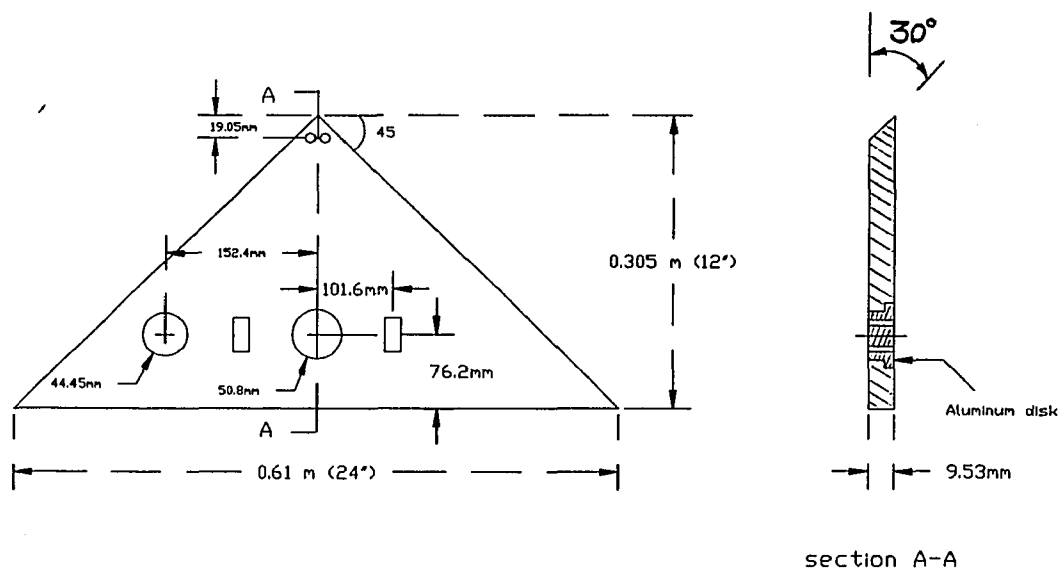


Figure 2.4. Sketch of the delta wing model used in the experiments. (not to scale)

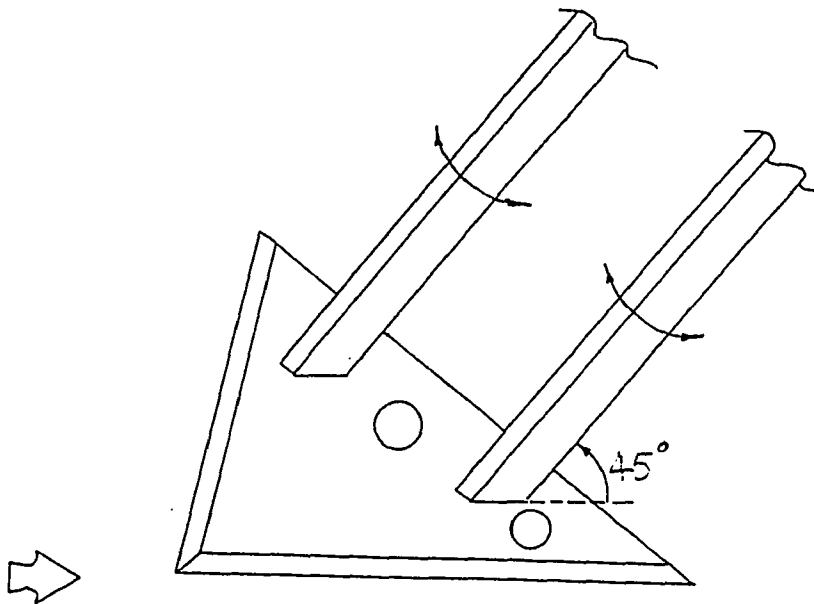
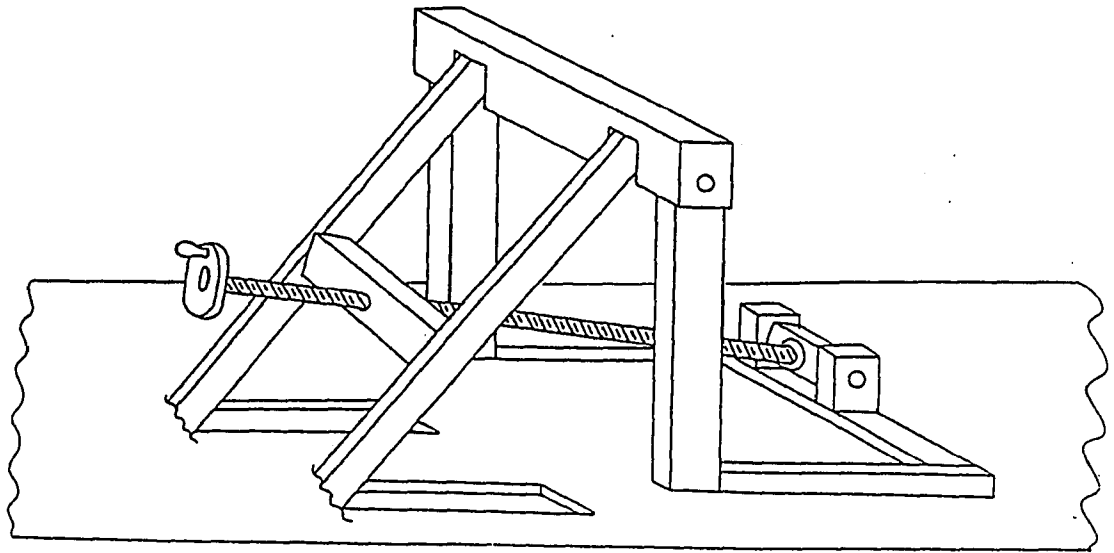


Figure 2.5. Support mechanism and installation of delta wing in the test section.

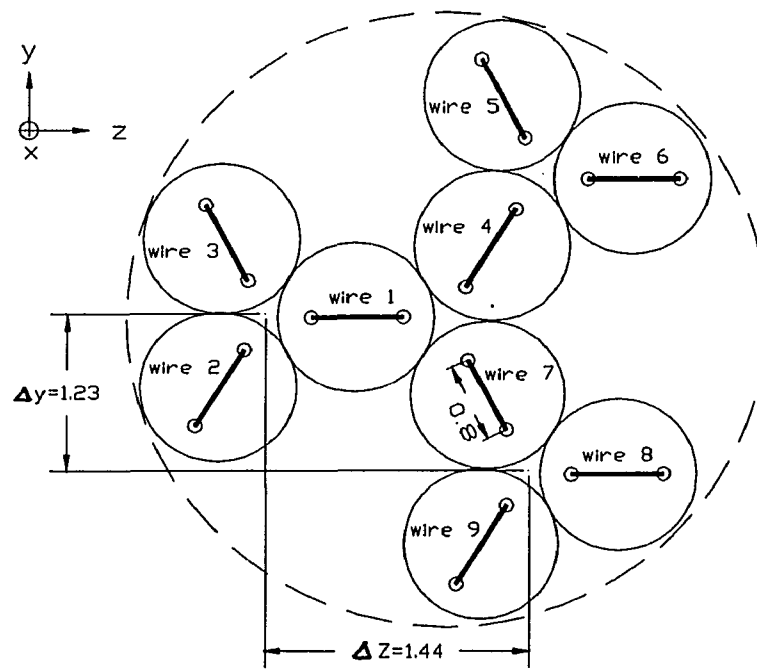


Figure 2.6 Schematic of the 9 hot-wire vorticity (3TOW) probe.

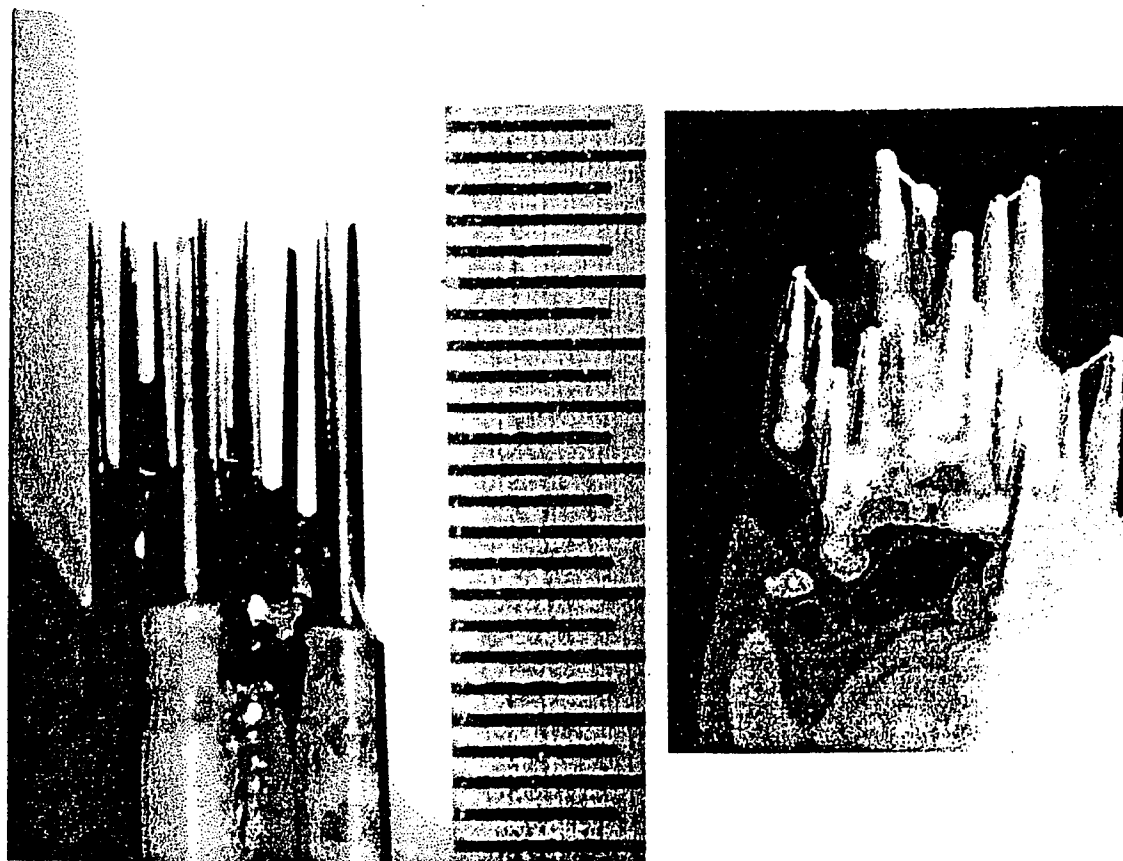


Figure 2.7. Enhanced photographs of the home-made 3TOW probe.

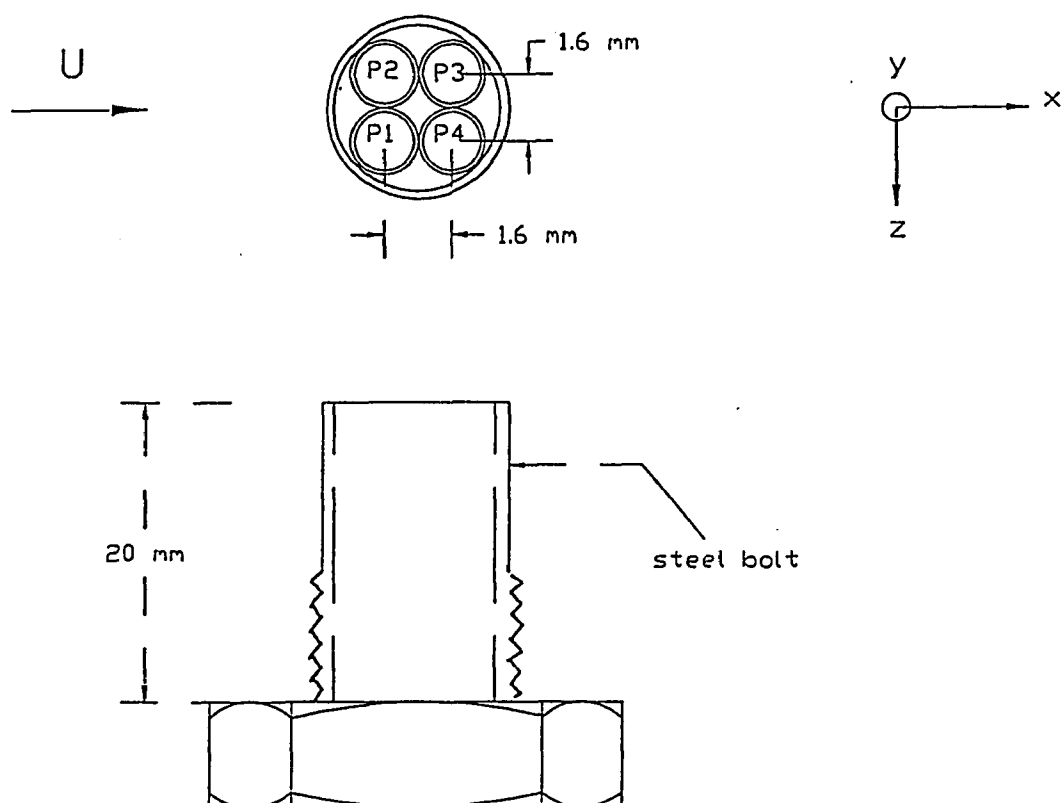


Figure 2.8. Diagram of the vorticity flux (Kulite/Entran) module.

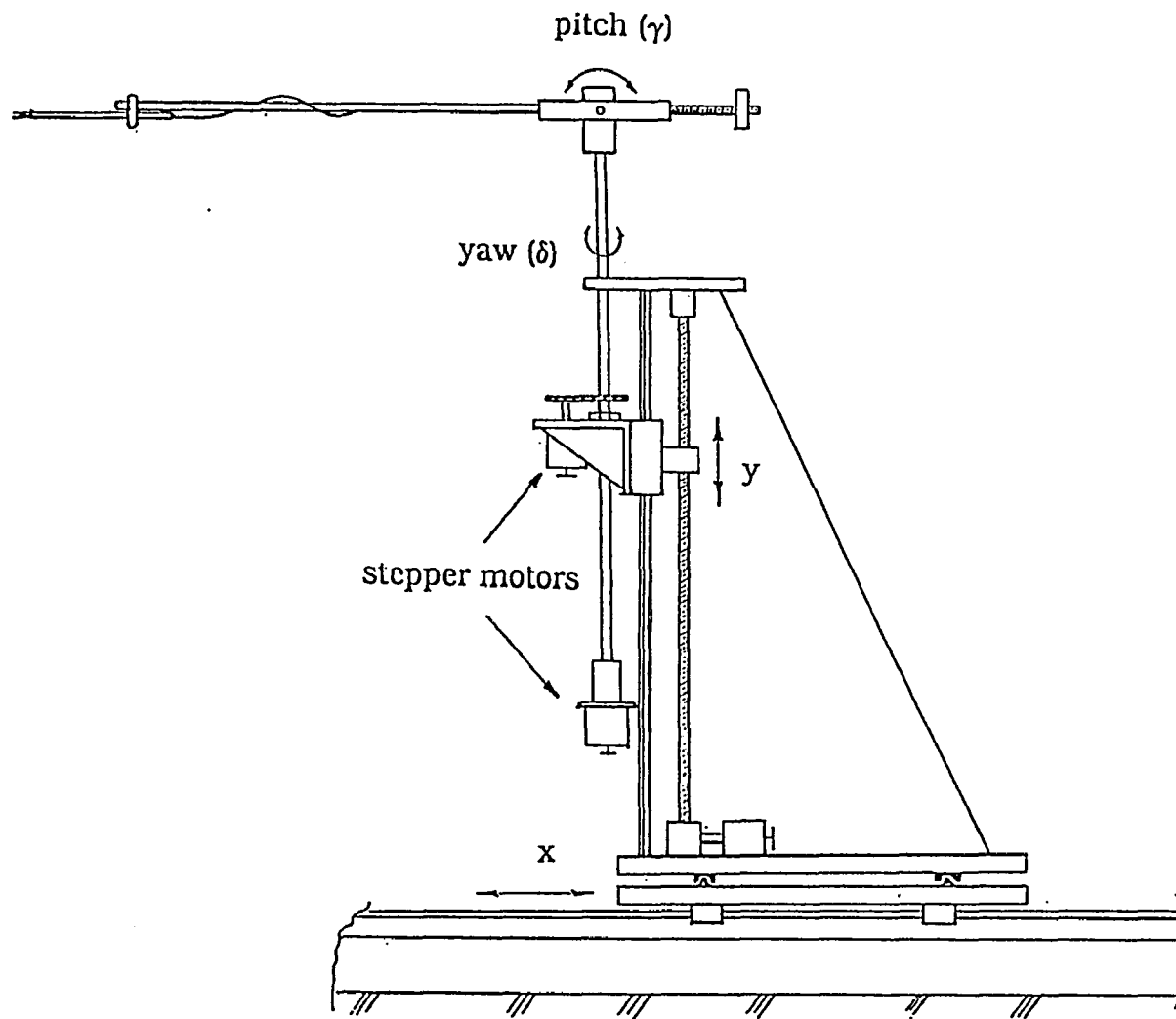


Figure 2.9. 3-d. traversing system with two independent rotations for yaw and pitch.

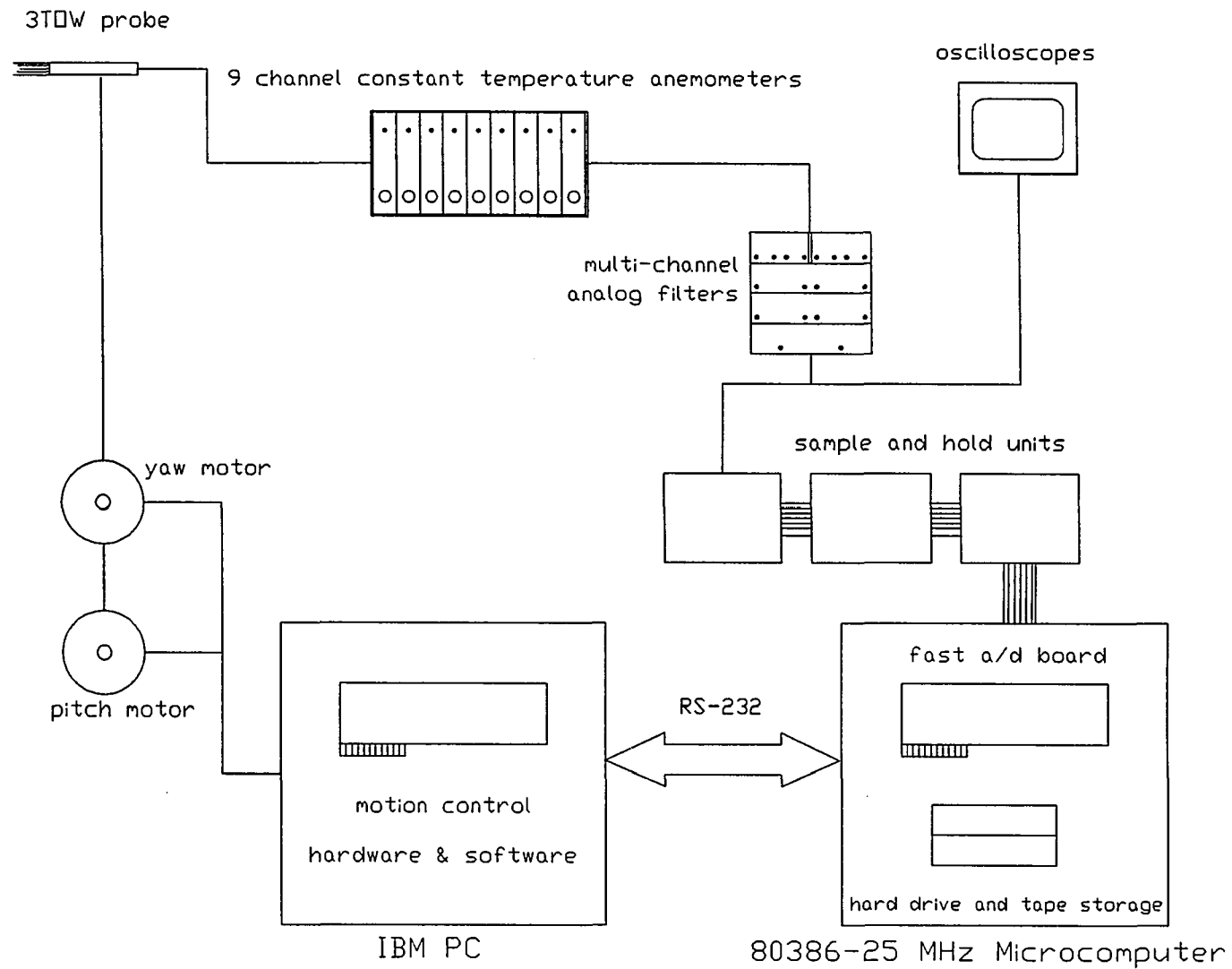


Figure 2.10. Block diagram of the experimental arrangement for velocity and vorticity measurements.

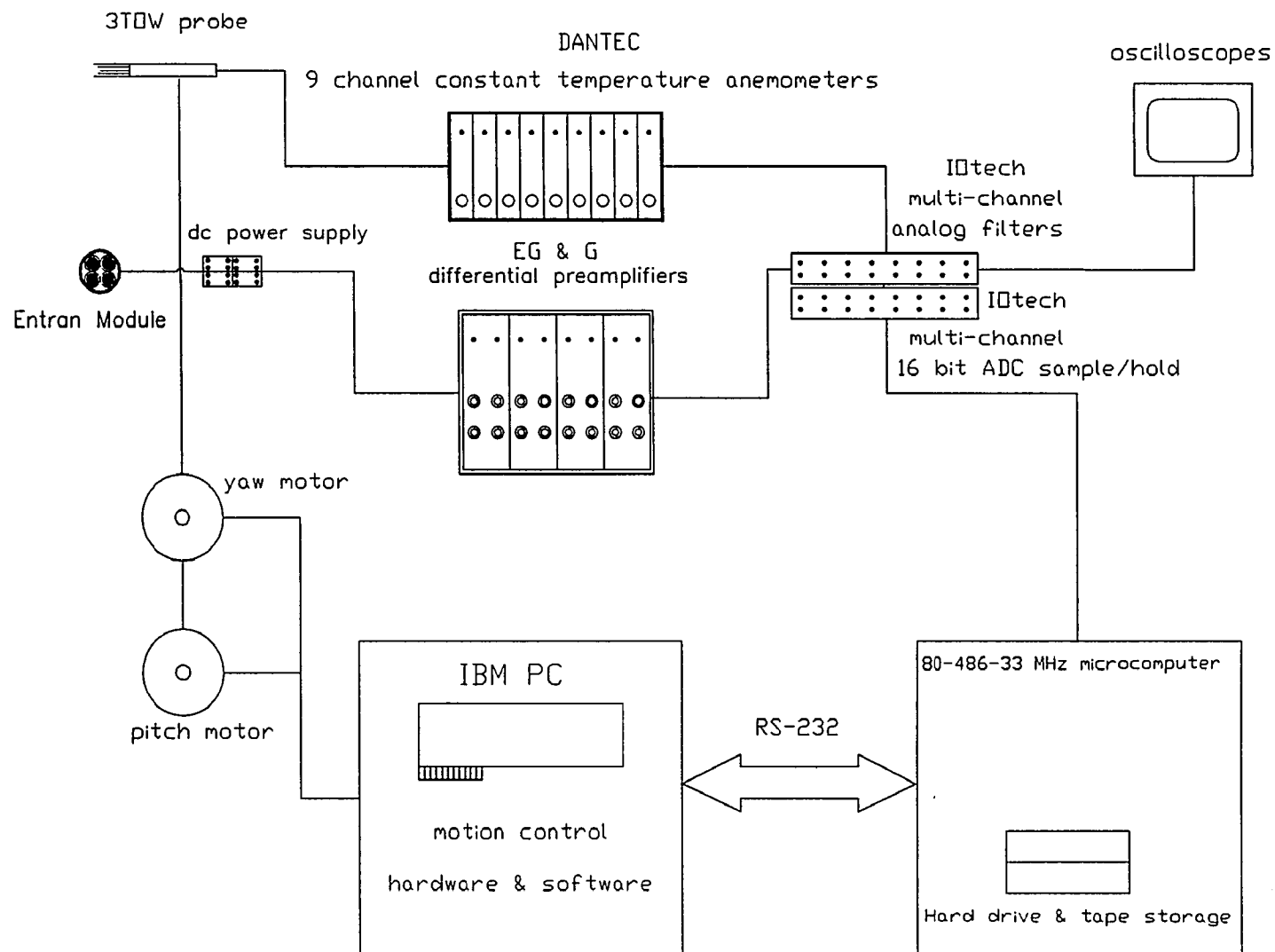


Figure 2.11. Block diagram of the experimental setup for simultaneous vorticity and wall pressure/vorticity flux measurements.

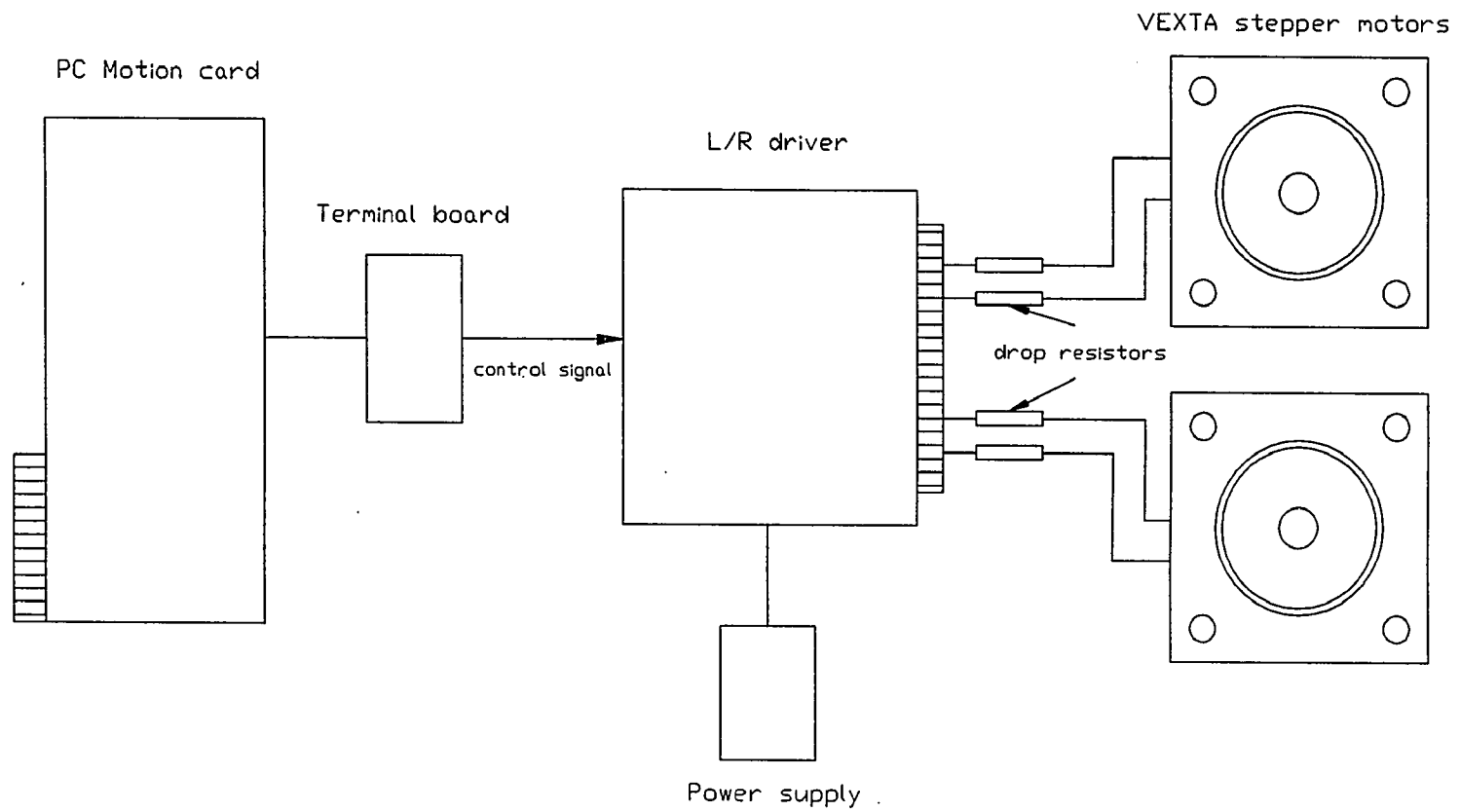


Figure 2.12. Block diagram of stepper motor hardware.

3. FLOW VISUALIZATION TECHNIQUES

Two techniques were utilized for flow visualization studies of delta wing flow.

3.1. Surface Flow Visualization :

The wet surface technique which based on the fact that when a surface coated with a mixture of tracer particles like lamp black and fast evaporating liquid, exposed to the flow, the tracer particles settle on a surface creating an imprint of the flow pattern. The surface of the wing was spray painted white first to obtain sharp contrast for still photography. Carbon powder was mixed with small quantities of deodorized kerosene and the mixture was spread on the entire surface of the delta wing. The wind tunnel was then turned on when the kerosene quickly started evaporating and the flow left its mark by way of carbon tracer particles settled on the surface. In order to obtain a well defined, clean picture the procedure was perfected by repeating the process several times by varying the proportion of carbon powder and kerosene and also controlling the duration of flow. The still photographs of the imprints were then shot by Nikon 35 mm SLR camera using Kodak 100 ASA black and white film. A flood lamp was also used for illuminating the surface picture of the flow.

Photographs were taken using above procedure for free stream velocity of 11 m/s only for angles of attack ranging from 0 to 45 degrees.

3.2. Laser Light Sheet Technique:

The second technique is by illuminating smoke or tracer particles in the flow regime under investigation by laser sheet. The smoke for this technique was generated by Optimist Fog and Smoke machine model 1280. It has the advantage of controlling remotely both, time and the amount of smoke and uses a water based fluid for flash evaporation forming 1-5 micron size particles. Smoke from this machine was then fed into a 10.16cm (4") diameter, about 90cm (36") long hollow aluminum pipe. The other end of the pipe carried a flexible rubber tube, about 25.4mm (1") inside diameter which could then be manipulated to get a uniform smoke at the required region inside the flow. The smoke was first fed from the apex by the tubes placed underneath the surface, second from an L shaped copper tube placed just upstream and above the leading edge tip and third from several other locations to obtain best possible pictures.

Spectra Physics Stabilite model 2550 Argon ion laser of 10 W power was used to generate laser beam which then was passed through Dantec 60x40 transmitter into a fiber optic probe. Unshifted green component (wavelength 514.5 nm) of the beam then was directed on to a resonating mirror of Scanner System model S11208, AX 730 supplied by General Scanning Inc. The mirror operated as a part of galvanometer, produced a thin, triangular light sheet which could be varied from a point to about 110 degree spread by changing the resonating frequency of the current supplied to the galvanometer. The mirror was mounted on an adjustable arm fitted on a tripod and laser probe was mounted at the base of the arm on the tripod thus allowing to adjust the mirror and laser beam in such a way as to align the laser sheet in different orientations with respect to the wing surface. A schematic arrangement is shown in figure 3.1.

The visual observations were then recorded by Sony model CCD-V99, video camera with a fixed frame rate of 30 frames per second, on Hi-8 8mm tapes. The shutter speeds available for the camera were from 1/60 s to 1/10000 s. The prints of still frames were done by Mitsubishi high resolution video printer.

Using the laser light sheet technique mentioned above, flow structure of the leading edge vortices was visually investigated for two free stream velocities of 3 m/s and 11 m/s and for 10, 15, 20, 25 and 45 degrees angle of attack. The observations were recorded by appropriately positioning video camera for each of the following three laser sheet orientations.

First, the laser sheet was placed normal to the flow and to the wing surface at two chord-wise positions $x/c = 0.5$ and 0.75 (lateral or cross-flow cut).

Second, the laser sheet was aligned approximately with the axis of the nearer vortex and also at the two edges with the sheet still normal to the surface (longitudinal cut).

Lastly, the flow was illuminated by positioning the laser sheet parallel and closest to the wing surface and then at a several locations away from the surface (horizontal cut). These three orientations are shown in Figure 3.2.

Image processing software, IMAGEPRO along with Frame-Grabber board were used to detect all edges in each of the frames and thus enhance the features embedded in the raw pictures.

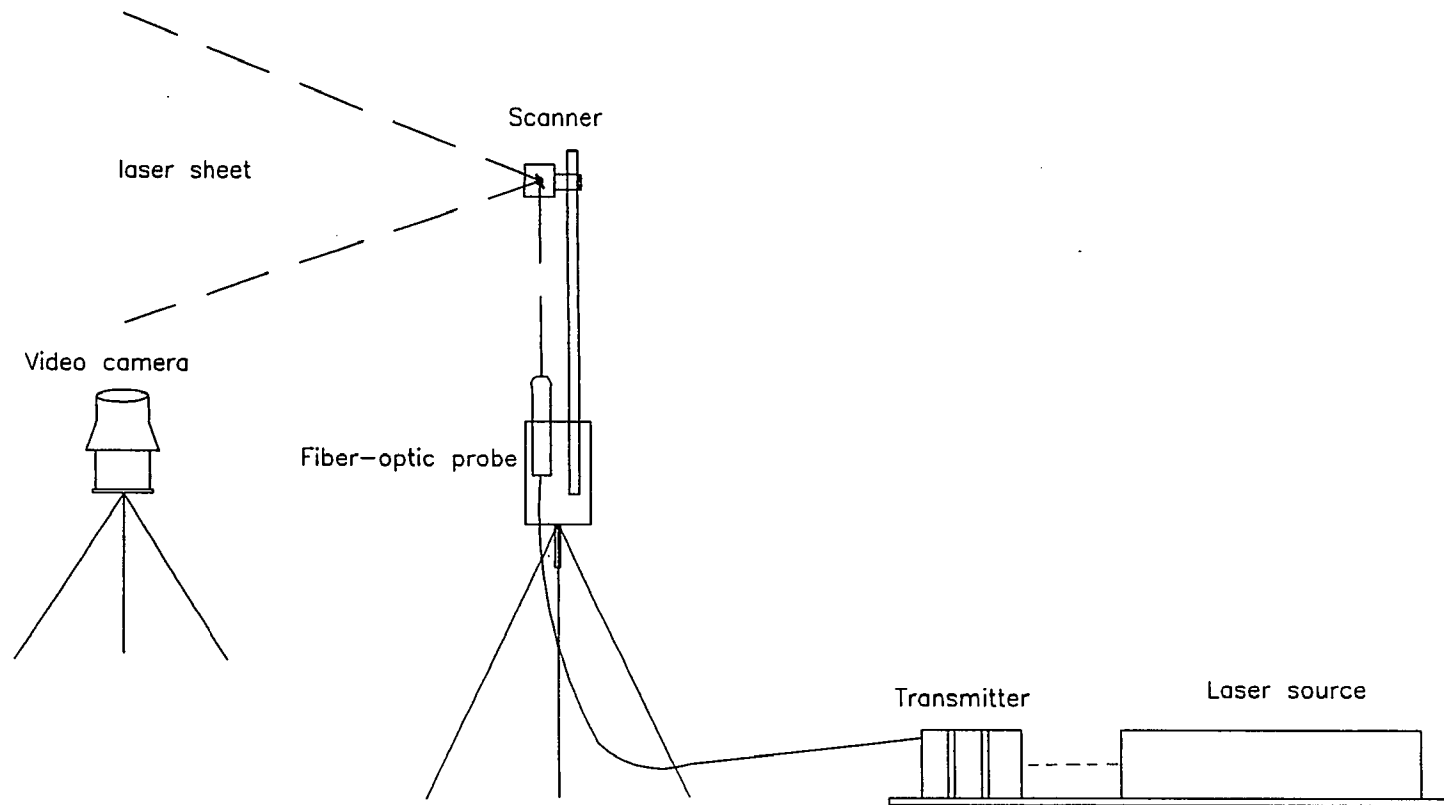
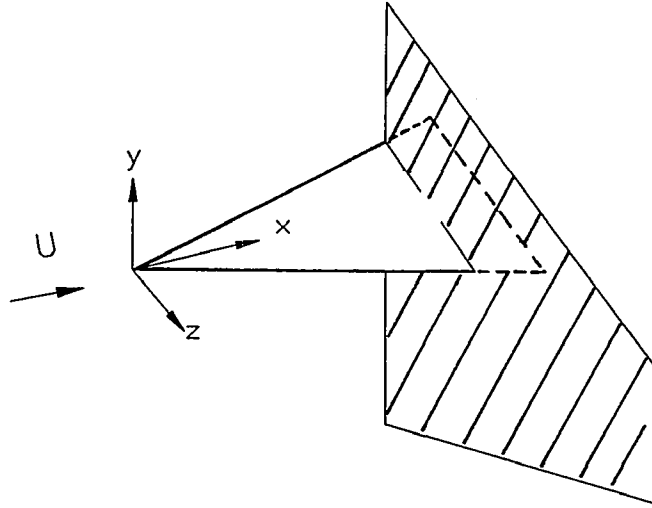
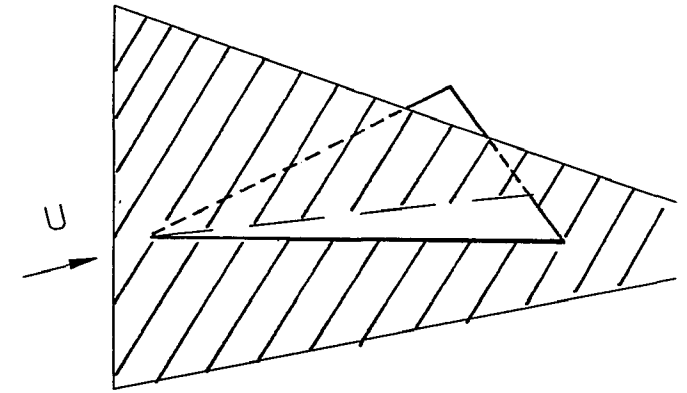


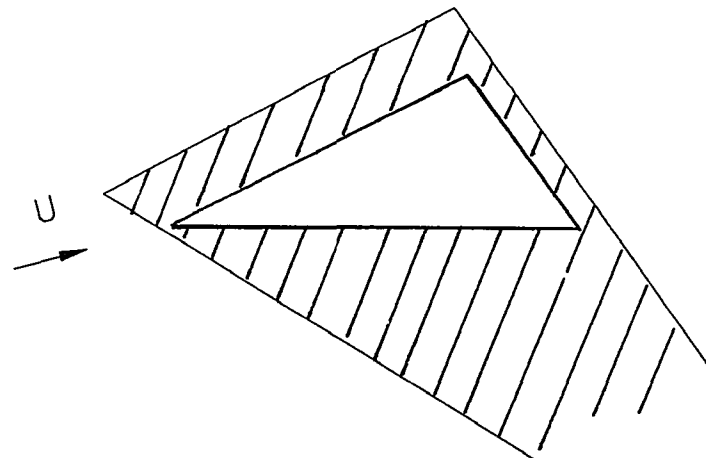
Figure 3.1. Schematic of the laser light sheet technique.



sheet parallel to yz plane (lateral cut)



sheet parallel to xy plane (longitudinal cut)



sheet parallel to xz plane (horizontal cut)

Figure 3.2. Orientations of the laser light sheet for delta wing flow visualization.

4. PRESENT APPROACH

4.1. Theory of operation of vorticity probe :

Since the probe essentially consists of a set of three triple nominally orthogonal hot-wires, it suffices to analyze the working of one triple wire. Two methods have been attempted for this purpose. A diagram showing normal, tangential and binormal velocity components for a single wire is displayed in figure 4.1.

4.1a. Analytical expression using King's law :

The hot-wire output voltage E is related to velocity, U_{eff} "as seen by the sensor" through the well known King's law:

$$E^2 = A + B \cdot U_{eff}^n \quad (4.1)$$

The effective cooling velocity is related to that measured during the calibration in at least three different ways; 1) "Cosine law" as stipulated by Bradshaw (1971), which utilizes the effect of cooling by only one component of velocity, 2) Hinze's (1959) relation, which accounts for two components on the cooling and 3) Jorgensen's (1971) expression which takes into consideration full three dimensional cooling effect on the sensor. The measurements made by the single or cross wires have always ignored the effect of at least one component of velocity on the hot-wire output. It has been demonstrated through many experimental tests on hot-wire anemometry that Jorgensen's equation accurately representing the directional response of the hot-wire to both yaw and pitch angles up to 70° and as such will also be used for the present probe. The effective velocity is related

to U_N , U_T and U_B the normal, tangential and binormal components of the velocity vector respectively, by

$$U_{\text{eff}}^2 = U_N^2 + k^2 U_T^2 + h^2 U_B^2 \quad (4.2)$$

where k and h are yaw and pitch coefficients. These are dependent on the aspect ratio length/diameter of the hot-wire and yaw/pitch angles and on the magnitude of the velocity.

For triple hot-wires arranged such that each sensor is parallel to the axes of a probe fixed orthogonal coordinate system, the velocity component along one sensor is normal to the second and binormal to the third. Thus if X , Y , and Z are velocity components parallel to x , y , z axis respectively in probe fixed coordinate system, the cooling velocities can be written as

$$U_{\text{eff1}}^2 = k_1^2 X^2 + Y^2 + h_1^2 Z^2 \quad (4.3)$$

$$U_{\text{eff2}}^2 = h_2^2 X^2 + k_2^2 Y^2 + Z^2 \quad (4.4)$$

$$U_{\text{eff3}}^2 = X^2 + h_3^2 Y^2 + k_3^2 Z^2 \quad (4.5)$$

or

$$\begin{bmatrix} U_{\text{eff1}}^2 \\ U_{\text{eff2}}^2 \\ U_{\text{eff3}}^2 \end{bmatrix} = \begin{bmatrix} k_1^2 & 1 & h_1^2 \\ h_2^2 & k_2^2 & 1 \\ 1 & h_3^2 & k_3^2 \end{bmatrix} \begin{bmatrix} X^2 \\ Y^2 \\ Z^2 \end{bmatrix} \quad (4.6)$$

and from King's law

$$\left[\frac{E_1^2 - A_1}{B_1} \right]^{2/n_1} = U_{\text{eff1}}^2 \quad (4.7)$$

$$\left[\frac{E_2^2 - A_2}{B_2} \right]^{2/n_2} = U_{\text{eff2}}^2 \quad (4.8)$$

$$\left[\frac{E_3^2 - A_3}{B_3} \right]^{2/n_3} = U_{\text{eff3}}^2 \quad (4.9)$$

Therefore

$$\begin{bmatrix} \left[\frac{E_1^2 - A_1}{B_1} \right]^{2/n_1} \\ \left[\frac{E_2^2 - A_2}{B_2} \right]^{2/n_2} \\ \left[\frac{E_3^2 - A_3}{B_3} \right]^{2/n_3} \end{bmatrix} = D \begin{bmatrix} X^2 \\ Y^2 \\ Z^2 \end{bmatrix} \quad (4.10)$$

D is the matrix of wire response coefficients. The exponents n_1 , n_2 , n_3 all vary between 0.4 and 0.5. In the data analysis these exponents are all taken equal to 0.45. The instantaneous velocity components X, Y and Z can now be obtained by solving above system of equations which is linear in X^2 , Y^2 and Z^2 as follows:

$$\begin{bmatrix} X^2 \\ Y^2 \\ Z^2 \end{bmatrix} = D^{-1} \begin{bmatrix} \left(\frac{E_1^2 - A_1}{B_1} \right)^{2/n_1} \\ \left(\frac{E_2^2 - A_2}{B_2} \right)^{2/n_2} \\ \left(\frac{E_3^2 - A_3}{B_3} \right)^{2/n_3} \end{bmatrix} \quad (4.11)$$

where D^{-1} is the inverse of matrix D .

Since two solutions for each component are possible, only those with positive signs are retained as valid ones for the reason that hot-wire acts like a rectifier and can not distinguish between positive and negative directions of cooling components. This problem of multiple solutions to the hot-wire response equations has been well documented by Willmarth and Bogar (1977), Chang *et al.* (1983), Willmarth (1984) and Lekakis *et al.* (1989). The instantaneous velocity components u , v and w in the space fixed coordinates can be easily computed by coordinate transformation matrix N in the relation:

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = N \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (4.12)$$

For the present probe these equations are determined as follows:

The orientations of the three wires as seen by the mean flow for each of the three triple wires are shown in figure 4.2.

For the first triple wire therefore

$$\begin{bmatrix} u_1 \\ v_1 \\ w_1 \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi\cos\phi & \sin\psi\sin\phi \\ 0 & -\sin\phi & \cos\phi \\ -\sin\psi & \cos\psi\cos\phi & \cos\psi\sin\phi \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} \quad (4.13)$$

where u_1 , v_1 and w_1 are velocity components at the center of the triple wire in space fixed coordinates, ψ is the nominal wire inclination angle 54.74° and $\phi=45^\circ$

Similarly for the second and third triple wires two triple wires the governing equations are

$$\begin{bmatrix} u_2 \\ v_2 \\ w_2 \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi\cos\phi & \sin\psi\sin\phi \\ -\sin\phi & \cos\phi & 0 \\ \cos\psi\cos\phi & \cos\psi\sin\phi & -\sin\psi \end{bmatrix} \begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} \quad (4.14)$$

and

$$\begin{bmatrix} u_3 \\ v_3 \\ w_3 \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi\cos\phi & \sin\psi\sin\phi \\ -\sin\phi & 0 & \cos\phi \\ \cos\psi\sin\phi & -\sin\psi & \cos\psi\cos\phi \end{bmatrix} \begin{bmatrix} X_3 \\ Y_3 \\ Z_3 \end{bmatrix} \quad (4.15)$$

respectively, where u_2 , v_2 , w_2 and u_3 , v_3 , w_3 are velocity components at the center of the second and the third triple wires respectively. Since each sensor is not inclined at the same ideal angle of 54.7 degrees the elements in the transformation matrix are modified with the coefficients which effectively take into account the small deviations from orthogonality. The cross products have been ignored in these modifications.

The King's law coefficient B in the equation 4.1 is not directly available and therefore has to be computed from the mean velocity calibrations as follows:

The relation of the output voltage E of a hot-wire to velocity components X, Y and Z , as mentioned above, is

$$E^2 = A + B (X^2 + k^2 Y^2 + h^2 Z^2)^{n/2} \quad (4.16)$$

For zero yaw and pitch angles during mean velocity calibration following relation for the velocity components X, Y, and Z in the probe fixed co-ordinates can be written:

$$\text{For } X = Y = Z = U_0 \cos \psi \quad (4.17)$$

$$E^2 = A + B (\cos \psi)^n (1 + k_0^2 + h_0^2)^{n/2} U_0^n \quad (4.18)$$

$$E^2 = A + B_0 U_0^n \quad (4.19)$$

$$B = \frac{B_0}{(\cos \psi)^n (1 + k_0^2 + h_0^2)^{n/2}} \quad (4.20)$$

$$E^2 = A + \frac{B_0}{(\cos \psi)^n} \left[\frac{X^2 + k^2 Y^2 + h^2 Z^2}{1 + k_0^2 + h_0^2} \right]^{n/2} \quad (4.21)$$

B_0 is the coefficient obtained by the least square fit of E^2 and $U_0^{0.45}$ for each wire, the value of which is then used in the above relation 4.2 to compute B. The effects of prong interference and sensitivity to yaw and pitch angles of the velocity vector will thus be accounted for during data reduction.

Since the rate of convection heat transfer from the hot-wire is dependent on the difference in temperature between the hot-wire and the fluid, a change in the temperature of the fluid could be interpreted as either increase or decrease in the velocity, although the hot-wire temperature is maintained fairly constant by the electronic circuitry. The compensation due to variations in the fluid temperature during the measurement period is therefore essential especially when variations of several degrees occur as in the case

of a closed-circuit wind tunnel.

The correction for temperature fluctuations in the flow is achieved in several different ways, e.g. by maintaining constant overheat ratio or by applying correction factors to the voltage output of the hot-wire. The latter method, being convenient, is employed in the present data analysis as below:

The resistance of a wire can be written as

$$R_w = R_{ref} \left[1 + \alpha_T (T_w - T_{ref}) \right] \quad (4.22)$$

where R_w is wire "hot" resistance at wire temperature T_w , R_{ref} is wire "cold" resistance at wire temperature T_{ref} , α_T is temperature coefficient of resistivity of the wire per °C.

If overheat ratio R is defined as

$$R = \frac{(R_w - R_{ref})}{R_{ref}} = \alpha_T (T_w - T_{ref}) \quad (4.23)$$

then for any temperature T other than the reference temperature T_{ref} , the ratio of voltages E and E_{ref} across the wire can be expressed as :

$$\frac{E}{E_{ref}} = \left[\frac{1 + \alpha_T (T_w - T)}{1 + \alpha_T (T_w - T_{ref})} \right] \quad (4.24)$$

or in terms of the overheat ratio R and the two temperatures as

$$E = E_{ref} \left[1 + \frac{\alpha}{2(R-1)} (T - T_{ref}) \right] \quad (4.25)$$

4.1b. Direct mapping through look up table :

This method became feasible as computing facilities became an integral part of experimental research. It is a straight forward process which involves measuring hot-wire voltages for different velocities with wide range of flow angles of yaw and pitch. The data is then used to construct a multi-dimensional look up table (LUT) similar to that used in the image processing, which has each output voltage mapped one-to-one to values of yaw, pitch and magnitude of the velocity. The main advantage of the method lies in the fact that the difficulties encountered in applying directional response equations to accurately represent the velocity vector with high pitch and yaw angles are eliminated and no assumptions about the cooling law need to be made nor the knowledge of the exact geometry of the probe is required. The draw back however is that it requires a large pool of calibration data in order to obtain higher resolution, large storage space and longer computer time for searching in the look-up table.

If each of the three output voltages of a triple hot-wire probe is assumed to be a continuous function of the velocity vector Q , pitch angle γ and yaw angle δ i.e.

$$E_1 = E_1(Q, \gamma, \delta)$$

$$E_2 = E_2(Q, \gamma, \delta)$$

$$E_3 = E_3(Q, \gamma, \delta)$$

Then the above equations define a mapping of (Q, γ, δ) - 3 dimensional space onto (E_1, E_2, E_3) 3 dimensional space.

Calibration of the 3TOW probe by this method then is essentially a mapping of anemometer output voltages E_1 , E_2 , and E_3 of a single triple hot-wire unit to the

magnitude of the calibration velocity Q , pitch angle γ and yaw angle δ .

$$[E_1, E_2, E_3] \Leftrightarrow [Q, \gamma, \delta] \quad (4.26)$$

If the above functions and their partial derivatives are continuous at any point inside a domain T of the 3 dimensional space, then the condition for the above mapping to be unique is given by

$$J = \begin{bmatrix} \frac{\partial E_1}{\partial Q} & \frac{\partial E_2}{\partial Q} & \frac{\partial E_3}{\partial Q} \\ \frac{\partial E_1}{\partial \gamma} & \frac{\partial E_2}{\partial \gamma} & \frac{\partial E_3}{\partial \gamma} \\ \frac{\partial E_1}{\partial \delta} & \frac{\partial E_2}{\partial \delta} & \frac{\partial E_3}{\partial \delta} \end{bmatrix} \neq 0 \quad (4.27)$$

The nine elements of the Jacobian J above are the sensitivities of each of the hot-wires. The first attempt to verify the uniqueness of the mapping for this type of orthogonal triple hot-wires was reported by Vrettos (1984). A typical plot of all partial derivatives which are considered as sensitivities of each wire is shown in figure 4.3 using the velocity, yaw and pitch calibration data of the 3TOW probe obtained as described in the section 4.3, while figure 4.4 shows a plot of the sign of the Jacobian as a function of pitch and yaw angles. It represents the validity domain or "acceptance cone" of the triple hot-wire unit as determined by the non-changing sign of the Jacobian. The sign of the Jacobian is found experimentally to be independent of Q for almost any yaw and pitch angles except those close to the outer edges of the validity domain. The sensitivities are computed from the finite differences of the corresponding quantities obtained by the calibration procedure as described in the next section 4.2. The following relations can be written for the mapping

$$\Delta E_1 = \frac{\partial E_1}{\partial Q} \Delta Q + \frac{\partial E_1}{\partial \gamma} \Delta \gamma + \frac{\partial E_1}{\partial \delta} \Delta \delta \quad (4.28)$$

$$\Delta E_2 = \frac{\partial E_2}{\partial Q} \Delta Q + \frac{\partial E_2}{\partial \gamma} \Delta \gamma + \frac{\partial E_2}{\partial \delta} \Delta \delta \quad (4.29)$$

$$\Delta E_3 = \frac{\partial E_3}{\partial Q} \Delta Q + \frac{\partial E_3}{\partial \gamma} \Delta \gamma + \frac{\partial E_3}{\partial \delta} \Delta \delta \quad (4.30)$$

in matrix form the above set of equations can be written as

$$\begin{bmatrix} \Delta E_1 \\ \Delta E_2 \\ \Delta E_3 \end{bmatrix} = J \cdot \begin{bmatrix} \Delta Q \\ \Delta \gamma \\ \Delta \delta \end{bmatrix} \quad (4.31)$$

or

$$\begin{bmatrix} \Delta Q \\ \Delta \gamma \\ \Delta \delta \end{bmatrix} = J^{-1} \cdot \begin{bmatrix} \Delta E_1 \\ \Delta E_2 \\ \Delta E_3 \end{bmatrix} \quad (4.32)$$

where J^{-1} is the inverse of the Jacobian matrix. A look-up table can now be generated from the sensitivities, three output voltages and corresponding values of the magnitude of calibration velocity Q , and the two angles γ and δ .

For any arbitrary set of 3 output voltages (E_{1i} E_{2i} E_{3i}) which are at ΔE_{1i} , ΔE_{2i} and ΔE_{3i} away from the nearest calibration voltage trio (E_{1a} E_{2a} E_{3a}), corresponding velocity vector (Q_i , γ_i , δ_i) is inferred from the look-up table using the relations

$$Q_i = Q_a + \left[\frac{\partial Q}{\partial E_1} \right] \Delta E_{1i} + \left[\frac{\partial Q}{\partial E_2} \right] \Delta E_{2i} + \left[\frac{\partial Q}{\partial E_3} \right] \Delta E_{3i} \quad (4.33)$$

$$\gamma_i = \gamma_a + \left[\frac{\partial \gamma}{\partial E_1} \right] \Delta E_{1i} + \left[\frac{\partial \gamma}{\partial E_2} \right] \Delta E_{2i} + \left[\frac{\partial \gamma}{\partial E_3} \right] \Delta E_{3i} \quad (4.34)$$

$$\delta_i = \delta_a + \left[\frac{\partial \delta}{\partial E_1} \right] \Delta E_{1i} + \left[\frac{\partial \delta}{\partial E_2} \right] \Delta E_{2i} + \left[\frac{\partial \delta}{\partial E_3} \right] \Delta E_{3i} \quad (4.35)$$

Thus the process basically involves "looking" for the nearest calibration voltage with a unique velocity vector in the mapping. Evidently, the accuracy of the velocity vector, inferred as above, depends on the resolution of the look-up table. It is therefore desirable to have the number of calibration points such that ΔE_{1i} , ΔE_{2i} and ΔE_{3i} are of the order of the resolution of the instrument by which the voltages are recorded. This would require that the measurements would have to be made at large number of points.

Alternatively a different approach is adopted to improve the accuracy of the look-up table generated with real measurements by considering the effective velocity in the King's law relation used in 4.1.1, which is now restated as

$$U_{\text{eff}}^2 = Q^2 f(\gamma, \delta) \quad (4.36)$$

For $\gamma=0$ and $\delta=0$, this relation then becomes

$$E^2 = A + B f^{n/2}(0,0) Q^n \quad (4.37)$$

replacing the coefficient of Q^n by B' , the relation simplifies to

$$E^2 = A + B' \left[\frac{f(\gamma, \delta)}{f(0,0)} \right]^{n/2} Q^n \quad (4.38)$$

Let

$$F = \left[\frac{f(\gamma, \delta)}{f(0, 0)} \right]^{n/2} \quad (4.39)$$

then

$$\frac{E^2 - A}{B'Q^n} = F(\gamma, \delta) \quad (4.40)$$

The function F represents yaw and pitch angles response of the hot-wire and is single valued for the yaw and pitch angles lying within the region of validity for the triple hot-wire. A plot of the angular response function F is shown in figure 4.5. The function F now is used to interpolate voltages for range of values of Q , γ and δ other than those obtained by the calibration measurements.

This approach established the realizability condition for the uniqueness of solution of the hot-wire response equations which is that the Jacobian of the matrix with nine elements which are the hot-wire sensitivities, should not change sign. The present probe satisfies this condition and therefore it can be concluded that the solutions are unique if they lie inside the domain of acceptance of the probe. An attempt was made to analyze the boundary layer data using the look-up table and existing computing capabilities, which proved to be marginally successful in that the statistical results were excessively high with often appearance of large spikes in all three instantaneous velocity traces. As the processing of each data point required unreasonably long time of searching in the look-up table, accompanied by other glitches in the processing, the analysis by this method was discontinued and planned to be carried out separately in future.

4.2. Vorticity Computations For 3TOW Probe :

In order to compute all three vorticity components, six derivatives need to be evaluated from the three velocity components measured at the three locations which are the centers of each of the three triple wires. These derivatives are evaluated as follows.

If the origin of a coordinate system is fixed at the centroid of the 3TOW probe as shown in figure 4.6 and subscripts 0, 1, 2 and 3 refer to quantities at the centroid of the 3TOW probe, centers of first, second and third triple wires respectively, then

$$\begin{aligned}\Delta Y_1 &= 0, & \Delta Z_1 &= -L_0 \\ \Delta Y_2 &= \frac{\sqrt{3}}{2}L_0, & \Delta Z_2 &= \frac{L_0}{2} \\ \Delta Y_3 &= -\frac{\sqrt{3}}{2}L_0, & \Delta Z_3 &= \frac{L_0}{2}\end{aligned}\tag{4.41}$$

Taylor expansion of velocity component u at the centroid neglecting higher order derivative terms yields

$$u_1 = u_0 + \left[\frac{\partial u_0}{\partial y} \right]_{x=y=z=0} \Delta Y_1 + \left[\frac{\partial u_0}{\partial z} \right]_{x=y=z=0} \Delta Z_1 \tag{4.42}$$

$$u_2 = u_0 + \left[\frac{\partial u_0}{\partial y} \right]_{x=y=z=0} \Delta Y_2 + \left[\frac{\partial u_0}{\partial z} \right]_{x=y=z=0} \Delta Z_2 \tag{4.43}$$

$$u_3 = u_0 + \left[\frac{\partial u_0}{\partial y} \right]_{x=y=z=0} \Delta Y_3 + \left[\frac{\partial u_0}{\partial z} \right]_{x=y=z=0} \Delta Z_3 \tag{4.44}$$

In matrix form:

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} 1 & \Delta Y_1 & \Delta Z_1 \\ 1 & \Delta Y_2 & \Delta Z_2 \\ 1 & \Delta Y_3 & \Delta Z_3 \end{bmatrix} \begin{bmatrix} u_0 \\ \frac{\partial u_0}{\partial y} \\ \frac{\partial u_0}{\partial z} \end{bmatrix} \quad (4.45)$$

The above system of linear equations in u_0 , $\frac{\partial u_0}{\partial y}$ and $\frac{\partial u_0}{\partial z}$ can be solved by inverting the first matrix on the right side which gives velocity component u , its derivative with respect to y and z as below:

$$u_0 = \frac{u_1 + u_2 + u_3}{3} \quad (4.46)$$

$$\frac{\partial u_0}{\partial y} = \frac{1}{\sqrt{3} L_0} (u_2 - u_3) \quad (4.47)$$

$$\frac{\partial u_0}{\partial z} = -\frac{1}{3L_0} (2u_1 - u_2 - u_3) \quad (4.48)$$

Proceeding in the same way for Taylor expansions of velocity components v and w at the centroid equations for other derivatives can be written down as:

$$v_0 = \frac{v_1 + v_2 + v_3}{3} \quad (4.49)$$

$$\frac{\partial v_0}{\partial y} = \frac{1}{\sqrt{3} L_0} (v_2 - v_3) \quad (4.50)$$

$$\frac{\partial v_0}{\partial z} = -\frac{1}{3L_0}(2v_1 - v_2 - v_3) \quad (4.51)$$

$$w_0 = \frac{w_1 + w_2 + w_3}{3} \quad (4.52)$$

$$\frac{\partial w_0}{\partial y} = \frac{1}{\sqrt{3}L_0}(w_2 - w_3) \quad (4.53)$$

$$\frac{\partial w_0}{\partial z} = -\frac{1}{3L_0}(2w_1 - w_2 - w_3) \quad (4.54)$$

Now the derivatives in the streamwise direction are obtained by the Galilean transformation as below:

Conservation of momentum equation, neglecting viscous terms and pressure gradient terms and applied at the centroid of the 3TOW probe for u component is as follows

$$\frac{\partial u_0}{\partial t} + u_0 \frac{\partial u_0}{\partial x} + v_0 \frac{\partial u_0}{\partial y} + w_0 \frac{\partial u_0}{\partial z} = 0 \quad (4.55)$$

i.e.

$$\frac{\partial u_0}{\partial x} = -\frac{1}{u_0} \left[\frac{\partial u_0}{\partial t} + v_0 \frac{\partial u_0}{\partial y} + w_0 \frac{\partial u_0}{\partial z} \right] \quad (4.56)$$

Similarly

$$\frac{\partial v_0}{\partial x} = -\frac{1}{u_0} \left[\frac{\partial v_0}{\partial t} + v_0 \frac{\partial v_0}{\partial y} + w_0 \frac{\partial v_0}{\partial z} \right] \quad (4.57)$$

$$\frac{\partial w_0}{\partial x} = -\frac{1}{u_0} \left[\frac{\partial w_0}{\partial t} + v_0 \frac{\partial w_0}{\partial y} + w_0 \frac{\partial w_0}{\partial z} \right] \quad (4.58)$$

are obtained by considering the momentum equations for v and w components respectively.

Finally, the temporal derivatives in the three equations above can easily be evaluated by the product of two successive velocity values and sampling frequency f_s which subsequently allows computation of the streamwise derivatives.

The final expressions for the vorticity components ω_x , ω_y and ω_z at the centroid of the probe therefore are:

$$\omega_x = \left[\frac{\partial w_0}{\partial y} - \frac{\partial v_0}{\partial z} \right], \quad \omega_y = \left[\frac{\partial u_0}{\partial z} - \frac{\partial w_0}{\partial x} \right] \quad \text{and} \quad \omega_z = \left[\frac{\partial v_0}{\partial x} - \frac{\partial u_0}{\partial y} \right] \quad (4.59)$$

4.3. Calibration for velocity, yaw and pitch :

In-situ calibrations of the 3TOW probe were carried out in the inviscid core of the flow, once prior to the data acquisition session and other at the end of the experiment for both boundary layer investigations and delta wing investigations. The probe was placed in the middle of the working section by using 3 ft. slender arm which was a part of 3-d traversing mechanism. Ensemble averaged values of 200 samples of data each for all nine wires were collected for range of mean speeds which included those possible in the flow to be investigated. The typical calibration curves of mean velocity for all 9 sensors during boundary layer investigations is shown in figure 4.7 by taking exponent

n in the King's law relation as 0.45. It can be seen from the plot that drift effects are minimal and do not affect the results within the degree of uncertainty that exists in these measurements.

Extensive yaw and pitch response measurements for each of the sensors were then obtained by elegant coordination of data acquisition on one microcomputer while performing required yaw or pitch rotations through motion control hardware interfaced to another. All angles from -30° to $+30^\circ$ were covered in steps of 5 degrees for both yaw and pitch for five different free stream velocities. A typical plot of voltage vs. yaw and pitch angles is shown in figure 4.8. The actual inclination angles for each wires was determined from the yaw-pitch data using the effective angle technique suggested by Bradshaw (1971) and it was noted that the wires were off by at the most 4 degrees. Velocity components therefore need to be corrected for non-orthogonality of each triple wire, ignoring the cross products as mentioned in section 4.1. The effects of non-orthogonality on the results are well described by Andreopoulos (1983).

4.4. Kulite/Entran Modules :

The configuration of pressure transducers shown in figure 2.8 facilitated the measurement of two pressure gradients in the streamwise and spanwise direction simultaneously.

The pressure gradient in the streamwise direction is obtained by computing the ratio of pressure difference and the separation distance of the two pressure transducers in the streamwise direction while the pressure gradient in the spanwise direction is obtained by the considering the same ratio but using spanwise separation distance. Thus

$$\left[\frac{\partial \omega_z}{\partial y} \right]_w = -\frac{1}{\mu} \left[\frac{\partial p}{\partial x} \right]_w \approx -\frac{1}{\mu} \left[\frac{p_4(x + \Delta x) - p_1(x)}{\Delta x} \right] \quad (4.60)$$

and

$$\left[\frac{\partial \omega_x}{\partial y} \right]_w = \frac{1}{\mu} \left[\frac{\partial p}{\partial z} \right]_w \approx \frac{1}{\mu} \left[\frac{p_2(z + \Delta z) - p_1(z)}{\Delta z} \right] \quad (4.61)$$

4.5. Kulite/Entran Modules Calibrations :

All four Kulite and Entran pressure transducers were calibrated simultaneously using calibrator made by Thermo Systems Inc. model 1125 which provided the required range of pressures. The voltage outputs of the transducers were then recorded against the seven different pressures measured by the micro-manometer with a resolution of 0.00254 mm of water. The calibrations of Kulites as well as of Entrans demonstrated that the response of each transducer was linear as expected.

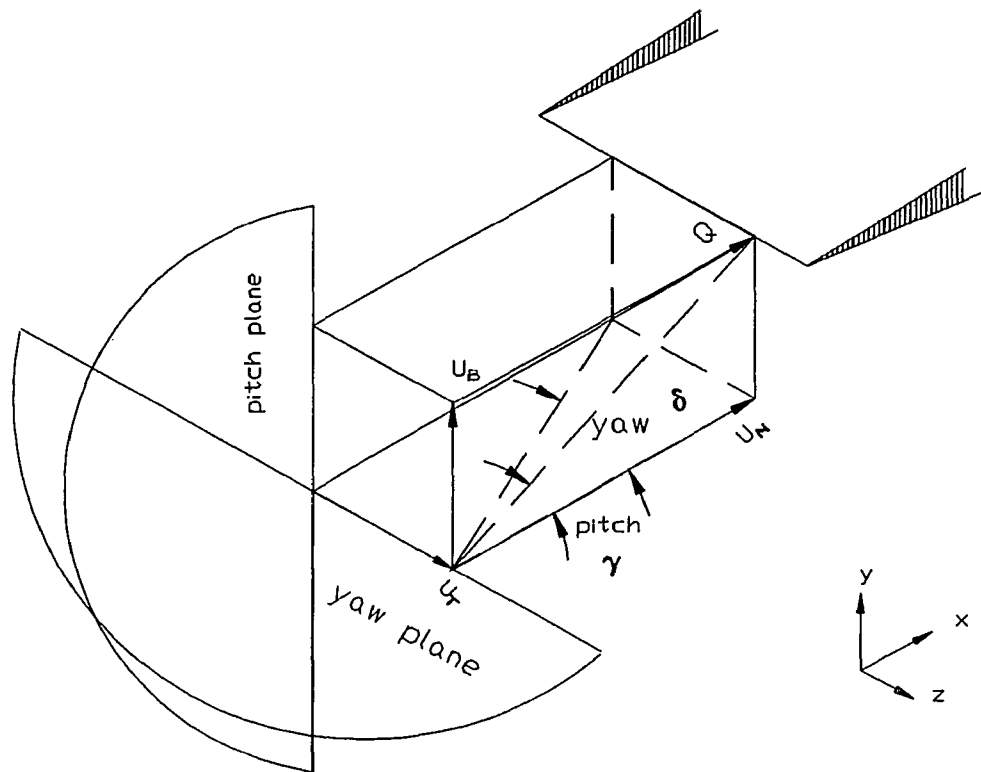


Figure 4.1. Sketch defining velocity components, yaw and pitch angles.

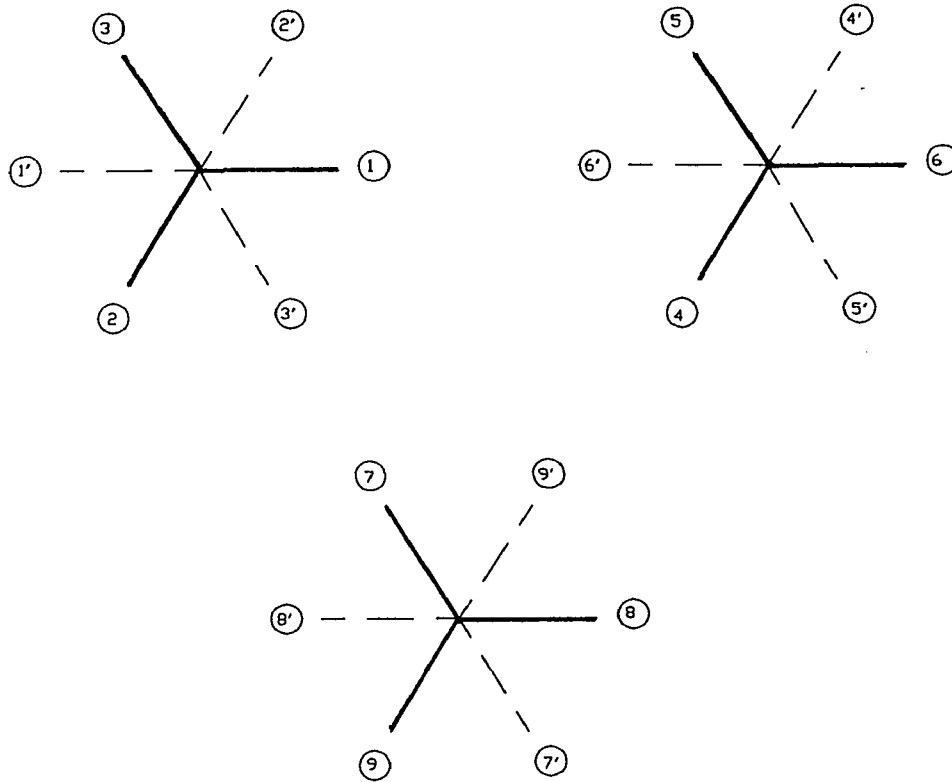


Figure 4.2. Orientations of each triple hot-wire in the 3TOW probe.

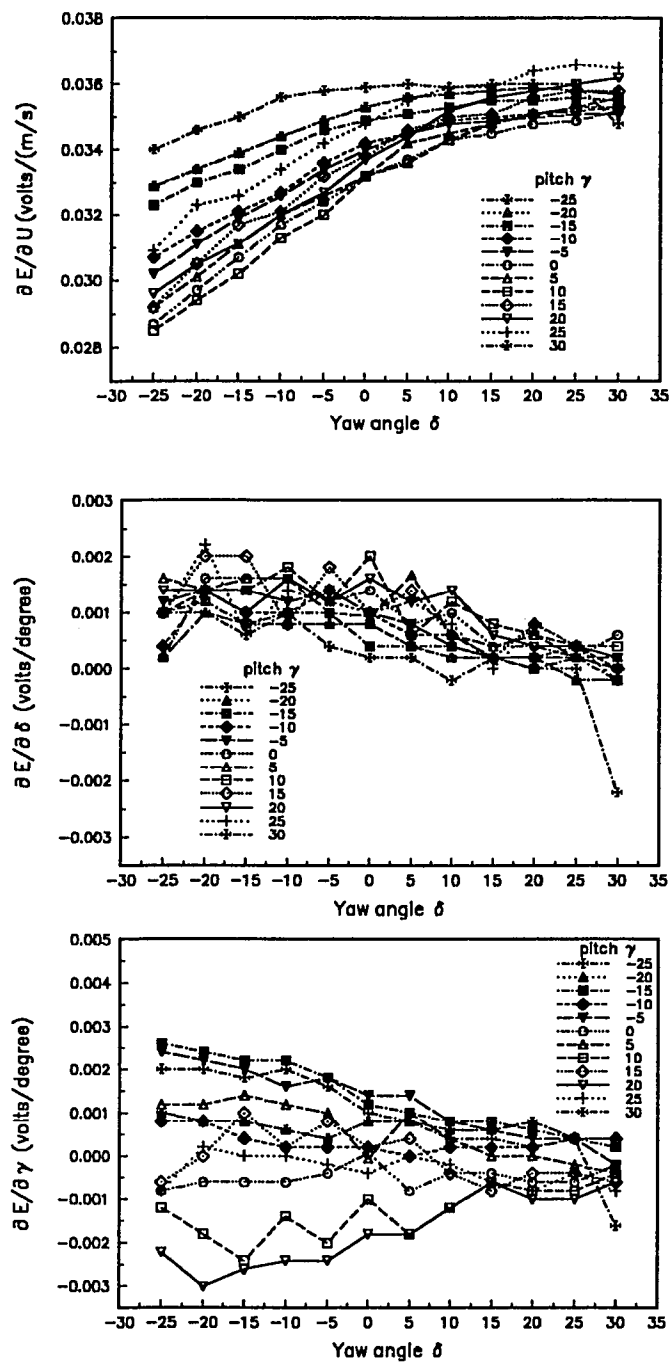


Figure 4.3. Typical plots of sensitivities $\partial E / \partial U$, $\partial E / \partial \gamma$ and $\partial E / \partial \delta$ for wire 1.

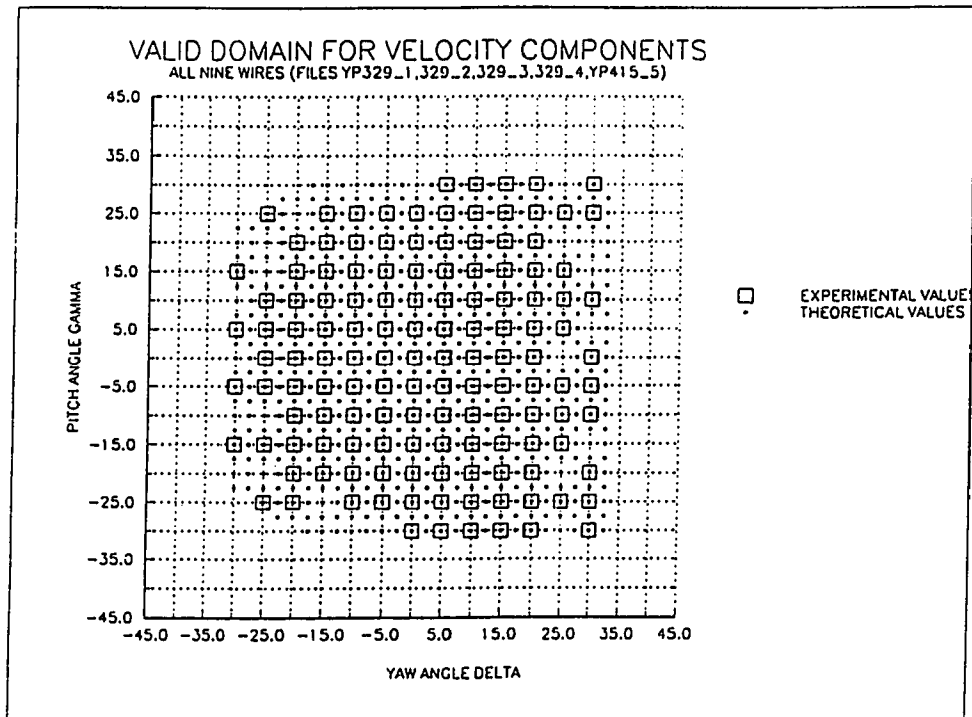


Figure 4.4. Domain of acceptability of velocity components by the three triple hot -wires of the 3TOW probe.

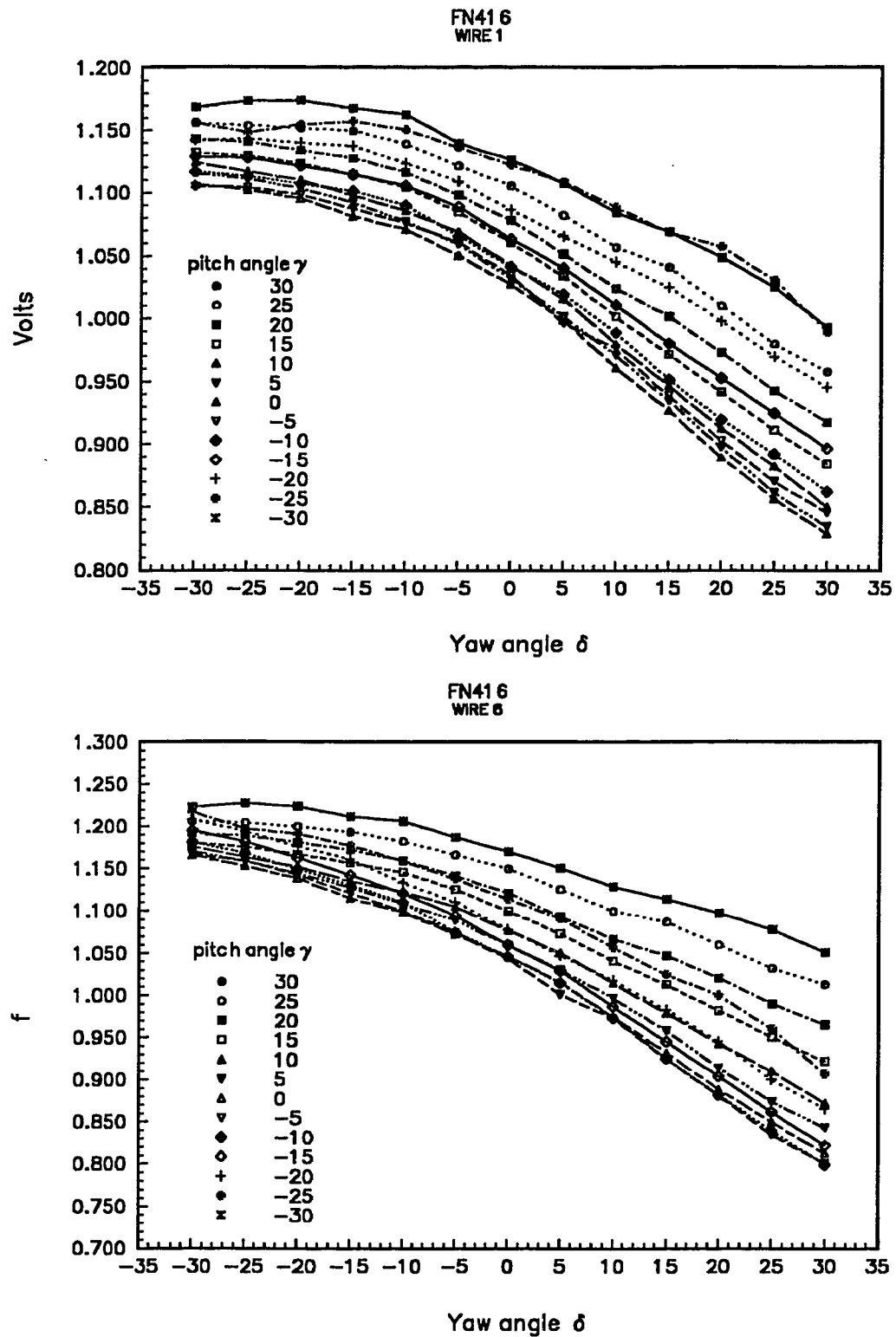


Figure 4.5. Plots of discrete function F vs. yaw angle for each wire computed from the calibration data at various pitch angles.

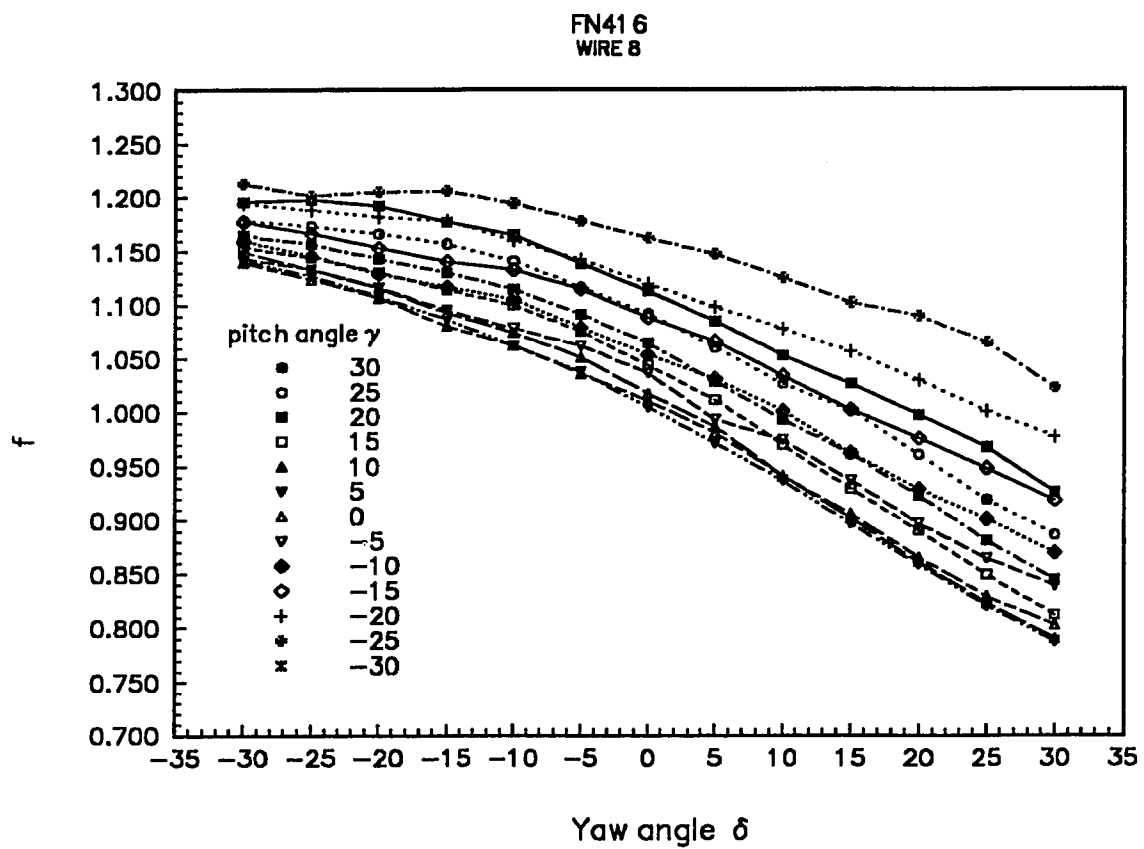


Figure 4.5. (contd.)

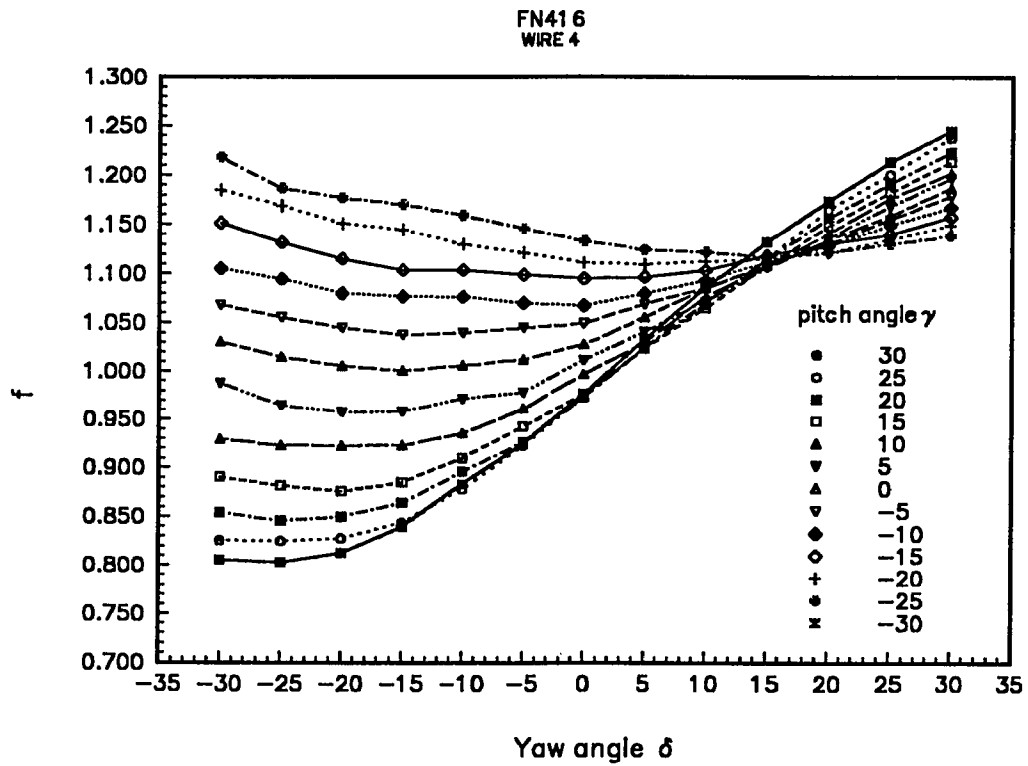
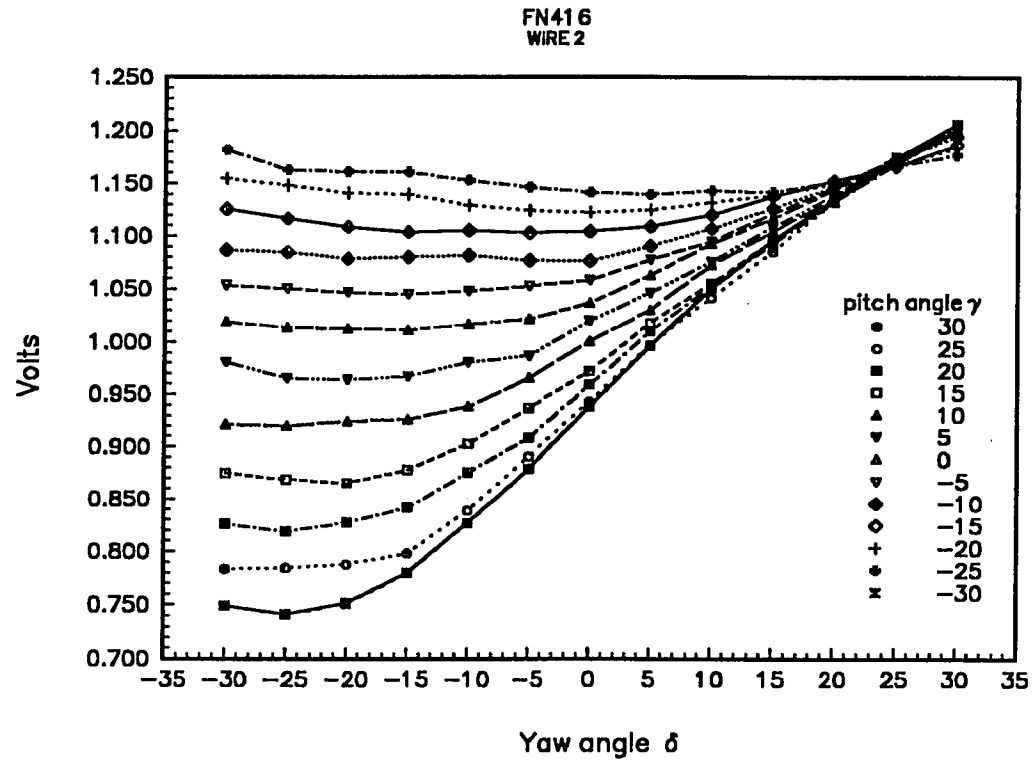


Figure 4.5. (Contd.)

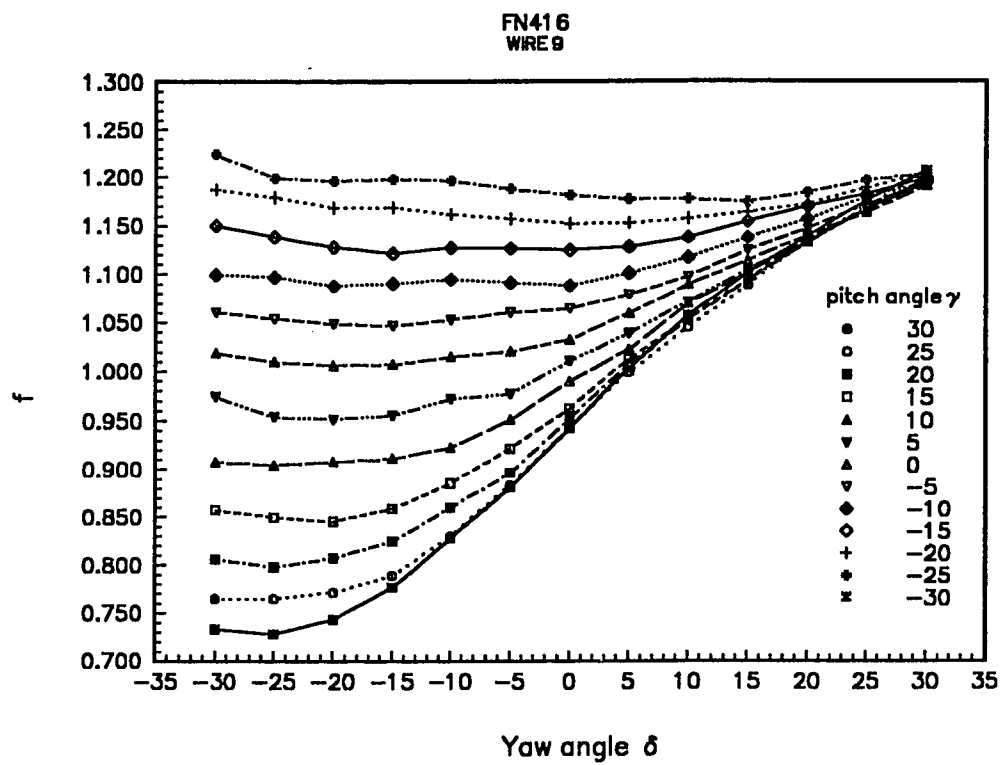


Figure 4.5 (Contd.)

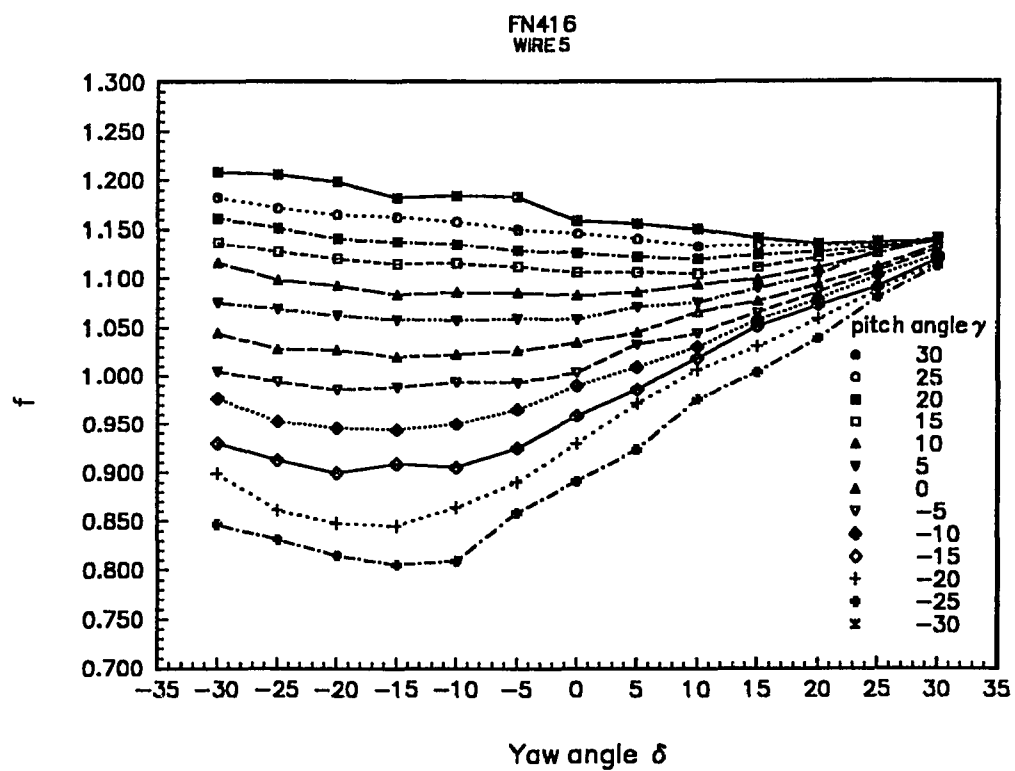
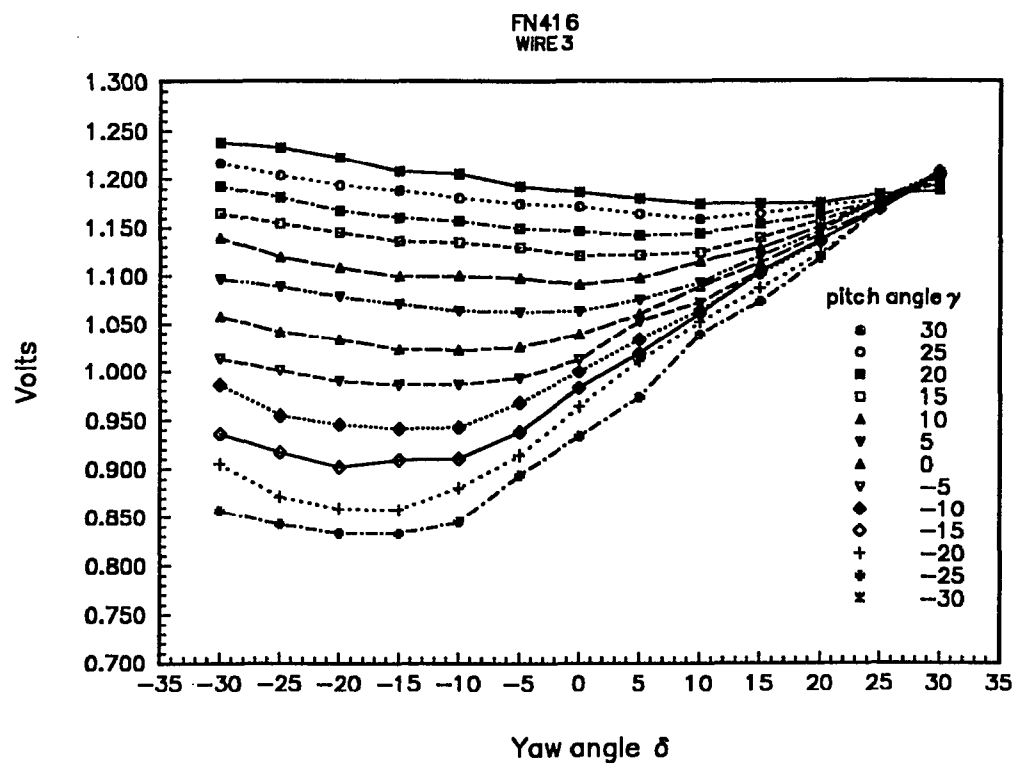


Figure 4.5(Contd.)

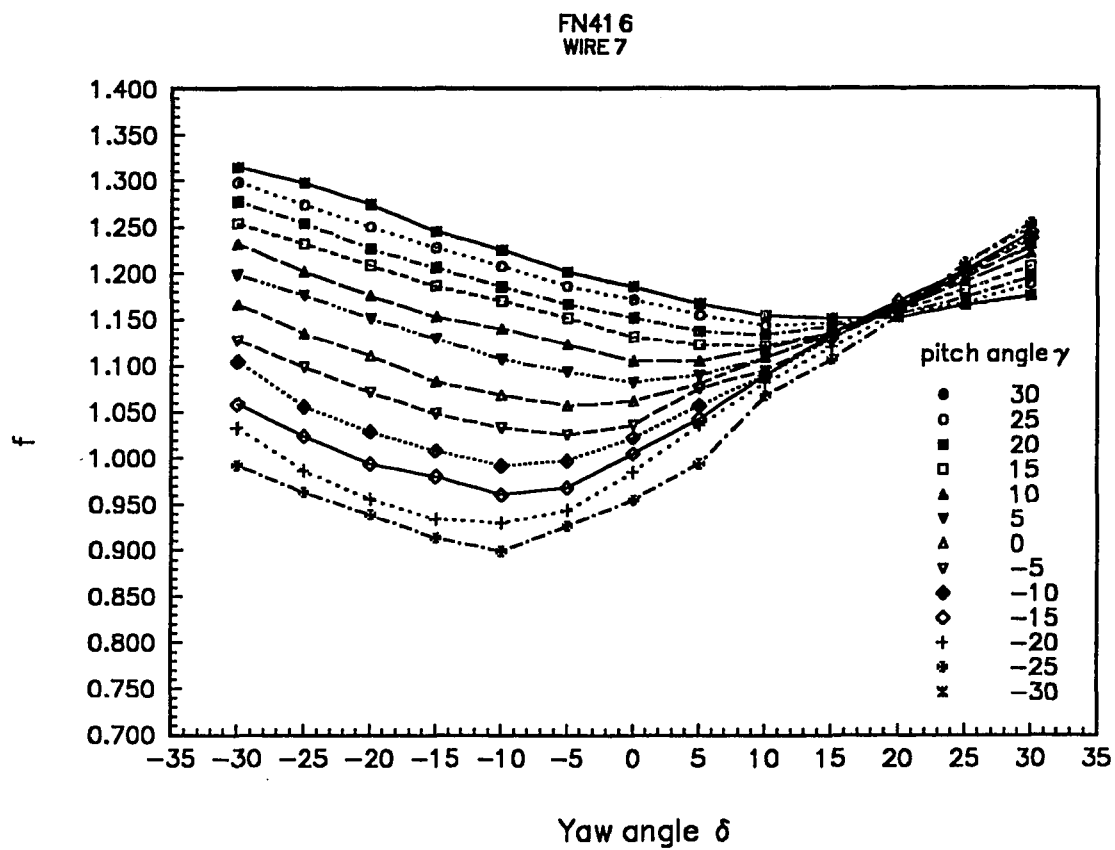


Figure 4.5 (Contd.)

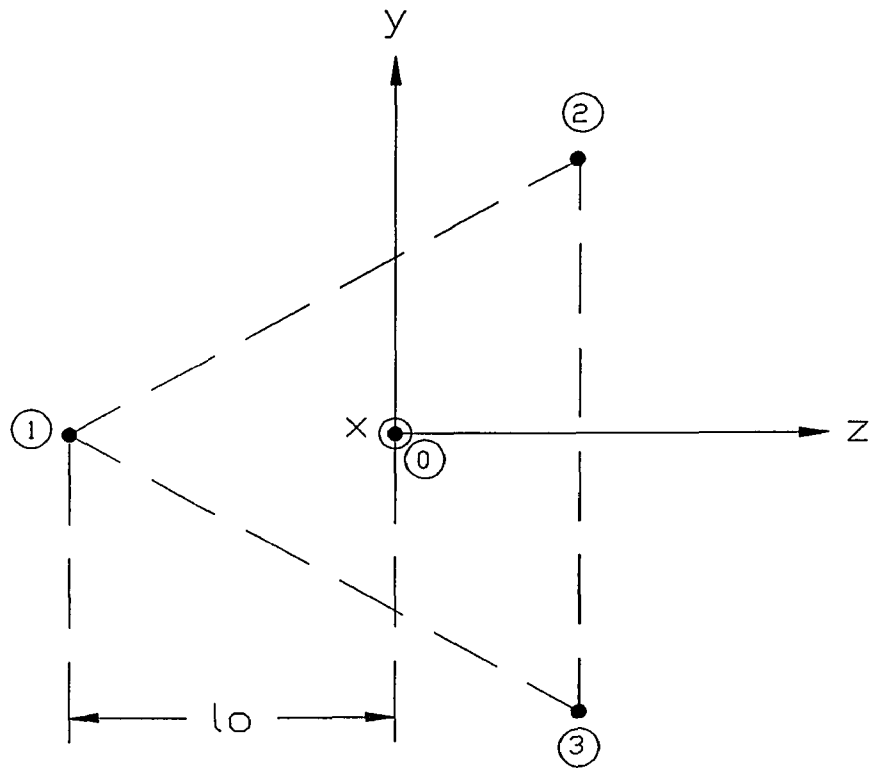


Figure 4.6. Co-ordinate system for vorticity computations.

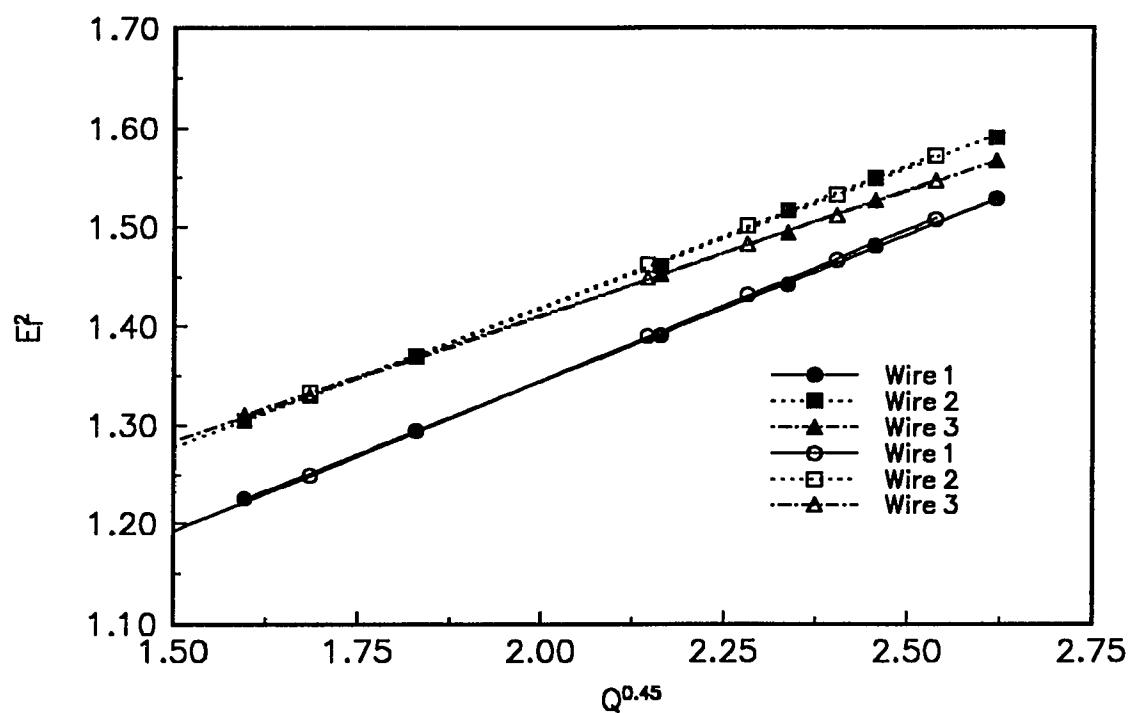


Figure 4.7. Typical velocity calibration plots for wires 1, 2 and 3. Filled symbols: calibration at the beginning and open symbols: calibration at the end of each experiment.

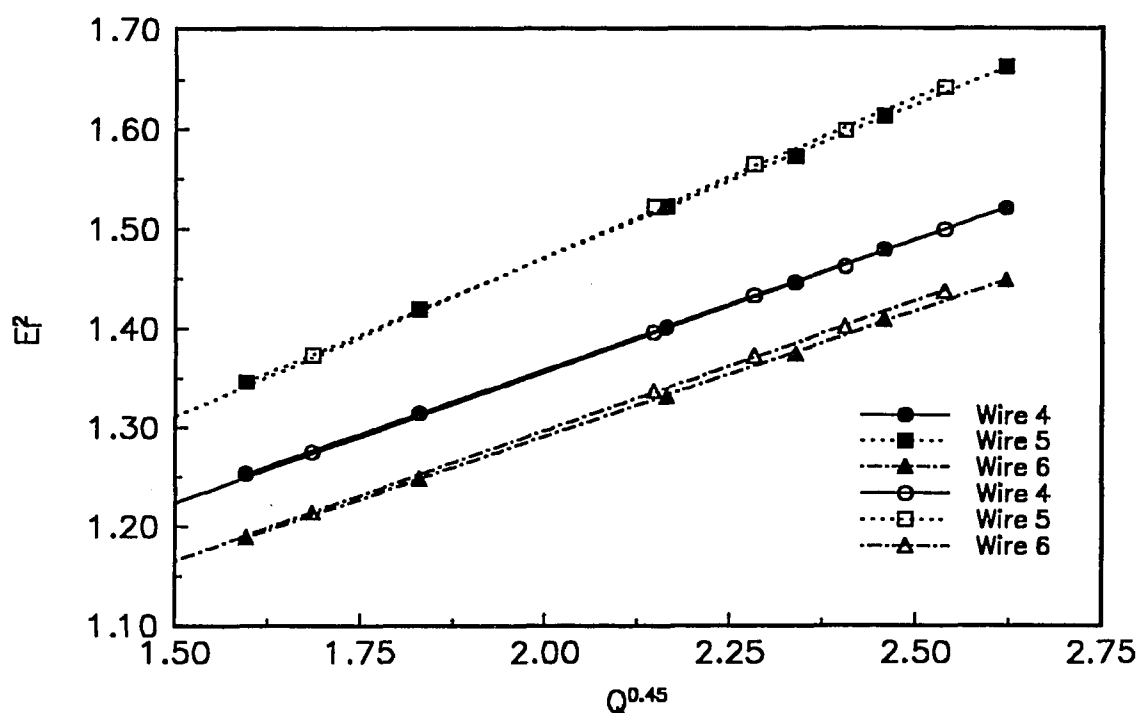


Figure 4.7 (contd): Typical velocity calibration plots for wires 4, 5 and 6.

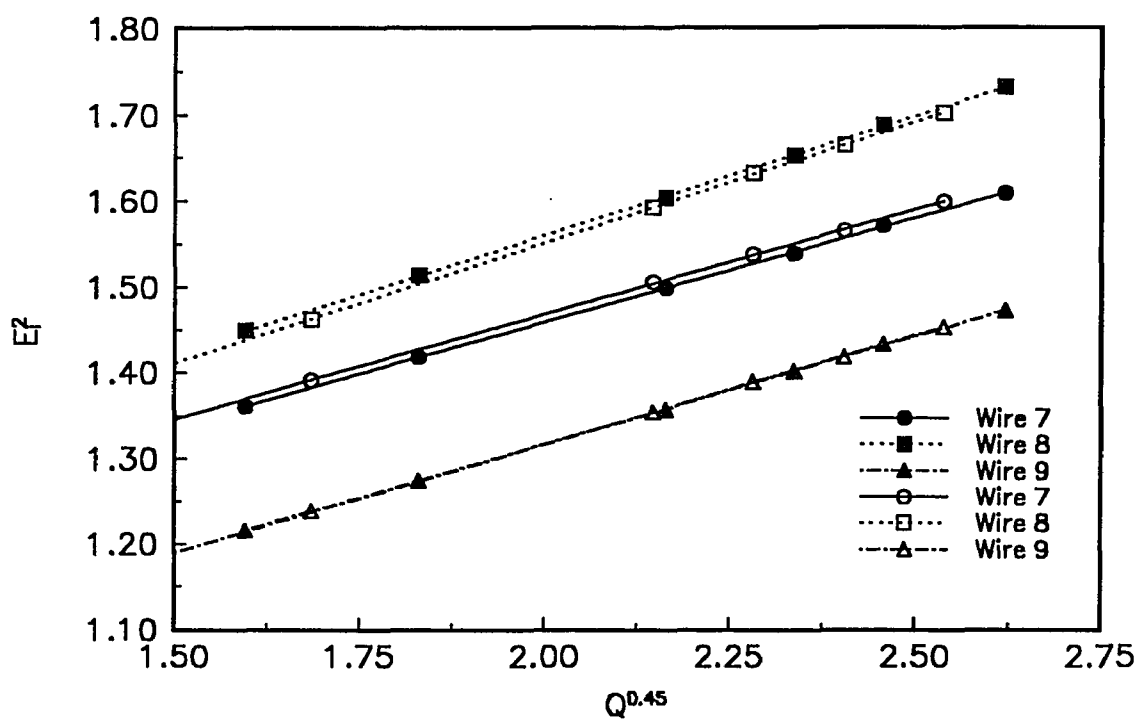


Figure 4.7 (contd). Typical velocity calibration plots for wires 7, 8 and 9.

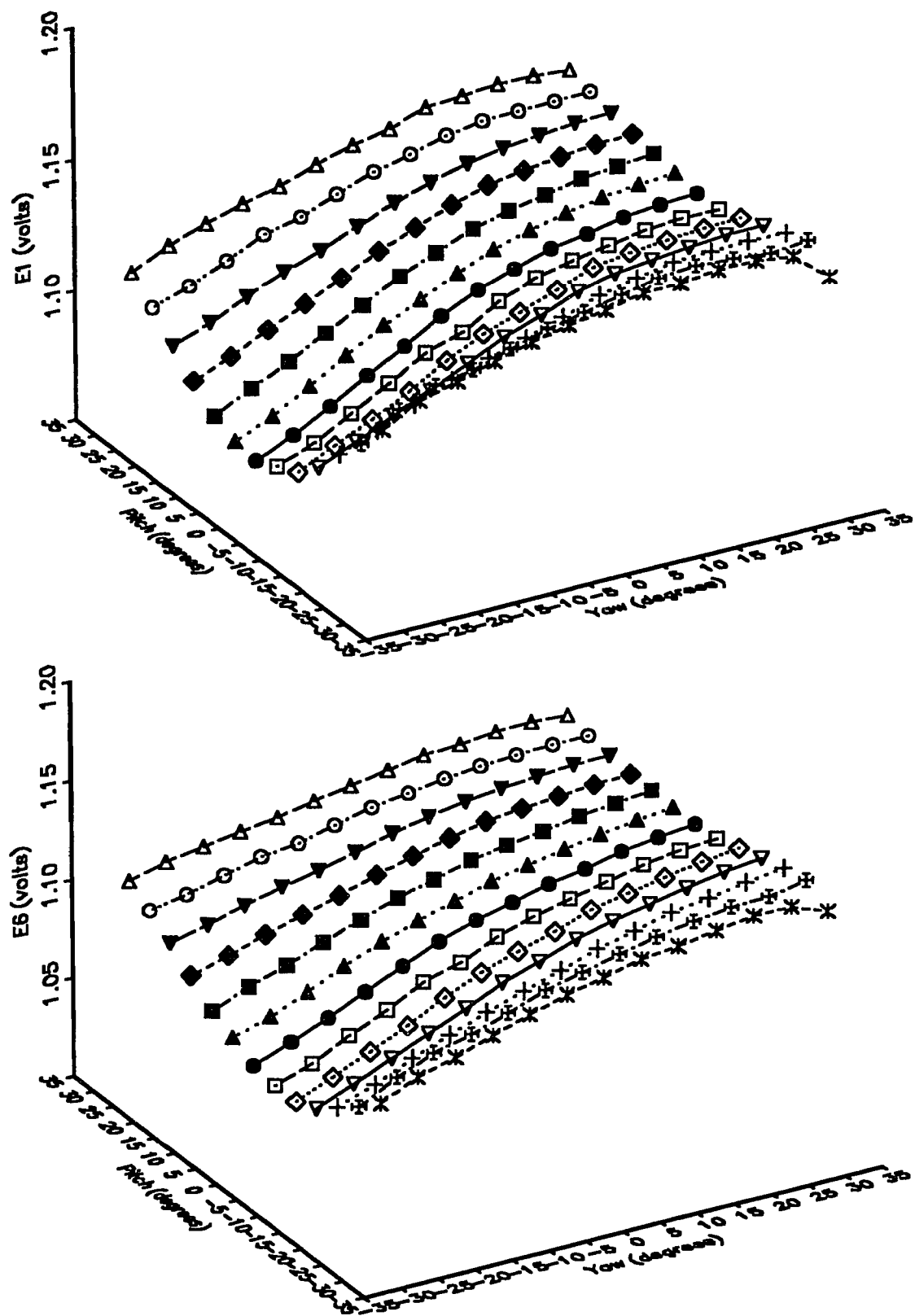


Figure 4.8. Yaw and pitch response of each hot-wire.

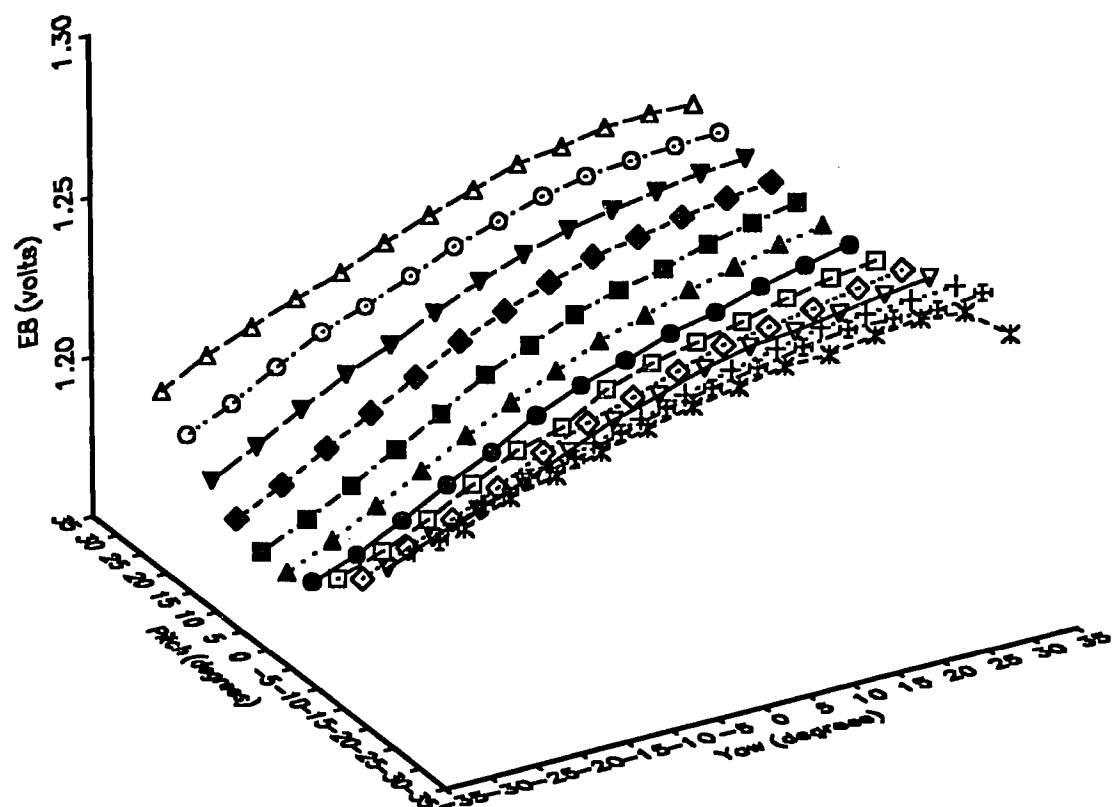


Figure 4.8. (Contd.)

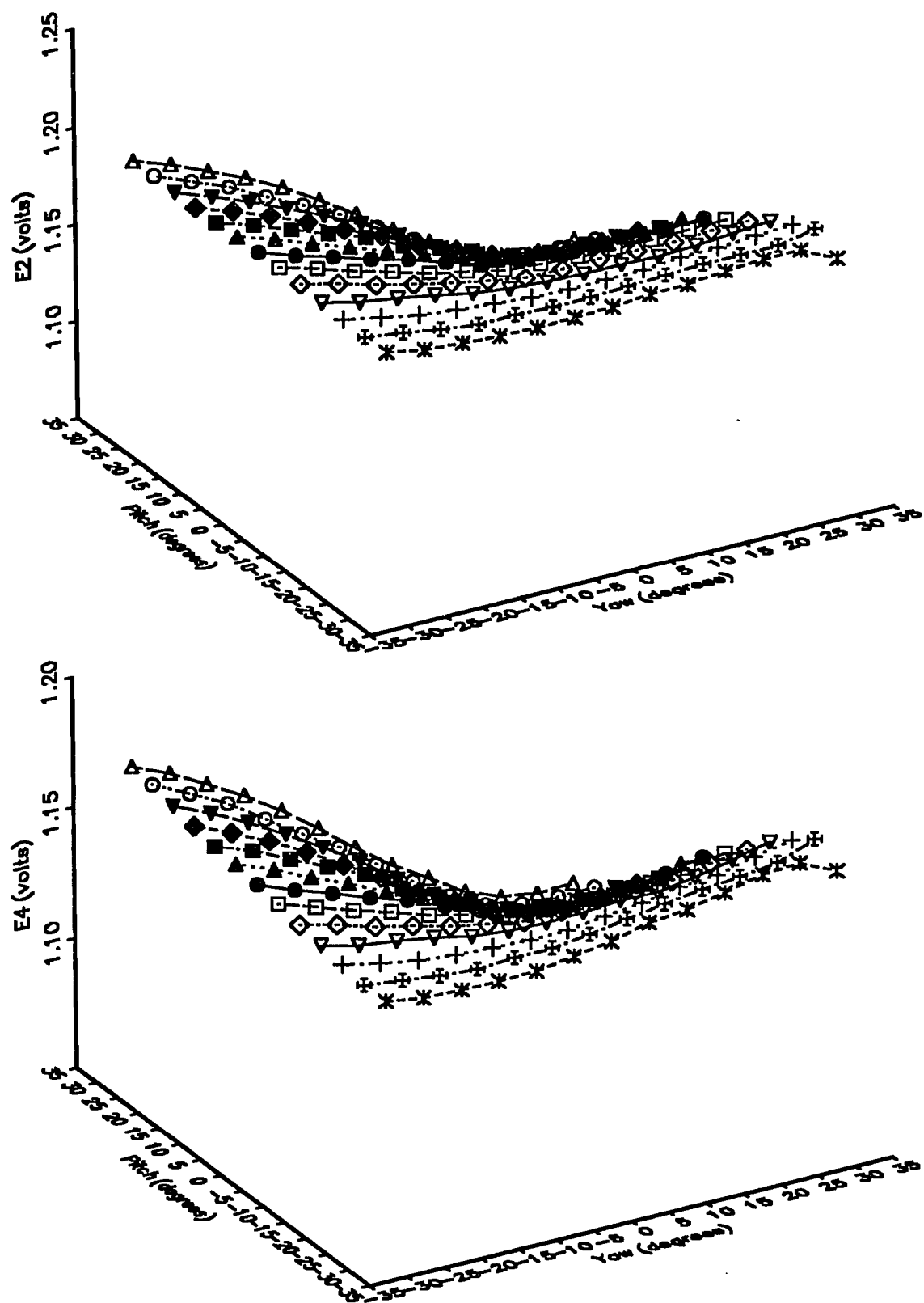


Figure 4.8. (Contd.)

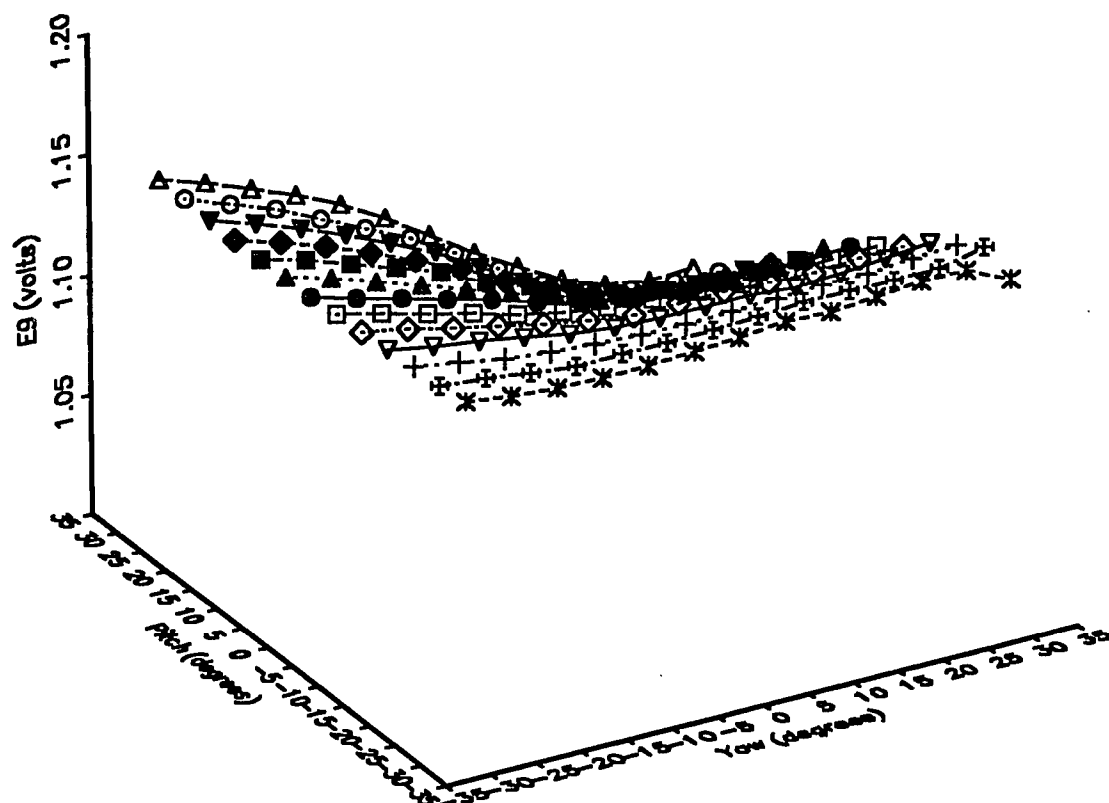


Figure 4.8. (Contd.)

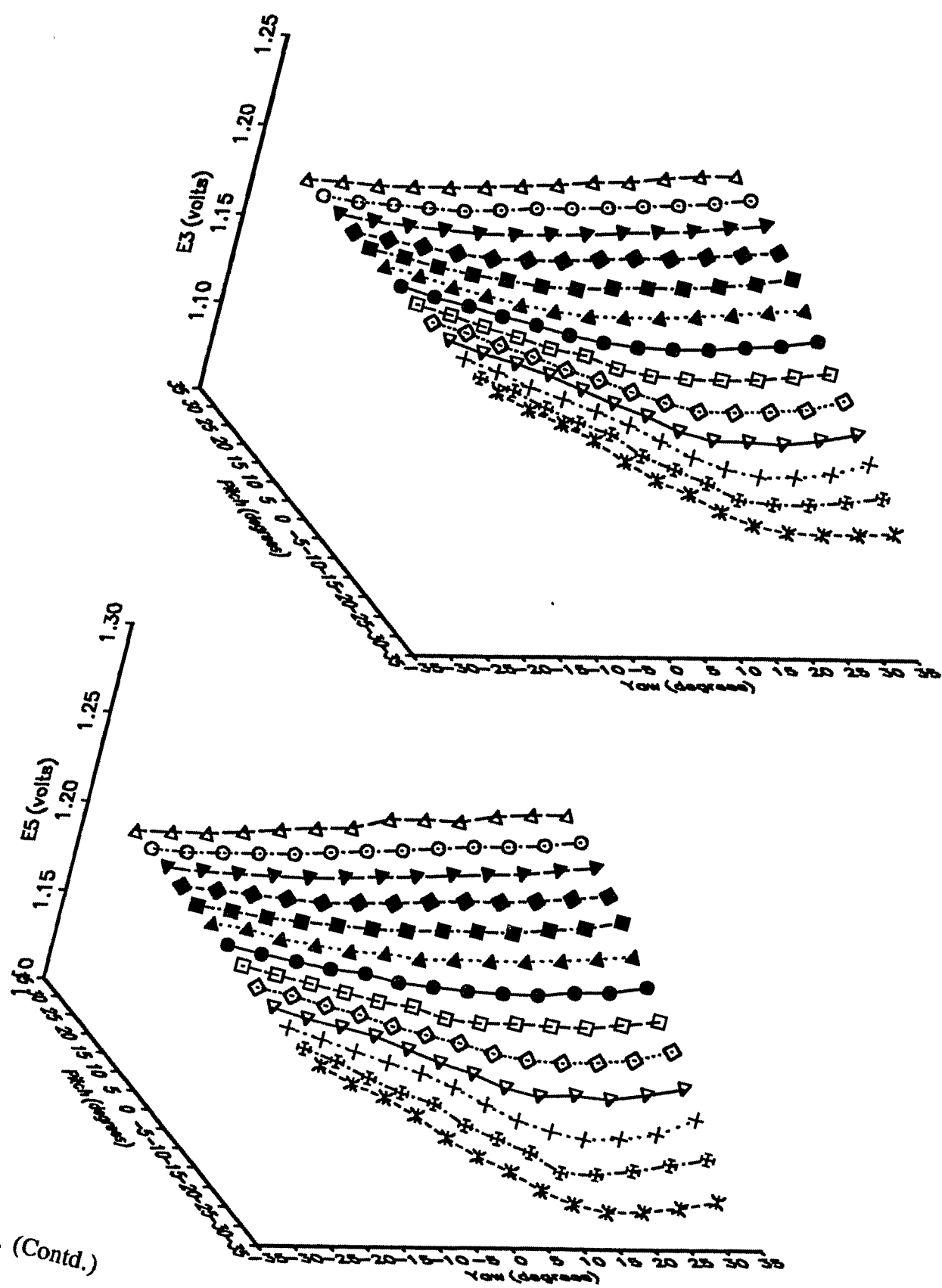


Figure 4.8. (Contd.)

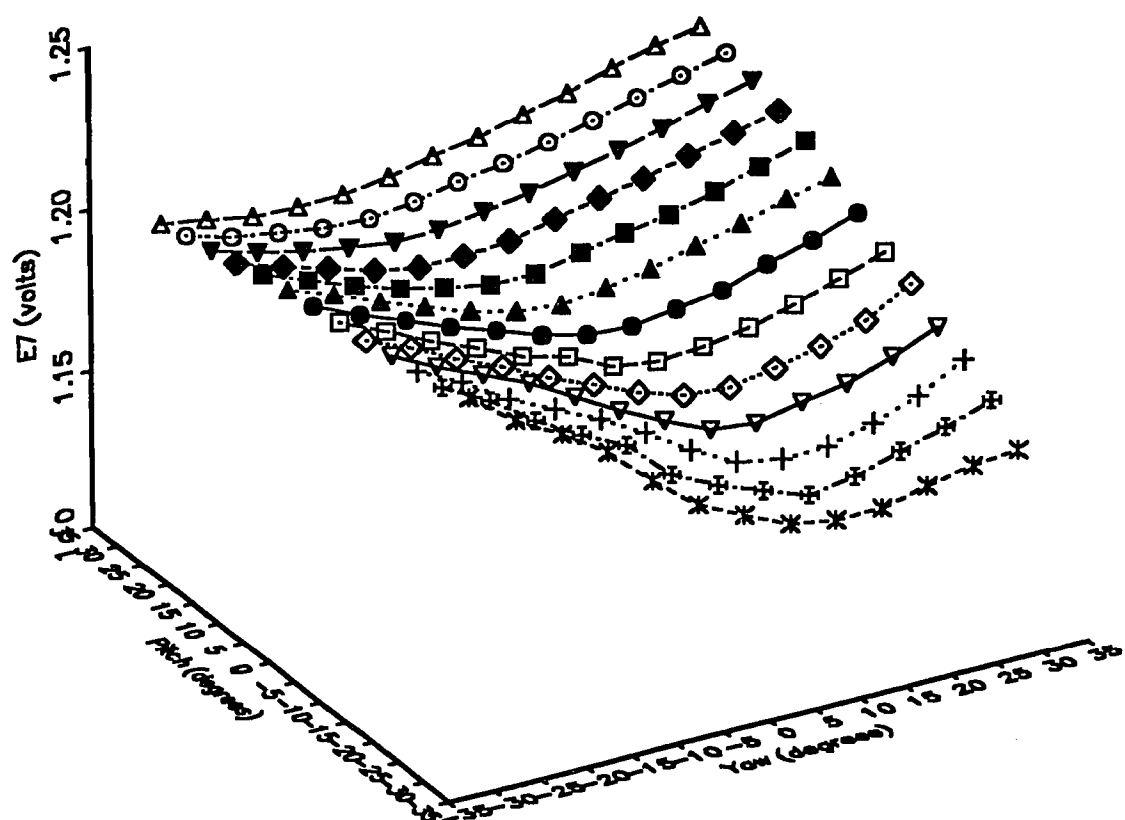


Figure 4.8 (contd)

5. MEASUREMENTS

The investigative experiments in the two dimensional turbulent boundary layer flows and inherently three dimensional delta wing flows were performed essentially in three parts.

a) Instantaneous measurements of three components of velocity and vorticity by 3TOW probe.

b) Time resolved measurements of axial and spanwise wall pressure gradients by the Kulite and Entran modules.

c) Combined instantaneous measurements of velocity, vorticity and vorticity flux by the 3TOW probe and Entran module.

In this dissertation the results of the time-resolved data of velocity and vorticity by 3TOW probe and the simultaneous data of velocity, vorticity and vorticity flux (through two pressure gradients along the wall) will be reported.

5.1. Boundary layer flow : Preliminary Experiment

Measurements By 3TOW Probe :

The flow characteristics of the turbulent boundary layer investigated by the 3TOW probe are listed in table 5.1. The spatial and temporal resolution of the probe are listed in the table 6.1. A plot of mean velocity measured during Pitot tube traverse in the boundary layer is shown earlier in figure 2.3. The streamwise location had to be carefully selected in order to eliminate the interference from the boundary layers present

on the side walls.

Data was collected simultaneously on all 9 wires with a sampling rate of 5kHz per channel for total duration of about 82 seconds at each point. Time of collection of data was adequate according to the criteria as prescribed by Klewicki and Falco (1990) for statistical convergence of ensemble quantities. The signals were low pass filtered at 2kHz before digitization and were corrected for contamination due to free stream temperature variations although these were very small to the extent of 1 to 2° F. All channels were continuously monitored by the oscilloscopes during the measurement session. No breakage of any of the nine sensors occurred during the experiment.

5.2. Boundary layer flow : Concluding Experiment

Simultaneous Measurements By 3TOW Probe & Entran module:

The redesign and extension of the working section of the wind tunnel permitted repeating the experiment in the turbulent boundary layer with increased resolution of the probe and therefore higher signal to noise ratio. The principal parameters of the flow are listed in table 5.1.

The Entran module was placed in the wind tunnel floor flush with the top surface and the 3TOW probe was then pitched 2° down before the data was acquired SIMULTANEOUSLY from the 9 hot-wires and 3 pressure transducers at a sampling rate of 5 kHz per channel. All signals were low pass filtered at 1 kHz and the data was streamed to the hard disk through the DMA. The pressure signals were amplified by 10000 and band pass filtered at 0.03 - 3 kHz by the differential preamplifier and further amplified by 20 and low passed at 10 kHz while anemometer outputs were amplified 5

times before acquisition.

5.3. Flow over delta wing:

The 3TOW probe was placed in the delta wing flow with free stream velocity of 3 m/s, Reynolds number based on the chord of the delta wing $Re_c = 58615$. The anemometer outputs of all nine hot-wires were low pass filtered at 2 kHz before digitizing at 5 kHz sampling rate. The signals were monitored frequently on the oscilloscopes during the experiment. The data was collected at the measurement position $x/C = 0.85$ measured from the apex of the wing for about 61 seconds and streamed to the hard drive before mass storage on tapes. The flow field was scanned at several spanwise and normal positions for delta wing at 15° angle of attack. At each measurement location the probe axis was aligned appropriately with anticipated mean flow direction. The table 5.2. shows the spatial measuring points at which the data was collected. The Pitot tube data was also recorded to keep track of any variations in the free stream velocity. The ambient temperature was monitored at regular intervals. Since the measurements of the velocity field were carried out in several sessions, it was essential to perform calibrations of each hot-wire at the start and the end of each such session.

The final analysis of the data was carried out on the DEC work station 5000 after transferring the data files stored on the tapes via Ethernet.

	U_{∞} m/s	δ m	δ^* m	θ m	Re_{θ}	u_r m/s	C_f
Prelim. Expt. 3TOW probe	3.0	0.120	0.0150	0.0120	2244	0.140	0.0040
Concl.Expt. 3TOW probe + Entran module	3.2	0.140	0.0175	0.0136	2790	0.130	0.0033

Table 5.1. Principal parameters of the turbulent boundary layers.

Angle of attack: $\alpha = 15^\circ$	probe alignment pitch, yaw	-5, 0	-5, +5	-5, +10	-5, +10	-5, +10	-5, +10	-5, +10	-5, +10	-5, +10
z in mm		0	65	85	110	135	160	185	210	225
y in mm		7	7	7	7	3	6	6	3	3
		19	13	13	12	6	7	7	5	5
		31	20	19	17	7	12	12	7	6
		43	28	25	22	12	17	17	10	7
		55	38	31	27	17	22	22	13	9
			48	37	32	22	27	27	15	12
			60	43	37	27	32	32	17	17
			75	49	42	32	37	37	22	22
			90	55	47	37	42	42	25	47
			107	61	52	42	47	52	32	72
				67	57	47	52	62	37	115
				73	62	52	57	72	42	155
				83	72	57	62	87	52	
				93	87	65	72	107	79	
					102	75	87	135	119	
					120	95	107	165	159	
						110	125			
						130				

Table 5.2. Locations of measurement points on the delta wing for 15° angle of attack for the 3TOW probe experiments.

6. RESULTS & DISCUSSION

6.1. Resolution considerations:

The wire length of each sensor, separation distance of each sensor and finally spacing of each of the three triple wires were the most important dimensions to be optimized very carefully in the final configuration of the 3TOW probe for good spatial resolution. Although these dimensions apparently independent, could not be varied independently to improve one performance characteristic without introducing an adverse effect on the other. Wire length for example should be kept as small as possible to resolve finer scales in the flow but too small an aspect ratio (length/diameter) of the sensor increases the heat conduction effects and therefore is likely to manifest in erroneous data and inaccurate flow quantities. The sensor separation should be as small as possible to satisfy the assumption that velocity is uniform across the measuring area, but then this has to be balanced by the thermal wake effects/cross talk between the wires. Further this separation should be less than the Kolmogorov length to capture the smallest structural scale but then this separation should also be greater than the Kolmogorov length according to Wyngaard (1969) so that the gradients are measurable. Both conditions in reality are impossible to satisfy simultaneously. The third dimension of spacing of each of the three triple wires should be short yet finite so that the velocity gradients to be evaluated in the computation of vorticity do not "disappear". This spacing, if too small, would result in unacceptably low signal to noise ratio as pointed out by George (1993).

The probe also required additional prongs to operate each sensor independently,

which increased only minimally the blockage effects due to the 6 extra prongs by about 2.5% over that of Balint *et al.* It is to be noted that their probe uses 12 prongs by making one common to a set of three hot-wires but which in turn, may create potential problems related to the dynamical imbalance at the time of measurement. The present probe due to mutually orthogonal orientation of wires, has a larger "acceptance cone" when compared to the probe of Balint *et al.* (1991) which has one wire at 45° to the plane of other two orthogonal wires and therefore the 3TOW probe is capable of measuring flows with larger turbulence intensities.

The estimates of flow scales resolutions expressed in viscous scale units and in Kolmogorov microscale units are given in tables 6.1 and 6.2 respectively. The Kolmogorov length scale $\eta = \left[\frac{\nu^3}{\epsilon} \right]^{1/4}$ indicates the smallest turbulent structure encountered in the flow. Determining η however, requires a good estimate of the turbulent kinetic energy dissipation rate ϵ , which is very difficult to measure directly in the laboratory. Previous studies obtained the value of ϵ by making assumptions to reduce some of the terms in the expression below for the dissipation of energy per unit time per unit mass

$$\epsilon = \nu \left[\overline{\left[\frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j} \right]} + \overline{\left[\frac{\partial u_i}{\partial x_j} \frac{\partial u_j}{\partial x_i} \right]} \right]$$

The dissipation rate ϵ has been computed from the measured values of the terms of the velocity gradient tensor by five different methods, all listed in table 6.2, which resulted in slightly different wire and probe resolutions. Although the assumptions involved in each method may not be valid at $y^+ = 12.5$, which is the closest to the wall

measurement location, the resulting resolution is comparable to that of Balint *et al.* (1991) and gets better as the wall normal distance increases. The present probe however is not immune to spatial attenuation problems caused mainly by the finite spacing of the individual triple hot-wire probes. The recent work of Ewing and George (1993) where estimates are provided of attenuation of the vorticity measurements by probes similar to the present one, suggests that the present measurements of r.m.s. vorticity components may be attenuated by about 11% to 18%. Although the assumptions made in such theoretical considerations are not always satisfied in each particular flow, they are useful in providing an estimate of the uncertainties involved in this type of measurements. The errors involved in calculating normal and spanwise components of vorticity were minimized by more accurate estimates of the velocity gradients in the streamwise direction which are computed using all the terms in the Taylor's "frozen flow" expression (see equations: 4.56-4.58).

The results of the present investigation are illustrated by adopting the scaling factors commonly used by many investigators for comparison which, it should be noted, implies that such scaling would collapse all quantities of turbulence onto a single curve. This notion of existence of such a universal scaling is neither well established nor well investigated. An experimental attempt by Wei and Willmarth (1989) in turbulent channel flows for a range of Reynolds number tried to address this issue. They concluded from their results that a) scaling by inner variables of turbulent quantities are, at least in the near wall region, Reynolds number dependent and b) where as the power spectra of axial velocity were found to scale with these inner variables, the power spectra of normal component as well as that of Reynolds shear stress did not. Lastly the boundary layer

flows on a flat plate, in a pipe, or in a channel are characteristically different especially at low Reynolds number. The conclusions drawn therefore need to be viewed in the light of the fact that the scaling laws for these flows are yet to be established fully by rigorous analysis.

6.2. Turbulent Boundary Layer : Preliminary Experiment

3TOW Probe:

Figure 6.1 shows that the mean velocity data obtained with nine-wire vorticity probe and computed at the centroid obeys the log-law. The mean velocity at the center of each of the triple hot-wires also followed the log-law. The r.m.s. values of the fluctuations of the three velocity components u , v and w in the near to the wall region are shown in figures 6.2a, 6.2b and 6.2c. The axial velocity results are in good agreement with those of Balint *et al.* (1991) but normal and spanwise velocity fluctuations are significantly higher especially for $y^+ \leq 40$. The higher rms values for v and w can not be attributed to the difference in spatial resolutions and to the size of the two probes although the probe with poorer resolution is found to overestimate the fluctuations of normal velocity. The higher values of v' and w' are also observed in the data from higher Reynolds number boundary layer experiment and this apparent discrepancy therefore is addressed in section 6.3. The shear stress $-\rho\overline{uv}$ distribution is plotted in figure 6.3. The data are normalized by the inner variables ν and u_τ . On these figures the experimental data of Balint *et al.* (1991) and direct simulations of Spalart (1988) and Kim, Moin and Moser (1987) are also plotted for comparison. Although the agreement of the present data with previous measurements is quite well in the regions far

from the wall, considerable differences are evident in the region close to the wall. The present shear stress measurements, for instance, are much higher than the measurements of Balint *et al.* (1991) in the region $y^+ < 40$. They are, however, closer to the results of Spalart (1988). Although the present vorticity probe is very similar to that used by Balint *et al.* (1991), some significant differences exist which will be pointed out later.

Figure 6.4a, 6.4b and 6.4c show the near wall distributions of the r.m.s. ω'_x , ω'_y , ω'_z of the fluctuations of the three vorticity components as they have been measured in the present work. Comparison with the existing data is also made. Again considerable disagreement exists in the values among different sets of data. The present data are higher than those of Balint *et al.* (1991). Since present technique resolves more fluctuations of velocity vectors with large yaw and pitch angles than the techniques of Balint *et al.* (1991), and that a more sophisticated calibration technique was used here which takes into consideration variation of the pitch and yaw response of each wire with pitch and yaw angles, this disagreement is not a surprise. In addition the values of r.m.s. $\partial u^+ / \partial y^+$ as they have been measured by Balint *et al.* (1991) are about 80% lower than the data of Lu and Smith (1988). This suggests that Balint *et al.* measurements may be underestimating the true values.

6.3. Turbulent Boundary Layer : Concluding Experiment

3TOW Probe and Entran module:

In this experiment an increase in signal to noise ratio and improvement in the resolution of scales were achieved by, first, extending the working section by 16 ft. which permitted larger boundary layer thickness without significant increase in the free

stream velocity, and second, using data acquisition hardware with 16 bit a/d converter and low noise integrated low pass filters. The results are discussed first for the data by 3TOW probe and then for the simultaneous data of 3TOW probe and Entran module. The flow characteristics of the existing datasets used in the comparison are given in table 6.3

Velocity components Statistics:

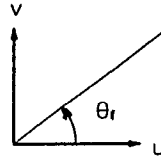
Figures 6.3.1, 6.3.2 and 6.3.3 show the rms values of axial, normal and spanwise velocity components normalized by the friction velocity u_τ plotted against the distance normalized by the outer scale δ . For $y/\delta > 0.1$ the axial velocity fluctuations agree well with those of Balint *et al.* (1991) but they are lower in the near wall region $y/\delta < 0.1$. On the contrary the normal velocity fluctuations show opposite trend in the near wall region but then agreement is quite well with the measurements of Balint *et al.* (1991), Klebanoff (1954) and the simulation results of Spalart (1988) in the rest of the boundary layer. The same three velocity fluctuations, scaled with inner variables ν and u_τ are plotted in figures 6.3.4, 6.3.5 and 6.3.6 for y^+ values up to 100. The streamwise fluctuations u' of Balint *et al.* (1991) are consistently higher but present results compare satisfactorily with those of Andreopoulos *et al.* (1984) in the lower part of logarithmic layer. In the boundary layer investigated the rms values of normal velocity are the lowest when compared with the rms levels of axial and spanwise velocity as expected and are comparable to those in LDA experiments of Wei and Willmarth (1989) made with remarkably low spatial resolution in the channel flow at Reynolds number lower than that in this investigation. Kastrinakis and Eckelmann (1983) measurements are slightly lower

but both illustrate the same trend as the current measurements. It is rather unusual to note that the data of Balint *et al.* (1991) to be considerably lower. The peak value of u' is observed to occur closer to the wall when compared with that of v' , which peaks further away from the wall. The rms of spanwise velocity fluctuations however are in good agreement with Balint *et al.* (1991) for $y^+ > 40$. But near the wall, these values deviate by significant amount although the data compared used the same wall variables. Wei and Willmarth (1989) have shown that the turbulence intensities lack similarity with this scaling. Spalart (1988) and Kim *et al.* (1987) have also pointed out that these quantities to be Reynolds number dependent.

Figure 6.3.7a shows the turbulent kinetic energy $\frac{1}{2}(\overline{u^2} + \overline{v^2} + \overline{w^2})$ distribution in the near wall region as computed at the centroid of the 3TOW probe while figure 6.3.7b illustrates these values at the center of each of the three triple wires. The present values agree remarkably well with Balint *et al.* (1991) for $y^+ > 30$ but are higher closer to the wall. Since the drop out rate during the data reduction of samples closer to the wall was not higher than that in the outer region of the boundary layer, the noticeable difference would possibly be attributed to greater number of velocity vectors being validated as a result of larger acceptance cone as mentioned elsewhere. The difference in the rms values of each of the three velocity components with Balint *et al.* (1991) reflect this effect. But these values of velocity fluctuations as computed at the center of the probe, are comparable to those of Kastrinakis and Eckelmann (1983) and channel flow results ($Re_{d/2} = 39582$) of Wei and Willmarth (1989). Therefore the turbulence intensity profiles of u , v and w in the present work are consistently higher and that the data do not seem to collapse even deep into the inner layer.

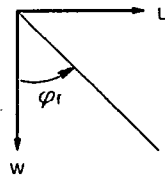
In order to investigate how large are the excursions of velocity vector and to verify if they are within the "acceptance cone" of the probe, the statistics of two flow pitch and yaw angles θ_f and ϕ_f are computed. These two flow angles defined as

$$\theta_f = \sin^{-1}\left(\frac{v}{\sqrt{u^2+v^2}}\right)$$



and

$$\phi_f = \sin^{-1}\left(\frac{w}{\sqrt{u^2+w^2}}\right)$$



together, describe the velocity vector orientation completely in space. The rms values of both these angles are plotted and shown in figure 6.3.8 as a function of normalized distance y^+ in the range 12.5-120. The peak rms value for flow pitch angle θ_f is about 8° and that of flow yaw angle ϕ_f is about 10° . These values as measured at the center of the third triple wire at the lowest y^+ of about 3 are also shown in this plot. This implies that instantaneous velocity signatures can vary by as much as $6 \text{ r.m.s} \approx 48^\circ$,

which indeed is the case as is demonstrated in figure 6.3.9 where typical instantaneous signatures of both flow angles θ_f and ϕ_f are plotted. The time series for flow yaw angle ϕ_f is shifted by 30 units for clarity. The data was further analyzed by computing the probability distribution functions of these angles as measured by the first sensor triplet of the probe. The probability density distribution of flow pitch angle θ_f , is shown as a function of the rms normalized angle in figure 6.3.10. This distribution is skewed to the left indicating that frequently occurring low amplitude fluctuations are countered by rare but strong positive fluctuations. This however is not the case for the flow yaw angle ϕ_f , since its distribution is quite even in that positive fluctuations are as likely as negative ones and that the tails are evenly distributed. High amplitude fluctuations of over four times the rms value of 8° , although less frequent, are observed in figure 6.3.11 which shows the probability distribution values of flow yaw angle ϕ_f against the angle expressed in terms of its rms value. It is therefore plausible, in the context of probe performance, that the probe of Balint *et al.* (1991) because of its geometry may not be able to capture these high fluctuations in magnitude and direction of the velocity vector.

The skewness factor being a third order moment of the random variable retains the sign and therefore contains important statistical information relating to the kinematics of coherent structures viz. accelerating or decelerating events. Thus any nonzero value of the skewness represents the degree of deviation from a Gaussian signal. The skewness factors $S(u)$, $S(v)$ and $S(w)$ of the three velocity components are computed and shown in figures 6.3.12, 6.3.13 and 6.3.14. Skewness factor for the streamwise component agrees well with Wei and Willmarth (1989) for $y^+ > 20$ but then shows a shift towards the simulation results of Kim *et al.* (1987) for $y^+ < 20$. The data of Kastrinakis and

Eckelmann (1983) and those of Kim *et al.* (1987) however are considerably negative although there is no evidence of Reynolds number dependence of these values as observed by Wei and Willmarth (1989). The skewness factor for normal velocity in the present case agrees well with the data of Kastrinakis and Eckelmann (1983), Kreplin and Eckelmann (1979) and Andreopoulos *et al.* (1984) which are positive for all values of y^+ near the wall where as the data of Kim *et al.* (1987), Wei and Willmarth (1989) and experimental results of Balint *et al.* (1991) show small negative value for $y^+ < 40$. High positive skewness values of normal velocity are suggestive of acceleration dominated events in the wall normal direction. The skewness factor for the spanwise component is zero for $y^+ > 30$ as seen in figure 6.3.14 which is expected because of the presumed symmetry in the flow.

The three flatness factors $F(u)$, $F(v)$ and $F(w)$ of the three velocity components are plotted in figures 6.3.15, 6.3.16 and 6.3.17 with the value of 3 for flatness factor of a Gaussian distribution, is also shown on each of them and the results are compared with those of Balint *et al.* (1991) and other investigators. The present data for the axial component are higher for $y^+ < 30$ but are in agreement with Balint *et al.* (1991), however a reverse trend is noticed for the normal component where the present results are much lower for $y^+ < 20$ but higher in the rest of the near wall region. The normal and spanwise velocities show pronounced intermittency associated with sweeps of high momentum fluid as the wall is approached but away from the wall the flatness factors of all three velocity components approach those for Gaussian variable. The flatness factor $F(w)$ for spanwise velocity shows similar variation as that of other investigators but that these values are consistently higher for $y^+ < 50$. The DNS results of Kim *et al.* (1987)

for channel flow are in compliance with the present measurements however a significant discrepancy is noticed for $F(v)$ closer to the wall where the flatness factor showed decrease as is the case with Wei and Willmarth (1989) and Kastrinakis and Eckelmann (1983) but the same values were found to increase in the case of Kim *et al.* (1987) and Balint *et al.* (1991). It should be mentioned therefore that since the skewness and flatness factors are higher order moments, any error in the measurement or in the computation is likely to get excessively amplified, especially at very close to the wall, because the numerator and denominator approach very small values.

Reynolds Shear stress:

The profile of Reynolds shear stress $-\rho\overline{uv}$ across the boundary layer is shown in figure 6.3.18. The rms values of the shear stress are normalized by the mean shear stress ρu^2 , and the wall normal distance by the outer variable δ . The present data agree quite well when compared with Balint *et al.* (1991), Spalart (1988) and Klebanoff (1954). The near wall comparison of the turbulent shear stress shown in figure 6.3.19 however reveals important deviation in that these values are higher than those measured by Balint *et al.* (1991). But the values of Spalart (1988) are higher than both sets of experimental results. When compared with the low Reynolds number data of Kim *et al.* (1987), their data appear to be higher than the present results in the buffer region but lower in the region $y^+ > 25$. The two data points for $y^+ < 12.5$ shown in this figure are for the third triple wire probe which is closer to the wall since it is below the centroid of the 3TOW probe. It is important to note that the measurement of the turbulent shear stress is one of the most difficult and critical tasks and therefore laboratory

measured values of the Reynolds shear stress in turbulent boundary layer flows show no consistent trend. On the contrary rather significant scatter of the data is observed regardless of the scaling parameter. The present values are found to be higher than those of Balint *et al.* (1991) in the near wall zone but then are in good agreement in the strong shear zone.

The correlation coefficient $-\overline{uv}/u'v'$ is shown in figure 6.3.20 as a function of y/δ . The data is comparable to the channel flow results of Wei and Willmarth (1989) in the region $y/\delta < 0.1$ and follow similar trend as that of Spalart(1988) in the log layer but are lower by about 10% which is within the experimental error. Balint *et al.* (1991) data lie higher in buffer and log layer. Previous investigations have shown that the correlation coefficient to be Reynolds number dependent and its value to be between 0.4 to 0.55.

The comparison of the present data with those of Balint *et al.*(1991) is well founded as the maxima of the Reynolds shear stresses occur around $y^+ \approx 50$ which is to be expected since the Reynolds number for both flows are comparable.

Production/Dissipation of Turbulent Kinetic Energy:

The rate of production of turbulent kinetic energy from the mean motion is given by

$$-\overline{u_i u_j} \partial \overline{U_i} / \partial x_j$$

and the rate of dissipation of turbulent kinetic energy to heat is given by the following expression:

$$\nu \left(\frac{\partial u_i}{\partial x_k} \right) \left[\left(\frac{\partial u_i}{\partial x_k} \right) + \left(\frac{\partial u_k}{\partial x_i} \right) \right]$$

The distributions of production and dissipation rates of turbulent kinetic energy in the boundary layer flow at both Reynolds numbers, normalized by inner variables ν/u_τ^4 , are plotted in figure 6.3.21 as a function of y^+ . The dissipation rates have been computed by considering all the terms in the above expression for ϵ because the flow near the wall clearly being anisotropic the cross products of the velocity derivatives may be just as important as the other terms. On this plot DNS data of Spalart, Wei, Mansour *et al.*(1988) and Balint *et al.*(1991) are superimposed. For reference the relation, $\epsilon^+ = 1/ky^+$ (where k is Karman constant) obtained by Tennekes and Lumley (1972) by assuming both rates to be equal in the logarithmic region, is also plotted. The present values of dissipation rate at both Reynolds numbers are slightly higher than Balint *et al.*(1991) and depart much more from Mansour *et al.*(1988) data but compare well with values of Spalart (1988). The production rate values however agree quite well with Balint *et al.*(1991) for the lower Re_θ and slightly larger for the higher Re_θ except very near the wall. These values however compare particularly well with Spalart (1988) simulations for $y^+ > 25$ and agree with Wei and Willmarth (1989) for $y^+ < 25$. The smaller values of production rate by Balint *et al.*(1991) as reported by them are attributed to the lower turbulent shear stress they measured in this region.

Vorticity and Spatial Derivatives statistics:

The rms fluctuations of the three components of vorticity across the boundary layer have been scaled by the boundary layer thickness δ and friction velocity u_τ and plotted in figures 6.3.22, 6.3.23 and 6.3.24. The values are then compared with the results of Spalart (1988) and Balint *et al.* (1991) for ω_x and ω_y . Additionally the measurements of Klewicki (1989), Klewicki and Falco (1990) are also indicated on the plots for ω_z . Very near the wall, Balint *et al.* (1991) data for ω_x are considerably lower to the present data but the disagreement vanishes quickly in the region $y/\delta < 0.1$. Spalart (1988) data are noted to be lower than both the experimental measurements. The present values of normal vorticity fluctuations ω'_y collapse well with Balint *et al.* (1991) in the near wall region but decrease much gradually in the rest of the boundary layer. The fluctuations of the dominant spanwise component of vorticity ω'_z as measured by this probe compare fairly well with the simulation data of Spalart (1988) and hot-wire results of Balint *et al.* (1991) although they are higher for $y/\delta > 0.05$, but are closer to the results of Klewicki (1989). These same three vorticity components now normalized by the boundary layer thickness δ and freestream velocity U_∞ shown in figures 6.3.25, 6.3.26 and 6.3.27 exhibit similar properties but the differences observed in the previous scaling are not as large. It is expected that in the near-wall region, inner variables ν and u_τ to be appropriate scales. The results, normalized by the inner variables u_τ and ν are shown in figures 6.3.28, 6.3.29 and 6.3.30. The apparently excessive differences in the near wall values of ω_x appear to be within the normal experimental variations and in fact are comparable to those of Spalart(1988) although at a much lower Reynolds number and only slightly larger than the simulated results of Kim *et al.* (1987). Balint *et al.* (1991)

attribute their attenuated values to the problems associated with the convergence of the solutions to the equations for the hot-wire outputs. The present values of the rms of ω_x lie between the two simulation results of Kim *et al.* (1987) and Spalart (1988). The values of ω_y are in good agreement with the results of Balint *et al.* but both results are lower than the data of Kim (1987) and Spalart (1988) for $y^+ < 50$. The spanwise component, ω_z is in close agreement with Balint *et al.* (1991) but again like the normal component, results of Spalart (1988) and Kim *et al.* (1987) as well as those of Klewicki (1989) are found to be much higher. The local flow isotropy is evident in the strong shear region as the rms values of all three vorticity components are approximately equal.

The skewness values of the present measurements are shown in figures 6.3.31, 6.3.32 and 6.3.33. The skewness of the axial vorticity component is close to zero while that of normal component is more negative when compared to Balint *et al* (1991). The expected all negative variation of skewness in the spanwise component is well reproduced although numerically much less than that of Kim *et al.* (1987) and Klewicki (1989) in the region $y^+ < 80$. There is rather poor agreement among the values of skewness for ω_y of all data sets suggestive of apparently false asymmetry in the flow for this component. Alternatively the scatter may be explained by the number of samples used in these computations which may be marginally adequate. The negative values for skewness for ω_z indicates rather large positive fluctuations of spanwise vorticity are less likely than the negative fluctuations of comparable magnitude, which in turn can be interpreted as stretching of spanwise component occurring more often than compression or the passage of vortical eddies.

The flatness values for the three vorticity components $F(\omega_x)$, $F(\omega_y)$ and $F(\omega_z)$ are

shown in figures 6.3.34, 6.3.35 and 6.3.36. A value of 3 corresponding to a Gaussian distribution is also shown for reference. Numerically simulated values of Kim *et al.* (1987) for ω_x are quite large especially in the region $y^+ < 20$. For $y^+ > 20$ present values agree fairly well with Balint *et al.* (1991). The experimental results of Klewicki (1989) for ω_z conform to the present data except for the first point. Flatness values of Balint *et al.* (1991) in comparison are found to be the lowest throughout the region displayed. For distances away from the wall, significant increase in the flatness factors for ω_x and ω_z components reflects the intermittent character of the flow with sporadic occurrence of streamwise vortices.

Computed rms values of all three spatial derivatives of u , v and w components, normalized by outer variables δ and u_τ , are plotted in figures 6.3.37, 6.3.38 and 6.3.39. The streamwise derivatives of all three velocity components are observed to be much lower in the entire boundary layer than those in wall-normal and spanwise direction, which themselves are noticeably approximately equal.

These derivatives for closer comparison are normalized by the inner variables and the plots shown in figures 6.3.40, 6.3.41 and 6.3.42. R.m.s. values of $\partial u/\partial z$ and $\partial u/\partial y$ are lower than those of Balint *et al.* (1991) however $\partial u/\partial x$ values are higher. The same trend is seen in the streamwise derivatives of v and w components; which can be explained in terms of how these derivatives are evaluated. The present data takes into consideration not only the time derivative but also, the other two derivatives in spanwise and normal directions (eqs. 4.56, 4.57 and 4.58). The $\partial u/\partial y$ data of Lu and Smith (1989) is much higher than all the other results. The data of Balint *et al.* (1991) for $\partial v/\partial x$ and $\partial v/\partial z$ are considerably lower however $\partial v/\partial y$ values agree fairly well in the region $y^+ <$

30. Similar differences are noted for $\partial w/\partial x$ and $\partial w/\partial z$. Large differences in $\partial w/\partial y$ and $\partial v/\partial z$ values when compared with those of Balint *et al.* (1991) account for in rather large values of streamwise component of vorticity fluctuations in this region.

Spectra of velocity and vorticity components:

In order to analyze the distributions of fluctuating velocity and vorticity over the range of frequencies in the flow, the spectra of the three velocity and the three vorticity components are computed from the respective instantaneous data. The power spectral density (p.s.d.) plots of the three velocity components at the center of the probe as a function of the streamwise wavenumber k_x non-dimensionalized by the outer scale δ are shown in figure 6.3.43, 6.3.44 & 6.3.45. The streamwise wavenumber $k_x = 2\pi f/U$ is computed with local axial mean velocity value as the convection velocity (Taylor's hypothesis). The data of Balint *et al.* (1991) are compared in these graphs for the wavenumber range of 10-100. The present data show good agreement, particularly for w component but are lower for v and higher for u in this range of wavenumbers. The higher spectral values of Balint *et al.* (1991) for normal velocity component v indicate its rms value to be significantly higher in comparison to that of the present experiment. This however is not the case as the present rms values of v are much higher as seen in figure 6.3.2. Their results therefore seems to be apparently inconsistent and hence it is difficult to explain significant disagreements between the two results for the v component although both are normalized by the same scales. The slopes of the two spectra however are approximately equal which suggests that the present probe gives as good a resolution if not better for the smallest scales of turbulence near the wall. It appears that the spectra

of axial and spanwise velocity fluctuations seem to collapse with the outer scale δ .

Figure.6.3.46, 6.3.47 and 6.3.48 show one dimensional power spectra of the three vorticity components at the same wall normal location of $y^+ = 12.5$ against the non-dimensional wave number on a log-log scale. The spectra of Balint *et al.*(1991) for the respective vorticity components but at $y^+ = 18$ are also superimposed. The agreement is good in the wavenumber range 10-50 but then their spectra drops off sharply for higher wave numbers. For both, axial and spanwise components the present values show much larger energy content, probably because the probe is able to resolve velocity gradients more accurately. The vorticity fluctuations are mainly as a result of contributions on a greater proportion by the smaller scales whereas the kinetic energy in the flow comes from the larger eddies, a comparison of the spectrum of kinetic energy to that of enstrophy is attempted in figure 6.3.49 where both spectra weighted by the wavenumber, are plotted. The maxima of the two spectra occur at approximately $k_x\delta=20$ and $k_x\delta=50$ respectively. This expected shift in the maximum energy content to higher wave numbers, presumably Reynolds number dependent, is not large for the flow investigated but it reinforces the above mentioned characteristic.

PDF distributions:

The probability distribution functions for axial, wall-normal and spanwise velocity components at the centroid of the probe are shown in figures 6.3.50, 6.3.51 and 6.3.52 at $y^+=12.5$. The abscissa values are expressed in terms of the corresponding rms values.

The u-component pdf is more symmetric near the wall which is reflected in its

flatness factor and the bimodal behavior suggests a possible periodicity in the flow. Similarly the normal component deviates from the Gaussian distribution and shows intense negative fluctuations to the extent of five times its rms value to occur although these events associated with intermittency are less frequent. The pdf of the spanwise component indicates positive events are as likely as negative ones and close to zero value for the skewness of w reflects two dimensional nature of the flow.

The probability distributions of all three vorticity components, as computed at the $y^+ = 12.5$ location are shown in figures 6.3.53, 6.3.54 and 6.3.55. It is evident that the dominant spanwise component is non-Gaussian as it is skewed to the negative while the axial component shows more random characteristic with approximately zero skewness value as seen in figure 6.3.53. The tails of pdfs of ω_y and ω_z are noticeably longer than those of ω_x . It is intriguing to note, as these tails indicate, very large amplitude deviations from the mean as much as 8-10 times the respective rms values in wall normal and spanwise vorticity to occur in the viscous sublayer. The probability however of occurrence of such violent eruptions is considerably small. Balint *et al.* (1991) however found erroneous negative skewness for this component as a result of positive bias of low amplitude fluctuations. The normal component of vorticity is observed to be skewed slightly towards negative but that very large fluctuations of both positive as well as negative amplitude are equally likely to occur and contribute significantly to the high rms value at this location.

Isotropy:

In order to check the isotropy in the turbulent boundary layer, profiles of turbulent intensity ratios u'/v' and u'/w' for wall normal distance y^+ up to 200 are plotted and shown in figure 6.3.56a. Close to the wall, for $y^+ < 20$ these ratios indicate significant anisotropy in the flow. Although these ratios appear to be closer to unity in the rest of the region, they do not provide conclusive evidence of isotropy. The profiles of vorticity fluctuations ratios ω'_x/ω'_y and ω'_x/ω'_z in the inner layer as observed in figure 6.3.56b, however suggest that the vorticity field is closer to local isotropy than the velocity field. Since vorticity fluctuations are dominated by the small scales of motion, the fluctuations of vorticity receive energy from large scales rather than directly from the mean flow, Kolmogorov(1941) proposed the cascade process of energy transfer to lose directional preference of energy containing large eddies. The statistical properties of vorticity therefore are expected to exhibit isotropic characteristics as noted in the profiles mentioned above. This concept of local isotropy as originally proposed by Kolmogorov(1941) is further verified by the relationship between the streamwise wavenumber and the ratios of one dimensional spectra of the three velocity components, $\text{psd}(u)/\text{psd}(v)$, $\text{psd}(u)/\text{psd}(w)$ as shown in figure 6.3.57 and the ratios of one dimensional spectra of vorticity components, $\text{psd}(\omega_x)/\text{psd}(\omega_y)$ and $\text{psd}(\omega_x)/\text{psd}(\omega_z)$ illustrated in figure 6.3.58. Both plots use log scale and the wavenumber is normalized by the outer scale δ . The wavenumber at which the vorticity components exhibit isotropy is higher when compared to the wavenumber at which it is indicated by the velocity components.

Kim and Antonia (1993) through their tests of spectral local isotropy on the DNS data of fully developed channel flow, observed the behavior of high wavenumber velocity

and vorticity spectra to be consistent with local isotropy. They also noted the spectra of pressure in the high wavenumber range supported this property and compared well with the calculations of Batchelor (1951). On the other hand, George and Hussein (1991) put forth a theory of locally axisymmetric turbulence in which they define the turbulence to be locally axisymmetric if it is invariant to rotations about a preferred axis. They believe velocity derivative moments are not good indicators of local isotropy since the four derivative ratios defined below:

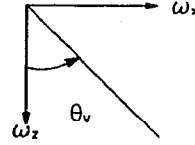
$$k_1 = 2 \frac{\overline{\left(\frac{\partial u}{\partial x}\right)^2}}{\overline{\left(\frac{\partial v}{\partial x}\right)^2}}, \quad k_2 = 2 \frac{\overline{\left(\frac{\partial u}{\partial x}\right)^2}}{\overline{\left(\frac{\partial w}{\partial x}\right)^2}}, \quad k_3 = 2 \frac{\overline{\left(\frac{\partial u}{\partial x}\right)^2}}{\overline{\left(\frac{\partial u}{\partial y}\right)^2}}, \quad k_4 = 2 \frac{\overline{\left(\frac{\partial u}{\partial x}\right)^2}}{\overline{\left(\frac{\partial u}{\partial z}\right)^2}}$$

should all be equal to unity. They state the conditions for local axisymmetry require that ratios $k_1=k_2$ and $k_3=k_4$ with x axis chosen as the axis of symmetry. These ratios of velocity gradients when computed in the present flow satisfied these requirements of axisymmetry only partially.

Further analysis by conditional sampling techniques:

To obtain further insight into the structural characteristics of the two predominant events namely: ejections and sweeps which are associated with the near wall turbulence, the time-dependent signals of all three vorticity components are interrogated using the conditional sampling technique as a tool for identifying these events. The projection θ_v of vorticity vector in the x-z plane is investigated in particular first. This angle θ_v is defined as follows

$$\theta_v = \tan^{-1}\left(\frac{\omega_x}{\omega_z}\right)$$



and is positive counter clockwise from the positive z axis. The detection of an event associated with the passage of a structure is triggered when the absolute value of the amplitude of the time series of ω_z is above a pre-determined threshold level $k(\omega_z)_{rms}$ and the absolute value of the amplitude of the time series of ω_x is above a pre-determined threshold level $k(\omega_x)_{rms}$. The probability distributions of these events conditioned with the threshold level of 0, 50% and 100% of the rms value of ω_z are shown in figure 6.3.59. Four distinct orientations with much higher probability can be noticed after conditioning, which are otherwise obscured. The pdfs show two primary peaks approximately 180° apart and two secondary peaks, one in each quadrant, and inclined at approximately 45° , -140° and -55° and 130° respectively. The primary peaks in the first and third quadrants are associated with structures carrying either positive ω_z or negative ω_z . In order to see if these peaks show any further preference in upper or lower quadrants of an octant, further statistical analysis with conditioning was applied to these signals. The pdf for θ_v for $\omega_y > 0$ (upper quadrants) is shown in figure 6.3.60 which indicates the preferred orientation in the first quadrant at about 45° is more probable than other three peaks found earlier. The conditioned pdf in figure 6.3.61 for θ_v when $\omega_y < 0$ (lower quadrants) indicates however that inclination of -135° (third quadrant) for this vector has the highest

probability. The application of conditioning technique to θ_v therefore reveals both events of positive and negative spanwise vorticity are more recurrent at this location. It should be noted that the signals of vorticity used in this analysis contained the mean component $\bar{\omega}_z$. It appears that by excluding $\bar{\omega}_z$ and using the fluctuating part of the signal in the present analysis, the results are not substantially affected. The reason being that vorticity fluctuations are about 3-4 times greater than $\bar{\omega}_z$. In fact the magnitude of $\bar{\omega}_z$ is about 70% of one r.m.s. of ω_z fluctuations.

Morrison *et al.* (1992) investigated the bursting mechanism in high Reynolds number turbulent boundary layer flows. They report that negative spanwise vorticity predominates ejections while positive vorticity is at least larger than that in ejections and it is associated with sweeps. In the light of this conjecture the primary peaks observed above may be associated with the burst/sweep sequence.

Other flow structures, however may also have orientations similar to the preferred ones shown in figures 6.3.60 and 6.3.61. "Hair-pin" or "arch-like" vortices, for instance, are characterized by negative ω_z everywhere in the vortex and positive ω_x and ω_y in one leg and negative ω_x and ω_y in the other. The peak at $\theta_v=130^\circ$ of figure 6.3.60 and the peak at $\theta_v=-140^\circ$ of figure 6.3.61 clearly support this notion.

Wallace *et al.* (1992) in their analysis of the properties of helicity density $h = (\vec{V} \cdot \vec{\omega}) / |\vec{V}| |\vec{\omega}|$, V and ω being velocity and vorticity vectors respectively, in turbulent boundary layer flow at $Re_\theta = 2685$ found in the regions of high dissipation rate e.g. near the boundaries, the velocity and vorticity vectors were nearly orthogonal and as the dissipation rate dropped the probability of these two vectors to align increased significantly. Ashurst *et al.* (1987), on the other hand examined the coupling of vorticity

and the three eigen vectors of the strain rate tensor for isotropic and homogeneous shear flows by numerical simulations. The matrix of strain rate tensor $S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$ being symmetric, has its eigen vectors orthonormal to each other and under incompressibility conditions the sum of all three eigen values is zero satisfying the continuity. Their results indicated vorticity to point in the direction of intermediate extensive strain (corresponding to the middle positive eigen value of the strain rate matrix) which they attribute to the conservation principle of angular momentum. The present data at $y^+ = 12.5$ (where the flow is considered to be highly inhomogeneous and slightly anisotropic) was searched to identify if any such linkage between the eigen vectors and the vorticity vectors exists. Figure 6.3.62 shows the plot of the pdf of the alignment of the vorticity vector with each of the three eigen vectors of the strain rate matrix obtained by computing all the terms through the spatial derivatives of velocity components. In this plot α_s , β_s and γ_s are the three eigen vectors associated with three real eigen values of the matrix formed by the strain tensor S_{ij} . This graph shows the higher probability of the vorticity vector to align with the middle eigen vector β_s and least likely to point in the direction of the most compressive strain (eigen vector corresponding to the most negative eigen value of the strain rate matrix).

In order to further investigate the type structures present in the flow the detection criteria of the conditional sampling procedure are now modified to distinguish high amplitude events identified with strongly non-Gaussian strain and vorticity fluctuations and to explore correlations of strong and weak regions with all other measured flow quantities. The signals were conditioned on the three vorticity components ω_x , ω_y and ω_z and two vorticity gradients at the wall, $\partial\omega_x/\partial y$ and $\partial\omega_z/\partial y$ independently. The algorithm

is made to lock on to that part of the signal to be conditioned, where the amplitude is above a given threshold k and counts as an "event" of duration 50 time units above and below the reference time when the signal is at its local extreme. While this period is somewhat arbitrary it is equivalent to about 21 viscous time units which is estimated to be the duration of the intense activity (see Haritonidis *et al*). Thus all reference points are brought into alignment and the ensemble average of all such captured events is considered a candidate indicator of a "typical structure". A positive peak event is declared whenever the signal exceeded threshold k and a negative peak event when the signal is less than $-k$. The number of events accumulated by this technique is dependent directly on the value of the threshold k set during the pass but these events, at least in a qualitative sense believed to focus on the same feature in the flow. This detection method has been previously used by Her (1986) to detect high amplitude pressure peaks and by Haritonidis *et al* (1988). This algorithm is slightly different from the commonly employed VITA (Variable Interval Time Averaging) technique of Blackwelder and Kaplan (1976) in which an event is counted when the short time r.m.s. value of signal is either above or below a predetermined value. Thus VITA technique detects structures mostly with positive and negative amplitude i.e. forces a change of sign while the present detection technique avoids this type of biasing. This is a substantial difference between the two techniques and it should be taken into account when interpreting the results. In other words when a typical structure obtained by the VITA technique contains a change of sign is not a surprise. However when the peak detection technique yields a typical structure with a sign change it indicates this type of structure really dominates over many others.

The ensemble averaged values are normalized by the rms value of the respective quantity and the time units are normalized by the viscous time ν/u_τ^2 before they are plotted. The negative abscissa is interpreted as downstream and positive as upstream with respect to the measuring location. The conditioned results are analyzed and compared to the dynamic events of streak formation, ejection, bursts and sweeps. It needs to be mentioned that a variety of structures, all related to the mechanism of turbulence, named for their shape and size e.g. horseshoe, hairpin, pancake/surfboard eddies arrowhead eddies etc. have been hypothesized in the extensive literature on the boundary layer flows. (See e.g. Perry et al. (1981), Landahl (1984), Blackwelder and Haritonidis (1983)). Shown in figures 6.3.63-64, 6.3.67-68, 6.3.71 and 6.3.72 are the conditioned ensemble averages on positive thresholds of ω_x , ω_y and ω_z for $k=2$ respectively, while 6.3.65-66, 6.3.69-70, 6.3.73 and 6.3.74 illustrate the results when conditioned on negative thresholds of ω_x , ω_y and ω_z for $k=-2$ respectively. The discussion is based mainly on the conditioning results for the two extreme values of $k = \pm 2$ with the assumption that the typical structures identified are the strongest. It was noted however that the results for other values of k exhibited similar qualitative variation in general. The conditioning process is expected to extract the coherent content from the stochastic background because the events are averaged after the mean value is subtracted. The turbulent structures associated with ω_x seem to be of longer duration when conditioned on ω_x . The velocity gradient $\partial w/\partial y$ dominates over $\partial v/\partial z$ and thus accounts for the most contributions to streamwise vorticity ω_x near the wall and at the wall its second derivative $\partial^2 w/\partial y^2$ is directly proportional to the spanwise pressure gradient $\partial p/\partial z$. Therefore these ω_x events, rather intense since the effect of suppressed mean ω_x is minimal, may also

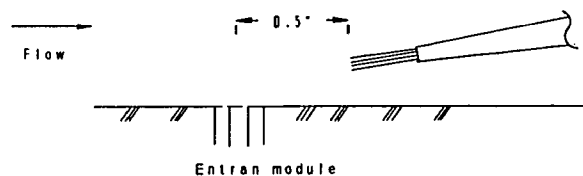
be associated with the passage of strong localized shear layers generated by the gradient $\partial w / \partial y$. They are reported to be more prevalent near the outer edge of the viscous sublayer ($y^+ \approx 15$) finally rolling up to form streamwise vortical structures. The high values of ω_x fluctuations have also been reported by Kasagi *et al.* (1993) to be linked to the streamwise streaks formation and regions of low pressure. The spanwise vorticity ω_z is noticeably inactive and mostly negative but the normal component ω_y shows small and sharp peak at the same time as that of ω_x , the structure therefore is considered to be sheet like (in xy plane). This typical structure recognized by ensemble averaging for $k=2$ appear to be tilted upwards by about 16° and moving away from the wall ($v > 0$). The decreasing u at the same time is suggestive of "bursting" phenomena while the sweeping motions are observed with these structures for $k=-2$ (figure 6.3.65), which are inclined towards the wall at about 10° and appear to be moving towards the wall ($v < 0$) with strong negative streamwise vorticity and eventually affecting the turbulent shear stress which shows a sharp negative peak. This event may also be viewed as one of the legs of the hairpin model being lifted up or that it may be isolated longitudinal vortex. This notion is supported by the fact that the spanwise velocity component w indicating the reversal of sign while uv reaches considerably high negative values for $k=2$ and ω_z is negative for both $k=2$ and $k=-2$. The turbulent shear stress also has a distinct negative peak for $k=-2$.

The events of ω_y and ω_z are found to be of very short duration when conditioned on ω_y and ω_z respectively. For the data conditioned on positive or negative ω_y amplitudes of all three vorticity components are comparable as a result of three dimensionality of the typical structure. The most notable characteristic is the change in sign of ω_z while

both, ω_x and ω_y remain positive. It is not clear what type of flow structure may be associated with this event. However ω_y is mostly associated with lifted up structure or the tip of a hair-pin vortex. The present results may represent lifted up structure for $T^+ < 0$ followed by the passage of hair-pin vortex. For $k=-2$ on the same component ω_y a distinct change of sign is observed on velocity w and that the turbulent shear stress affected the least by the structures in which large fluctuations of normal component of vorticity persist. It appears that this event, with strong negative ω_y , represents rather clearly, the flow pattern produced by the passage of one leg of a hair-pin vortex. Conditional results of positive and negative ω_z show the structures to be in the y - z plane with very weak streamwise vorticity which is seen to change sign from positive to negative for $k=-2$ at about $T^+ = -6$ while large peak appears for turbulent shear stress $-uv$ pattern. The absence of substantial ω_x vorticity combined with large negative v component of velocity at $T^+ = 0$ indicates a pattern carrying positive ω_z towards the wall, which is very much indicative of sweeps. It should be also noted that this event is associated with the largest value of shear stress ever detected in any of the present patterns. This value of -2 is twice the average $\overline{uv}$ and therefore this type of structure is associated with the peaks in the skin friction.

It is apparent that the normal gradient $\partial u / \partial y$ is the dominating term for ω_z near the wall and its spatial gradient term $\partial^2 u / \partial y^2$ strongly correlates with the axial pressure gradient $\partial p / \partial x$. The vorticity flux $\partial \omega_z / \partial y$ then is expected to exhibit this correlation. The signatures of wall pressure p_1 , vorticity fluxes at the wall $\partial \omega_x / \partial y$ and $\partial \omega_z / \partial y$, vorticity components ω_x , ω_y and ω_z , velocities u , v and w along with the turbulent shear stress $-uv$ when conditioned on $\partial \omega_x / \partial y$ for $k=1.5, 2$ and $k=-1.5, -2$ are shown in figures 6.3.75-86

while the same quantities when conditioned on $\partial\omega_z/\partial y$ are illustrated in figures 6.3.87-98. The first observation to be made is that the patterns are independent of the level of threshold k : The patterns obtained with $k=\pm 2$ are qualitatively similar to those obtained with $k=\pm 1.5$. It should be noted that Entran module for wall pressures/vorticity flux measurements was placed approximately 12.5 mm (1/2") upstream of the vorticity probe as shown below



so that the measurements by the pressure sensors are not adversely affected by the probe disturbance and interference. This difference in the position as a consequence, translates to about +8 viscous time units for the patterns wall pressure and the two vorticity fluxes to reach the hot-wire position in the conditional results.

The vorticity flux data should be interpreted as the vorticity shed off the solid wall and sensed, to a first order approximation, at a near by point inside the flow at a distance Δy from the wall as:

$$\Delta \omega_z = -\left(\frac{\partial \omega_z}{\partial y}\right)_w \cdot \Delta y, \quad \Delta \omega_x = -\left(\frac{\partial \omega_x}{\partial y}\right)_w \cdot \Delta y$$

The pressure data when conditioned on $\partial\omega_x/\partial y$ indicate more of a wavy pattern but also demonstrate distinct peaks when conditioned on $\partial\omega_z/\partial y$. The pressure wave trains were also observed by Haritonidis *et al.* (1988) in their experiment in the turbulent boundary layer flow at $Re_\theta = 4340$ which they believe to be associated with flow

instability in the buffer region. The regions of intense spanwise vorticity presumed to be related to the tails of the hairpin vortices thus illustrate strong correlation with wall pressure event.

The data shown in figures 6.3.87 and 6.3.90 indicate that the local maxima/minima of pressure occur at the same time $T^+ = 0$ as the maxima/minima of $\partial\omega_z/\partial y$. Since the pressure leads velocity and vorticity data the effects attributed to active events of spanwise vorticity flux in any of the three vorticity components are visualized with a time delay.

The relative strengths of the peaks of $\partial\omega_z/\partial y$ and $\partial\omega_x/\partial y$ are similar for $k=2$ as those for $k=-2$. Although no salient peaks are noticed on any of the three vorticity components, their signatures show periodic behavior with almost no particular excursions at $T^+ = 0$ except for the data conditioned on $\partial\omega_z/\partial y$. The velocities u and w are very small and constant but spanwise velocity w is of period about 12 viscous time units while Reynolds stress uv is zero upstream with large positive amplitudes downstream. The conditional results for $k=\pm 2$ on $\partial\omega_z/\partial y$ show that vorticity $\Delta\omega_x$ and $\Delta\omega_z$ shed off the wall at $T^+=0$ is in phase with the vorticity sensed at $T^+ = 8$.

CONCLUSIONS:

The basic statistical properties of velocity and vorticity field computed from the measurements by the miniature 3TOW probe in the boundary layer experiments are consistent with the existing datasets obtained in different facilities, under different conditions and by a wide range of spatial resolution and more importantly confirmed the recent results of Balint *et al.* (1991). In particular, their demonstration for the first time

of the shift of maximum energy to higher wavenumbers by comparing the spectra of velocity and vorticity is strongly supported by the similar shift noted in the spectra of enstrophy and turbulent kinetic energy of the present flow at comparable Reynolds number. Further the probability density distributions of all three fluctuating vorticity components also confirmed those of Balint *et al.*, especially the distinct long tails in the pdfs of ω_y and ω_z . However, near the wall, velocity and vorticity fluctuations in both boundary layer flows investigated were consistently higher and significant deviations observed in some of the results particularly in individual velocity gradient statistics which can be explained in terms of key differences between the present 3TOW probe and the one used by Balint *et al.* which are mentioned as below:

a) The present probe does not use a common prong and therefore permits to electronically operate each sensor independently.

b) The 3TOW probe, because of its different geometry, has "cone of validity" of instantaneous velocity vectors much larger than that of Balint *et al.* which has one wire inclined 45° to the plane formed by the other two, whereas present probe has the same wire inclined at 90° since each of the three wires are mutually orthogonal.

c) Each sensor of the 3TOW probe could be operated at higher overheat ratios and allowed to take into account variations of yaw and pitch responses of each wire which are intrinsically unique for each sensor.

d) The streamwise velocity derivative terms of normal and spanwise vorticity have been more accurately estimated by computing all the terms of Taylor's hypothesis.

One of the major observations is that the profiles of higher moments of velocity and vorticity did not collapse under a variety of different scales attempted indicating the

difficulty of proper scaling parameters which has been reported by the other researchers.

In addition to the confirmation of the flow properties reported by Balint *et al.* of turbulent boundary layer, in this investigation the following new results have been obtained.

i) The profile of flow yaw and pitch angles θ_f and ϕ_f in the near wall region and their probability density distributions at $y^+ = 12.5$ location indicate rather rare but intense fluctuations of the velocity vector orientation.

ii) The probability density distributions of the orientation of vorticity vectors in the plane of the mean flow reveal preferential directions when conditioned at various threshold levels of $(\omega_z)_{rms}$. These are believed to be associated with a pair of counter-rotating structures of organized spanwise vorticity.

iii) The conditional properties of the simultaneous measurements of wall pressures, the three components of velocity and vorticity and the two wall-normal gradients of axial and spanwise vorticity are investigated for the first time. They identify the structures near the wall are almost always associated with positive and negative spanwise vorticity of comparable magnitude. The pressure peaks, reported to be strongly related to the near wall shear layer and the wavy patterns associated with buffer region flow instability, (Haritonidis *et al.* (1988)) were also observed in these results and finally,

iv) The relationship of the strain rate matrix and vorticity vector showed the vorticity vector at the position closest to the wall to be least likely to align with the most compressive eigen vector of the strain rate matrix. The modified conditioning technique in a limited sense revealed some of the complex structural characteristics of turbulence mechanism near the wall.

In summary, the experimental study of the turbulent flows demonstrated that the probe can successfully measure time dependent velocity and vorticity vectors in a flow with greater turbulent intensity and with good spatial resolution. A large data bank has been established which will allow further analysis to be carried out.

6.4. DELTA WING

6.4.1 Flow Visualization:

Still photographs and still frames from the video film have been digitally processed using video analysis software. In particular, edge detecting filter routines were used to identify global features associated with different vortical structures in the flow.

Figures 6.4.1 and 6.4.2 show two such surface imprint for angle of attack of 20° and 45° respectively. The imprints of two distinct vortices are seen from apex to the trailing edge without any apparent break down. In the central part of the wing the limiting streamlines are parallel to the wing chord indicative of no interaction of the shear layers emanating from either leading edges. The vortices grow in size and activity as the angle of attack is increased and start to interact. This interaction of the two separating shear layers at 45° angle of attack is clearly visible in figure 6.4.2.

Figure 6.4.3 shows two frames at 10° angle of attack and 3 m/s free stream velocity. The leading edge vortex with isolated center is clearly visible. A smaller secondary vortex formed close to the surface with shear layer wrapped around is also visible but not distinct.

Secondary vortical structures in the feeding shear layer can be identified in the figure 6.4.4, 6.4.5 and 6.4.6 which shows lateral cross section at 15° and 3 m/s. These

are also extremely clear in figure 6.4.7 which is lateral cut but at half the chord from the apex. The existence of these small streamwise vortices riding on the shear layer was first suggested by Squire (1961) by his oil flow visualization experiments. Gad-el-Hak and Blackwelder (1987) from their experiments, both in a water towing tank and in the wind tunnel, established the leading edge vortices originate as a series of discrete vortices that are shed into the shear layer at well defined frequency. They report also that the shedding frequency is a function of Reynolds number based on the chord and the angle of attack.

In figure 6.4.8 distinct outline of the shear layer as it winds smoothly into the vortex center. Figure 6.4.9 and 6.4.10 show outer edges of the vortex as the laser sheet is orientated approximately along the axis of the inboard vortex and normal to the surface.

6.4.2 3TOW probe:

The results are discussed for the case when the angle of attack of the delta wing was 15° at a nondimensional chord location of $x/C = 0.85$ measured from the apex of the model. The measurement locations are shown in some of the 3-d plots cited below as a reference. Figure 6.4.11 shows the iso-contours of mean axial vorticity projected onto a cross flow plane. The spanwise and normal distances are normalized by the local semi span. The streamwise vortices generated inside the shear layer as it wraps around the wing can be identified by the pockets of high positive mean axial vorticity. The secondary vortices with much lower axial vorticity and of opposite sign manifest near the wall at about $z/s=0.7$. The iso-contours of mean streamwise, normal and spanwise

velocities, normalized by the mean freestream velocity are plotted in figures 6.4.12, 6.4.13 and 6.4.14 respectively. The velocity vectors as measured at the center of the probe are projected on the cross plane and plotted in figure 6.4.15 which clearly demonstrate the direction of turning of the flow as it encounters the leading edge of the delta wing. If it assumed that the axial vorticity peaks near the eye of the vortex where the pressure is lowest then it can be argued that the flow accelerates over the apex and the axial velocity increases over its freestream value reaching maximum at the center of the vortex. These indicators allowed to estimate the location of the center to be at approximately $z/s \approx 0.6$ and $y/s \approx 0.2$ as observed in the plots of mean axial vorticity and mean axial velocity. Near the wing surface however the separated flow slows down as noted by the lower values normalized mean axial velocity. Closer to the leading edge for $z/s > 0.6$ and near the wall, mean normal velocity is downward as indicated by the negative sign and for $z/s < 0.6$ it points upwards toward the wing surface. This clearly illustrates that the streamlines in the cross-flow plane are curved, which is also evidenced by the change of sign of the mean binormal velocity.

The iso-contours of the rms values of the fluctuations of the axial, normal and spanwise velocity components are shown in figures 6.4.16, 6.4.17 and 6.4.18 while figure 6.4.19 illustrates the turbulent kinetic energy contours projected in a cross flow plane. It is noticed that the peak fluctuations of velocity do not occur at the center of the vortex but inside the shear layer and in regions closer to the wall as the secondary separation generates turbulence. Figure 6.4.20 shows the plot of constant enstrophy contours. Since the leading edge vortex is strongly 3-dimensional, the contributions to the enstrophy by each of the three vorticity components is significant and comparable.

Figures 6.4.21, 6.4.22, 6.4.23 and 6.4.24 show the surface plots of the fluctuating axial, normal and spanwise velocity components and the turbulent kinetic energy. These plots are obtained by a software generated 3-d spline fit of the measured data. Two peaks are observed on all three plots. One peak at approximately $z/s=0.2$ suggests the position where the primary attachment of the shear layer takes place while the second peak at about $z/s=0.7$ in the vicinity of the center of the primary vortex. The intensities of the fluctuations at these positions are of the same magnitude for u and w while the v fluctuations in the shear layer are much larger than those closer to the center.

The rms values of the three vorticity components ω_x , ω_y and ω_z across the fore vortex region normalized by the local semi-span and freestream velocity are shown as surface plots in figures 6.4.25, 6.4.26 and 6.4.27. The two peaks, as in the case of velocity fluctuations, are also observed in all these graphs. The intensity of fluctuations ω_y in the shear layer is smaller when the shear layer is near the leading edge than that when the shear layer is further away as it merges to form the primary vortex but for ω_x the fluctuations in the shear layer everywhere on the suction side of the wing are comparable. The ω_z component shows a different trend in that the intensity of fluctuations is larger near the center of the vortex while the fluctuations in the shear layer are comparable to those of axial component. The computed enstrophy values are shown in the surface plot shown in figure 6.4.28.

CONCLUSIONS:

The surface imprints show the central part of the delta wing remain unaffected since the limiting streamlines are parallel to the wing chord but as the angle of attack is

increased to its maximum the interaction of two shear layers becomes visible. The laser sheets normal to the flow illustrate the feeding shear layer with secondary structures as it develops. The flow visualization experiments, both on the surface of the wing as well as those by illumination of the area occupied by the leading edge vortices with laser sheet depicted realistic description of the flow field on the suction side of the delta wing.

The statistical results of three velocity and vorticity components measured simultaneously in the flow over the delta wing in this work have not been otherwise obtained experimentally to date. The axial vorticity being the dominant part in this flow, the iso-contours plots show the pockets of positive mean vorticity inside the shear layer associated with the streamwise vortices which merge and form the strong leading edge vortex with maximum value of the mean axial component of vorticity. Induced vortices having vorticity of opposite sign and lower intensity are also observed in these plots.

Based on the iso-contours of mean axial vorticity, a sketch of probable structure of the vortex flow is shown in figure 6.4.29. The separated leading edge shear layer with embedded streamwise vortices grows thicker as it wraps around and impinges on the suction side of the wing surface. The flow then divides and culminates in large vortex on one side and a pair of counter rotating mushroom like regions of much smaller strength are formed near the center of the wing. Secondary fluid near the surface lifts off from the surface because of no-slip condition and reattaches closer to the leading edge. The flow in the strong separated sheet is turbulent while the rest of the flow away from the surface remains turbulence free.

	wire length		wire separation		probe separation			
	l_w (mm)	l_w^+	l_s (mm)	l_s^+	l_v (mm)	l_v^+	$(\Delta t)^+$	f_s (Hz)
3TOW PROBE Prelim. Expt	0.80	7	1.23	11	2.10	19	0.50	5000
3TOW PROBE Concl. Expt	0.80	6	1.23	10	2.10	17	0.22	5000
ENTRAN MODULE Concl. Expt	0.50	5.8	1.5	10.5	$\Delta x^+ =$	Δz^+	0.108	5000

Table 6.1. Probe resolution in viscous units.

<u>Method of computation</u>	<u>Preliminary Expt</u>			<u>Concluding Expt</u>		
	η_w	η_p	η_v	η_w	η_p	η_v
1. production = dissipation	4	6	11	2	4	6
2. Isotropy $\epsilon = 15 \nu \left(\frac{\partial u}{\partial x} \right)^2$	4	5	9	3	5	9
3. Isotropy and enstrophy measurements $\epsilon = \nu \langle \omega_i \omega_i \rangle$	4	6	10	3	5	9
4. All terms in dissipation	5	7	11	4	6	10
5. Axisymmetric isotropy W.K. George and H.J. Hussein (1991)	4	6	10	3	5	9
6. Isotropy and assumptions of Klewicki & Falco (1990)	4	6	10	4	6	10

Table 6.2. Probe resolution in Kolmogorov microscale units with η at $y^+ = 21$ for preliminary experiment and η at $y^+ = 12.5$ for concluding experiment.

	Re_θ or $Re_{\delta/2}$ or Re_δ	U_∞ (m/s)	δ (m)	θ (m)	u_τ (m/s)	Flow
Balint <i>et al.</i> (1991)	2685	3.51	0.125	0.0121	0.144	boundary layer
Klewicki (1989)	2870	1.75	0.205	0.0245	0.071	boundary layer
Spalart (1988)	1410					DNS boundary layer
Kastrinakis and Eckelmann (1983)	12600	2.00			0.090	channel
Wei and Willmarth (1989)	22776	2.33			0.0745	LDA channel
Kim <i>et al.</i> (1987)	3300	0.639		0.00696	0.0351	DNS channel
Klebanoff (1954)	78000					boundary layer
Andreopoulos <i>et al.</i> (1984)	3624	6.33	0.0739	0.0086	0.25	boundary layer

Table 6.3. Principal parameters of the existing datasets used in the comparison.

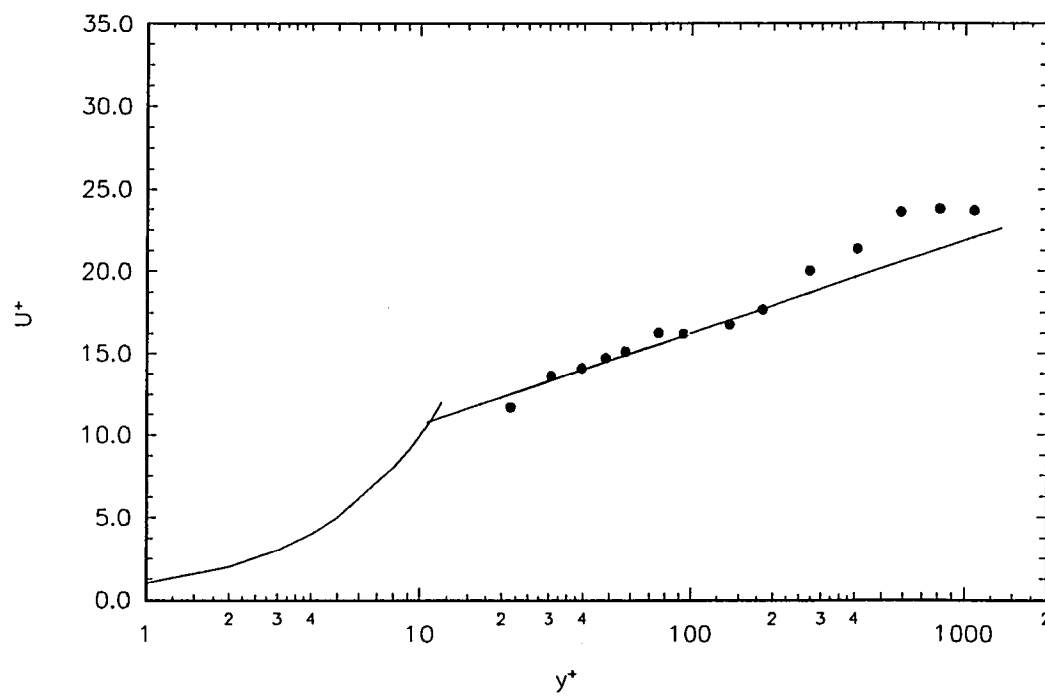


Figure 6.1. Mean velocity profile in the boundary layer as measured at the center of the probe.

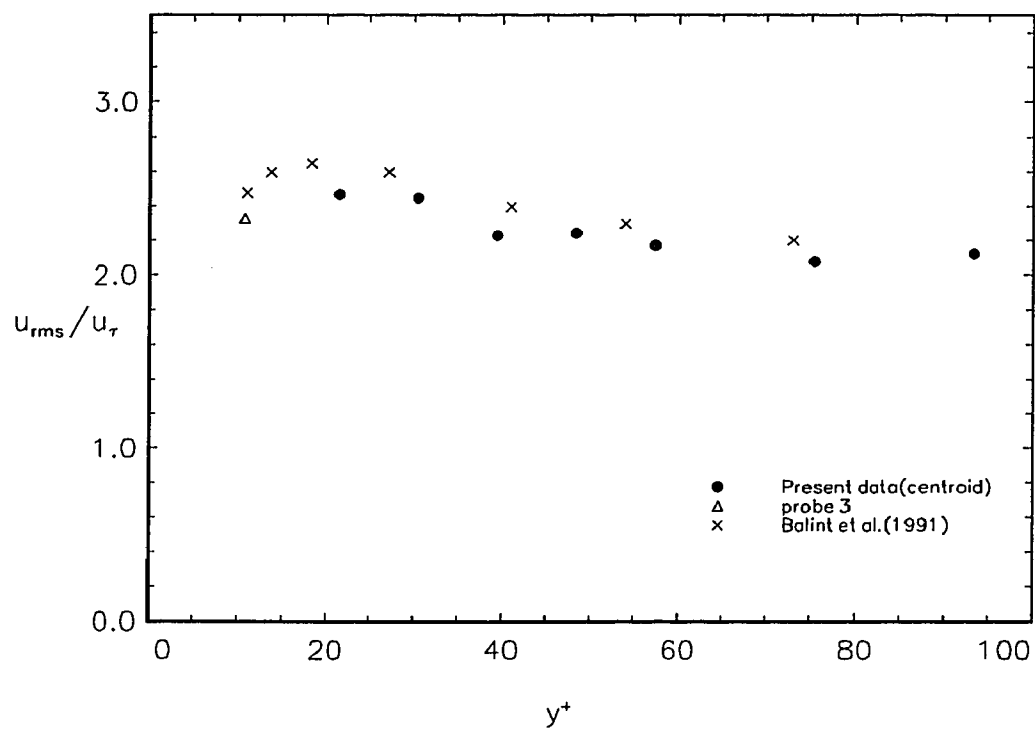


Figure 6.2a. Normalized r.m.s. axial velocity fluctuations u'

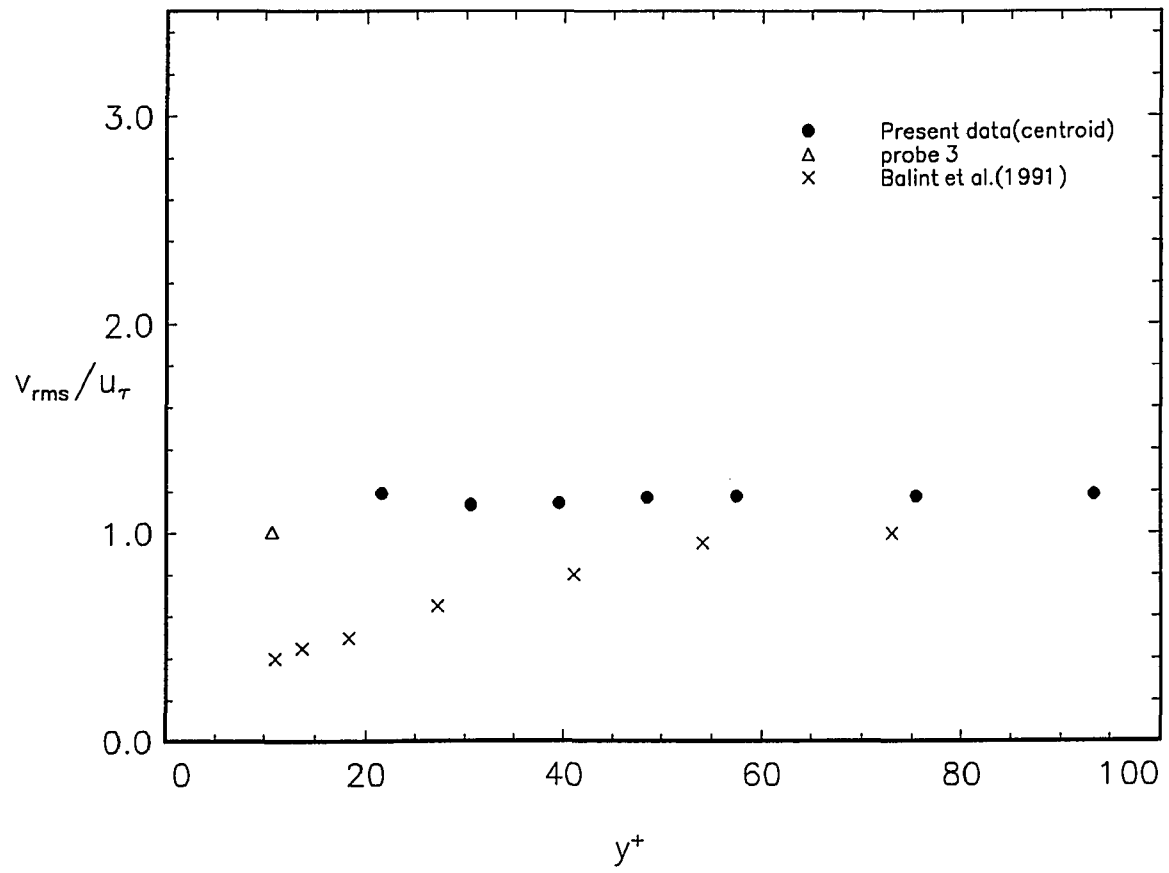


Figure 6.2b. Normalized rms values of normal velocity fluctuations v' .

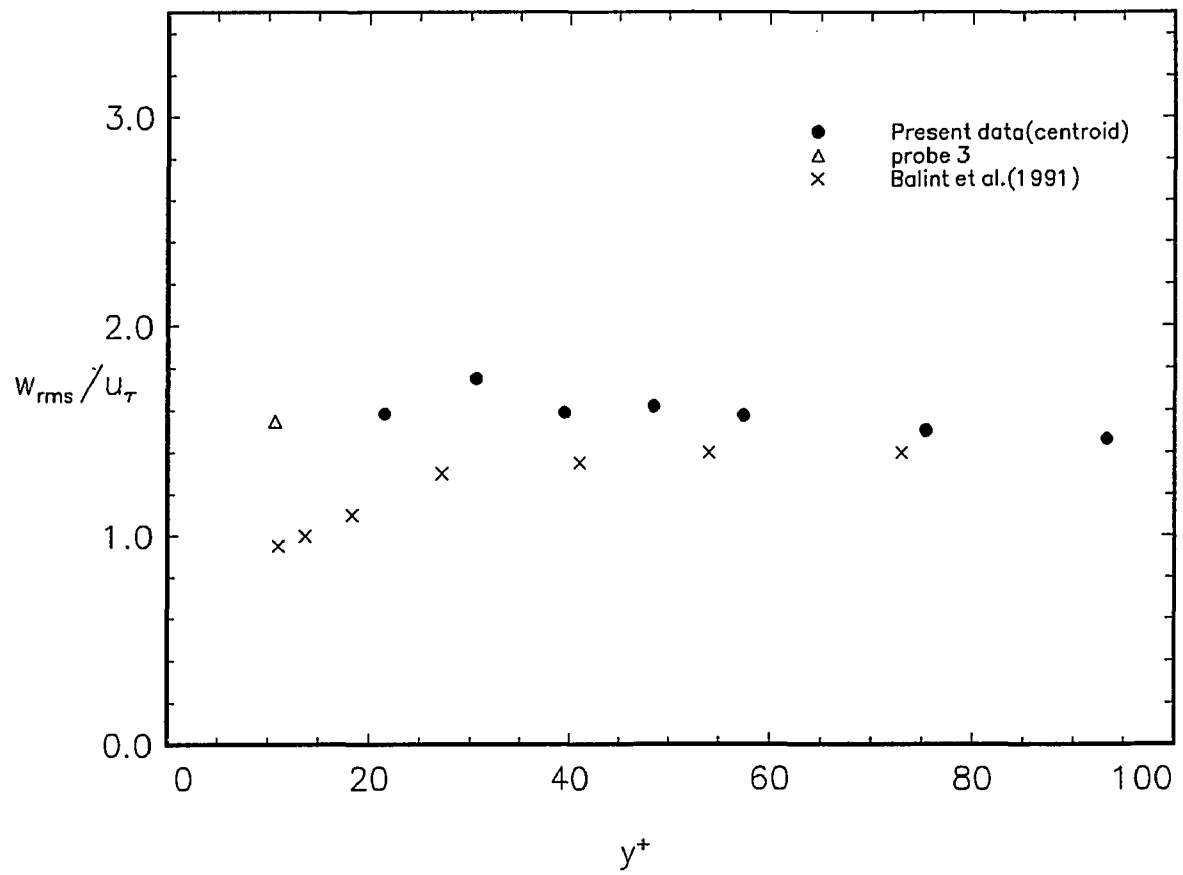


Figure 6.2c. Normalized rms values of spanwise velocity fluctuations w' .

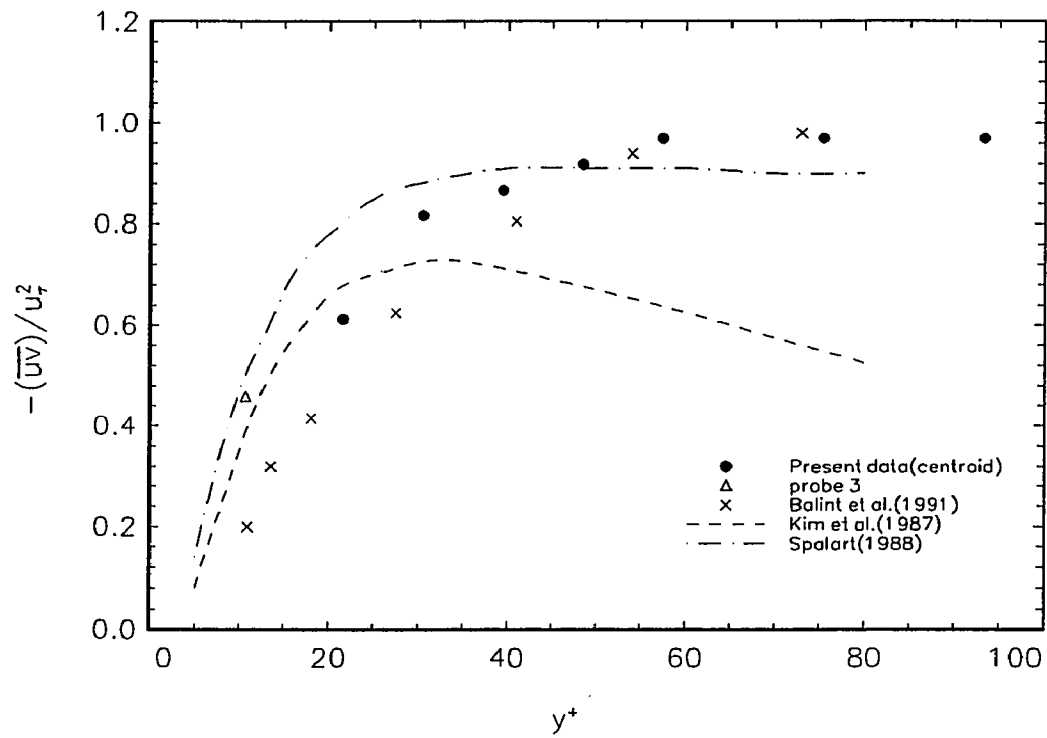


Figure 6.3. Normalized Reynolds shear stress $-\overline{uv}$ in the near-wall region.

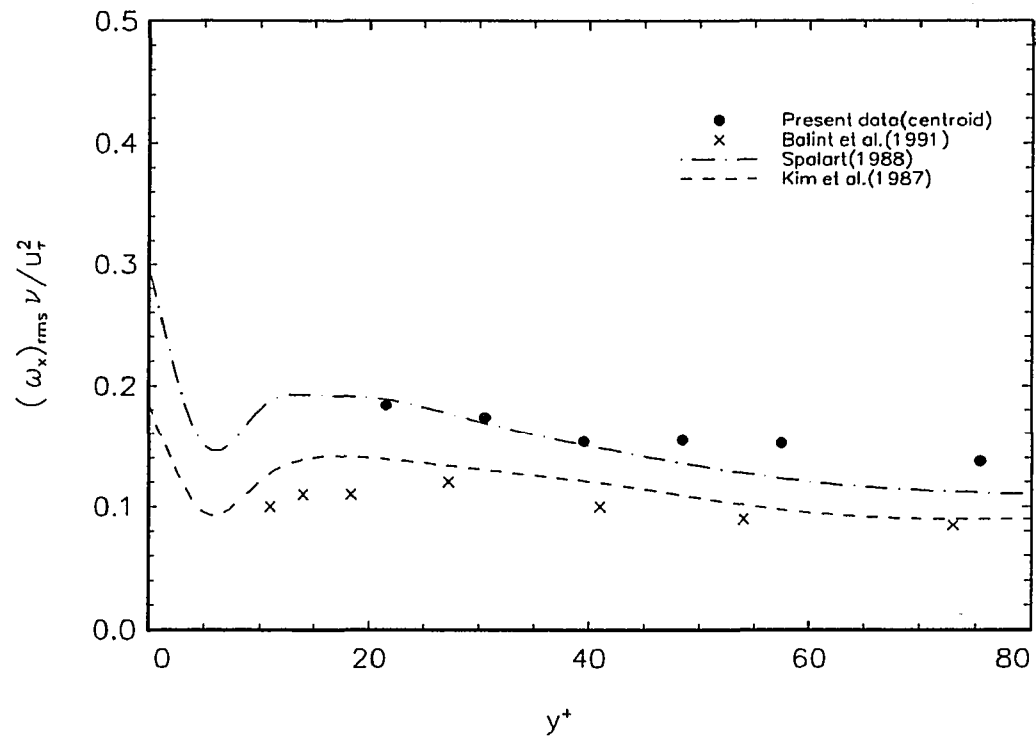


Figure 6.4a. R.m.s. axial vorticity fluctuations ω'_x normalized by inner variables u_τ and ν .

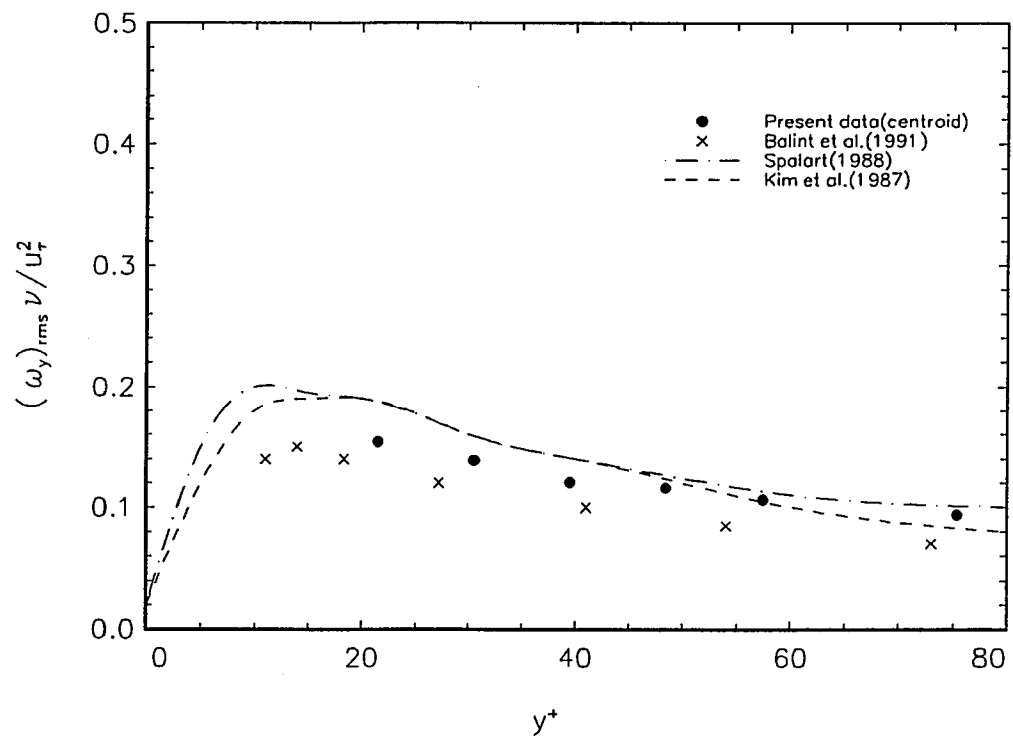


Figure 6.4b. R.m.s. normal vorticity fluctuations ω'_y normalized by u_τ and ν .

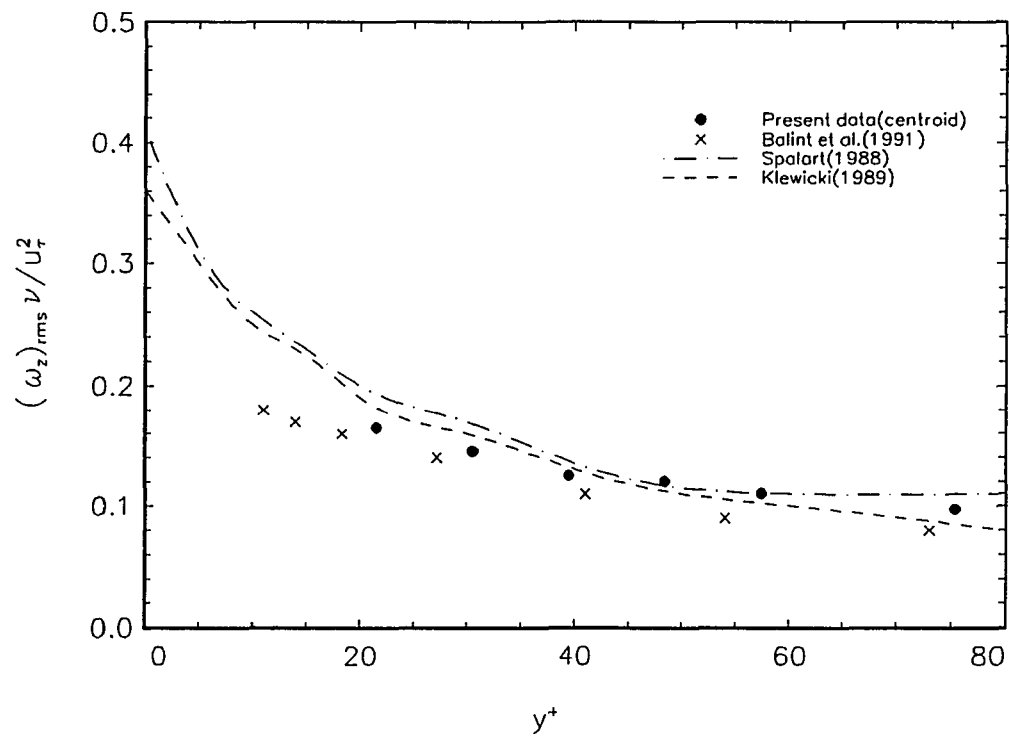


Figure 6.4c. R.m.s. spanwise fluctuations ω'_z normalized by inner variables u_τ and ν .

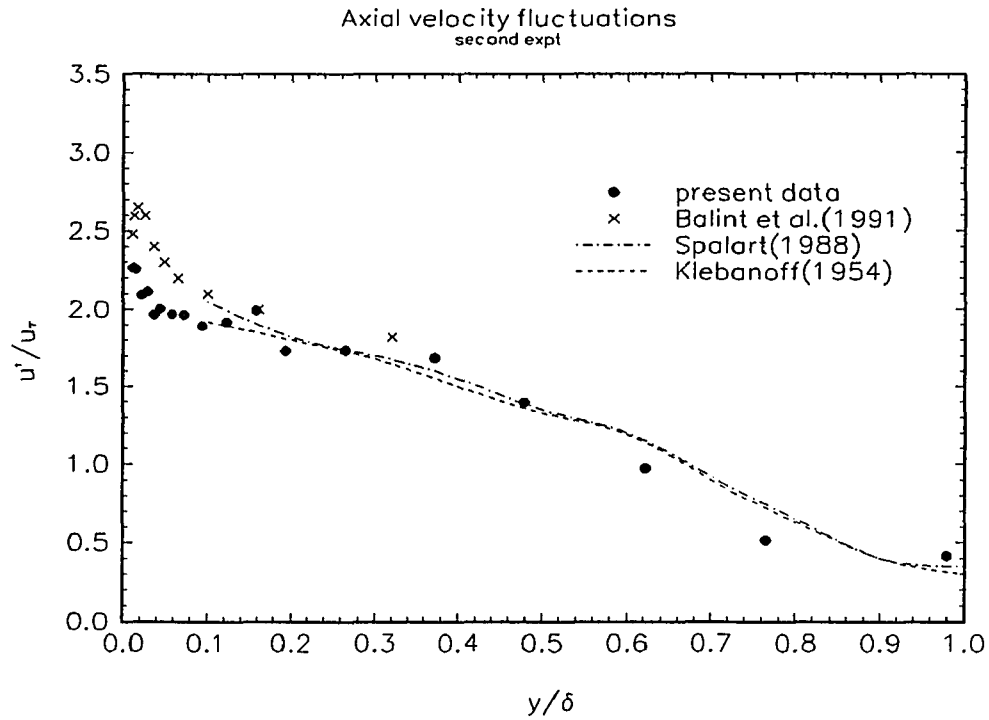


Figure 6.3.1. Measured r.m.s. of axial velocity fluctuations u' normalized by u_τ and δ .

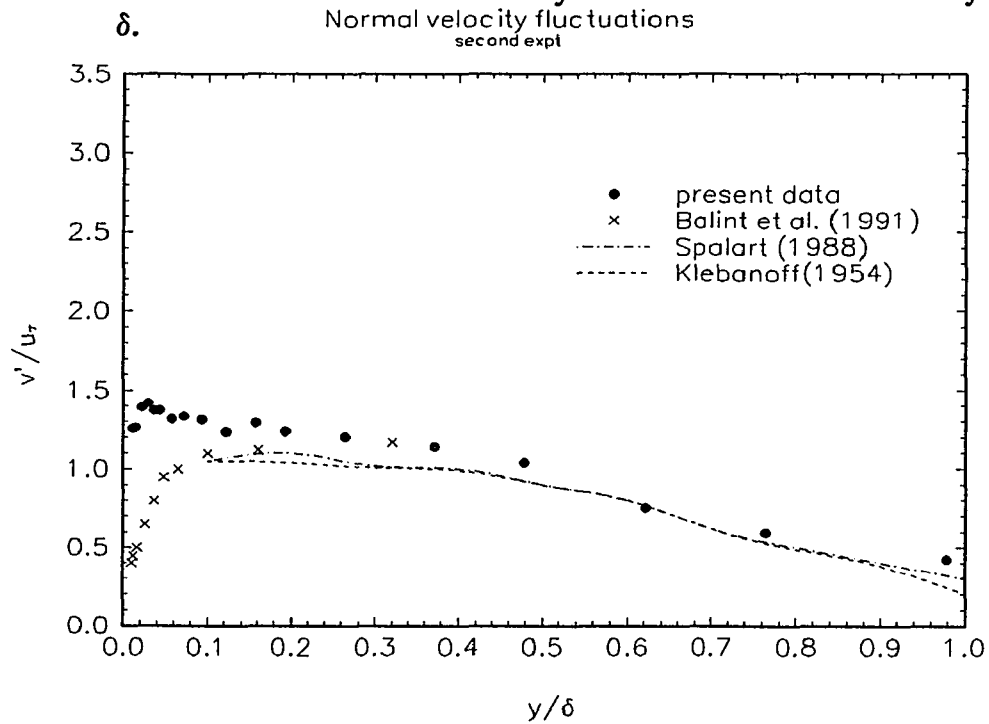


Figure 6.3.2. Measured r.m.s. of normal velocity fluctuations v' normalized by u_τ and δ .

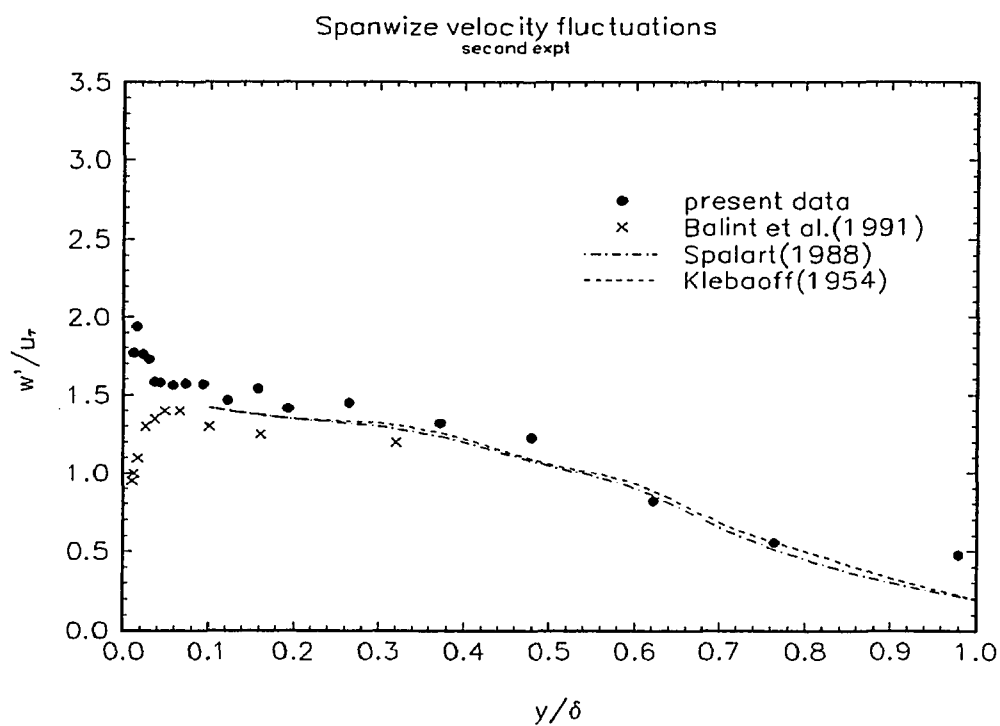


Figure 6.3.3. Measured r.m.s. of spanwise velocity fluctuations w' normalized by u_τ and δ .

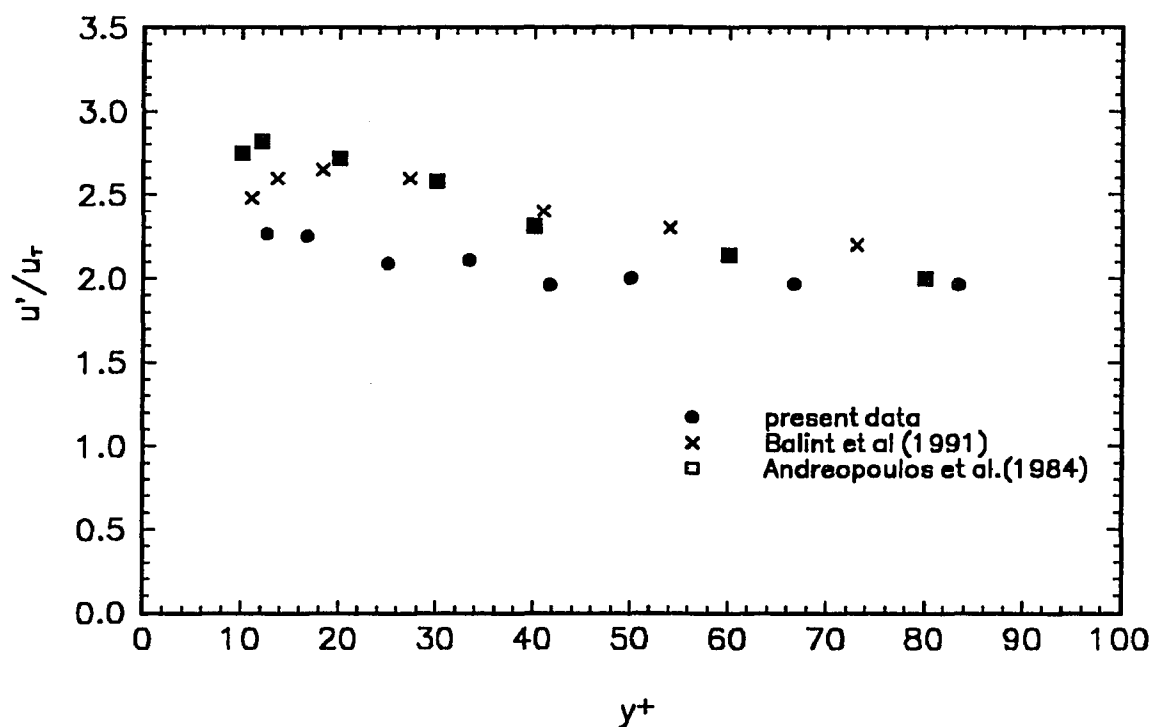


Figure 6.3.4. Measured distributions in the near-wall region of axial velocity fluctuations u' normalized by u_τ and ν .

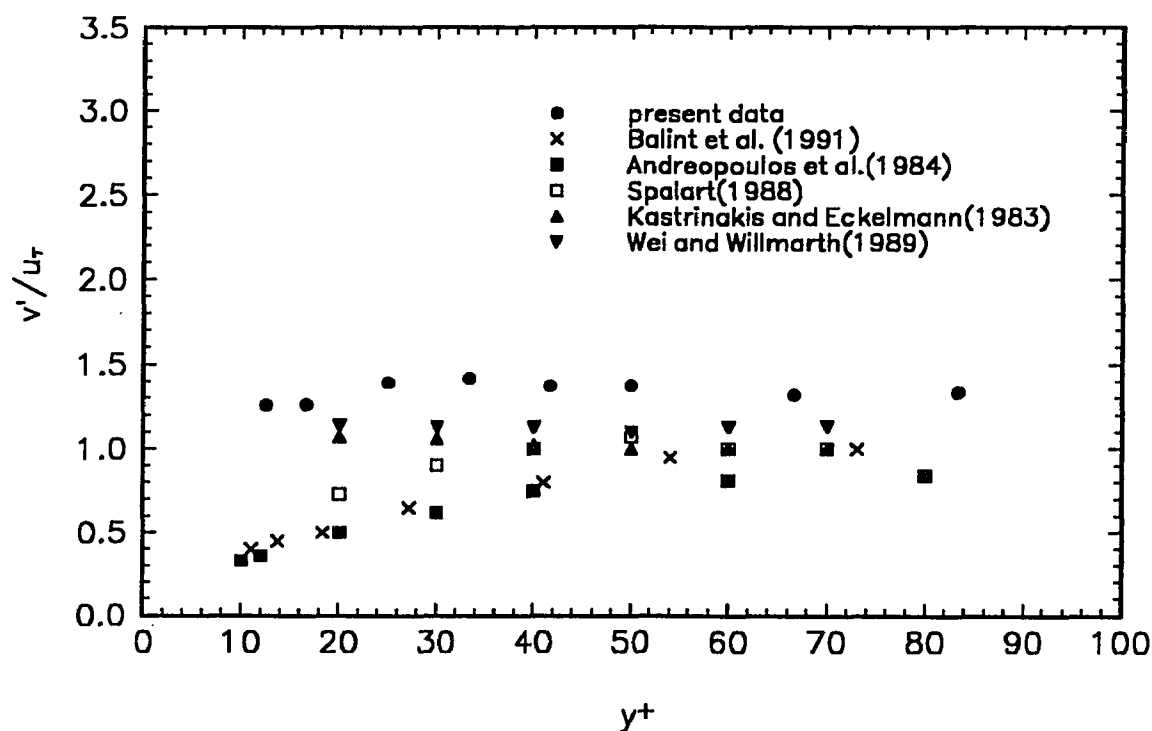


Figure 6.3.5. Measured distributions in the near-wall region of normal velocity fluctuations v' normalized by u_τ and ν .

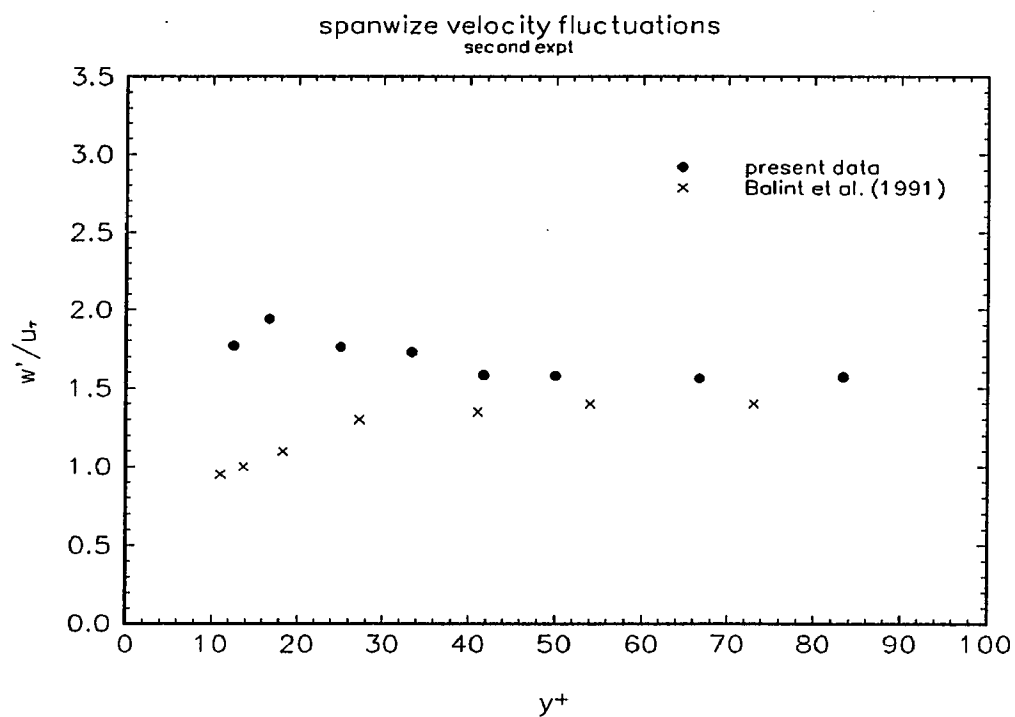


Figure 6.3.6. Measured distributions in the near wall region of spanwise velocity fluctuations w' normalized by u_τ and ν .

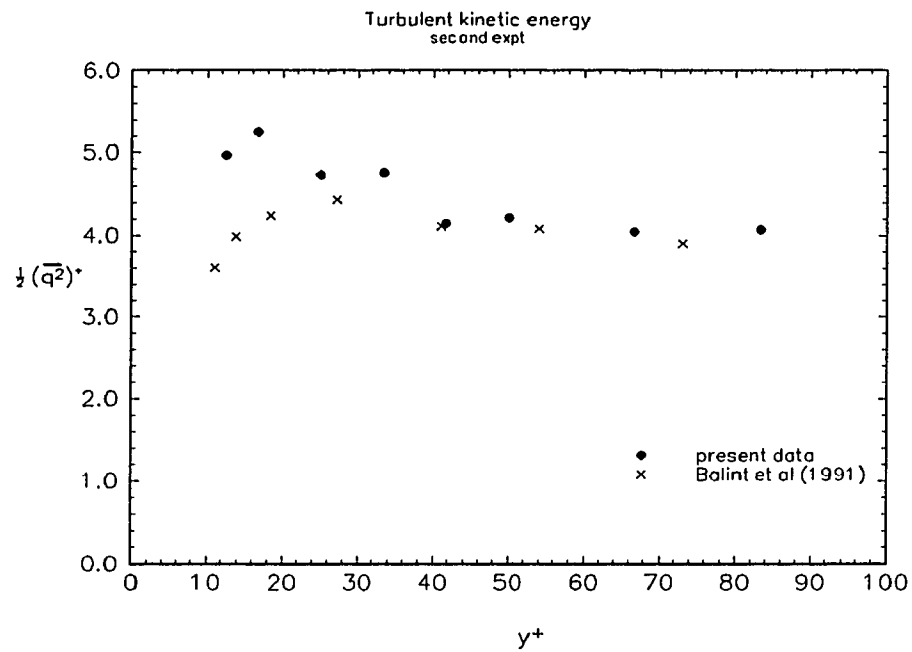


Figure 6.3.7a. Measured distributions in the near wall region of turbulent kinetic energy normalized by u_τ and ν .

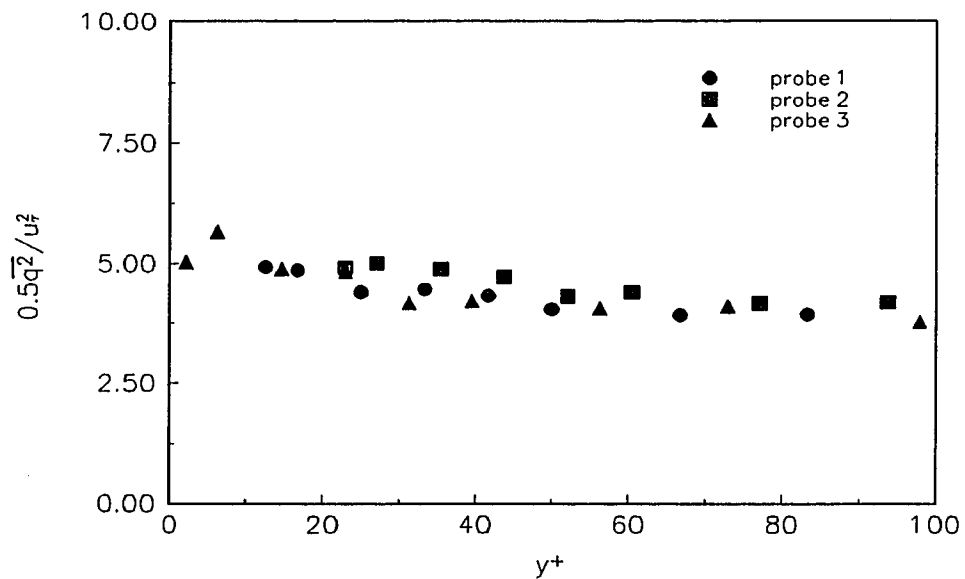


Figure 6.3.7b. Normalized Turbulent kinetic energy distribution in the near wall region as measured by each of the three triple hot-wires.

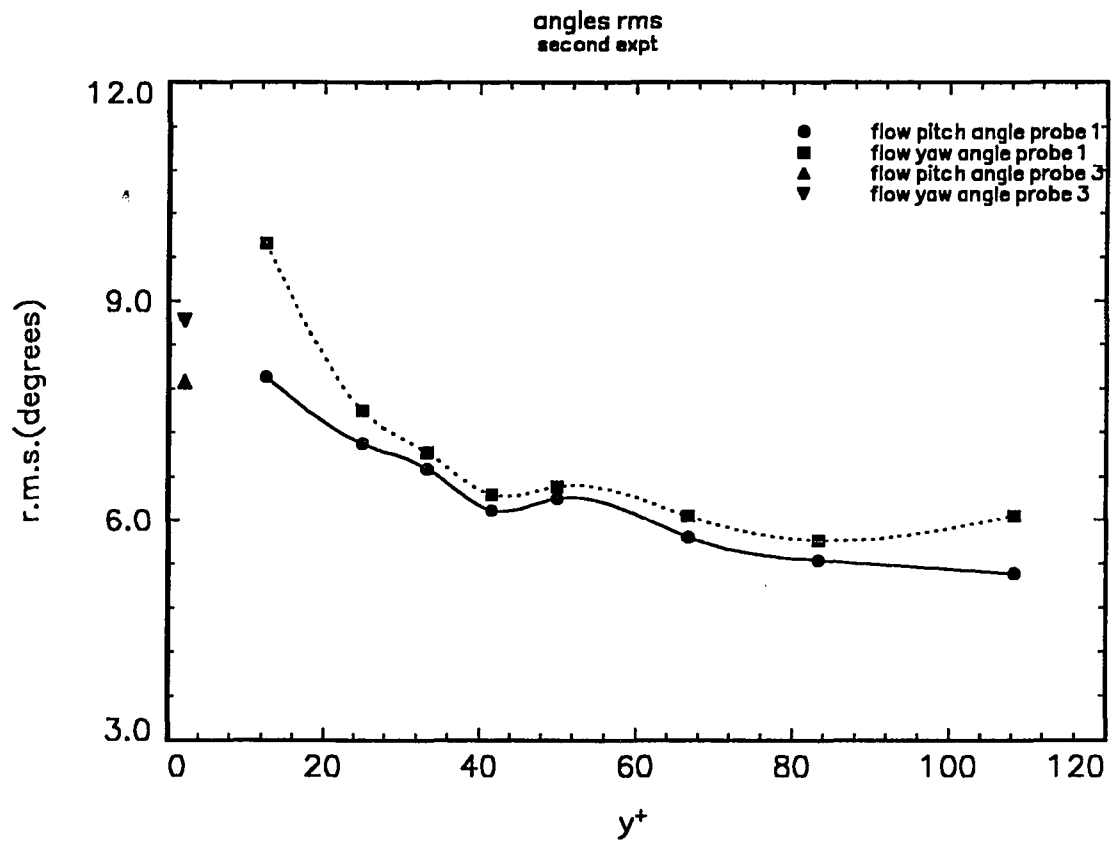


Figure 6.3.8. Measured distributions in the near wall region of r.m.s. flow angles θ_f and ϕ_f fluctuations.

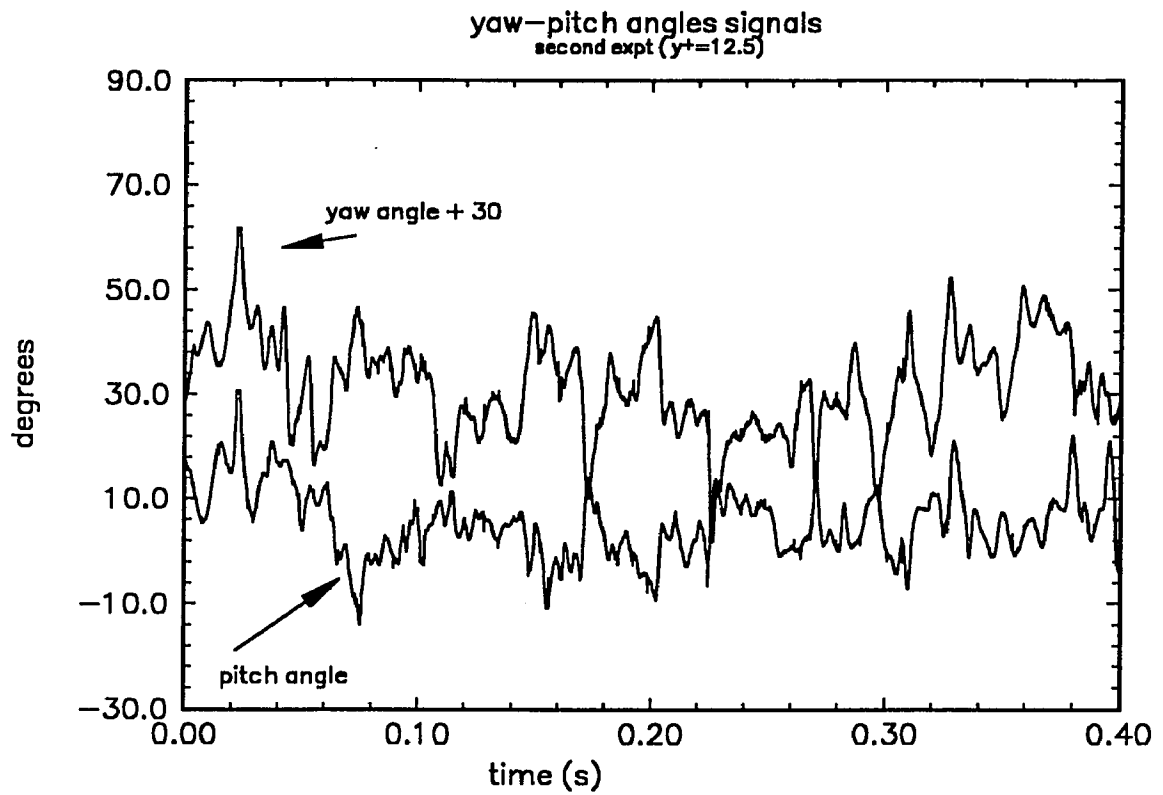


Figure 6.3.9. Typical time series records of flow angles θ_f and ϕ_f .

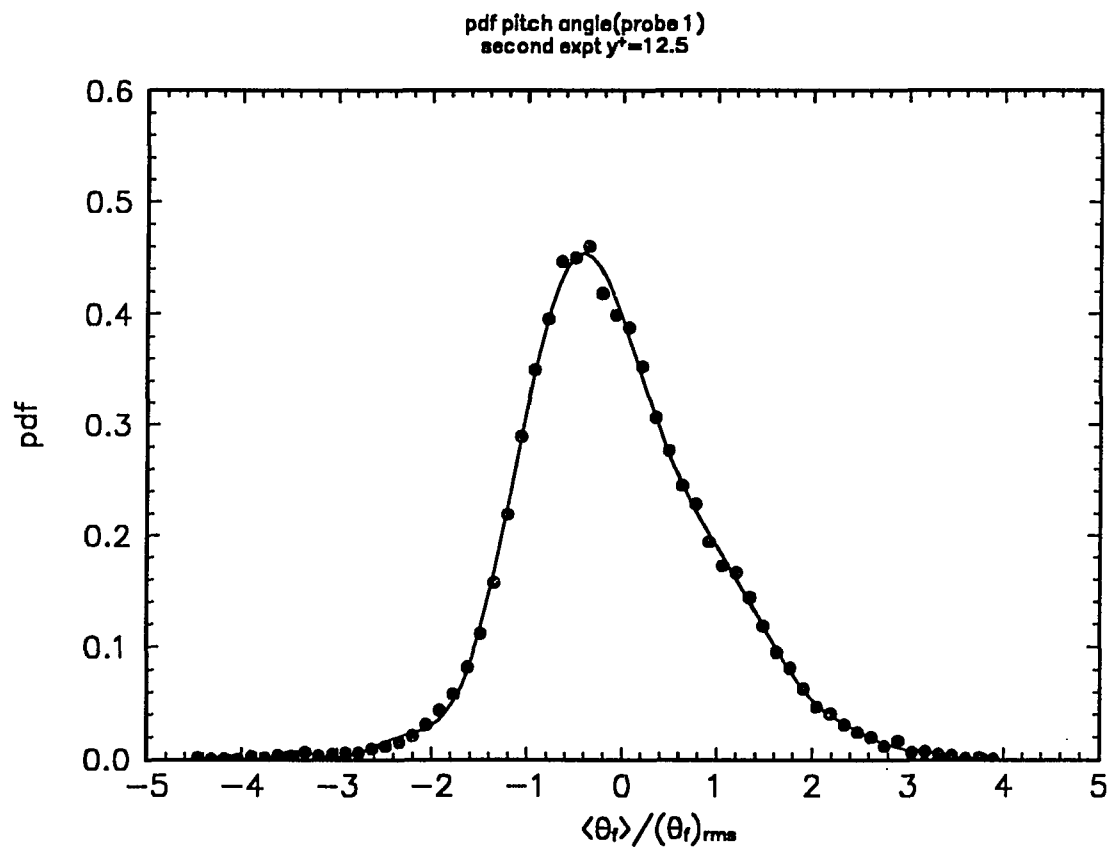


Figure 6.3.10. Probability density function of flow angle θ_f measured at the center of probe 1.

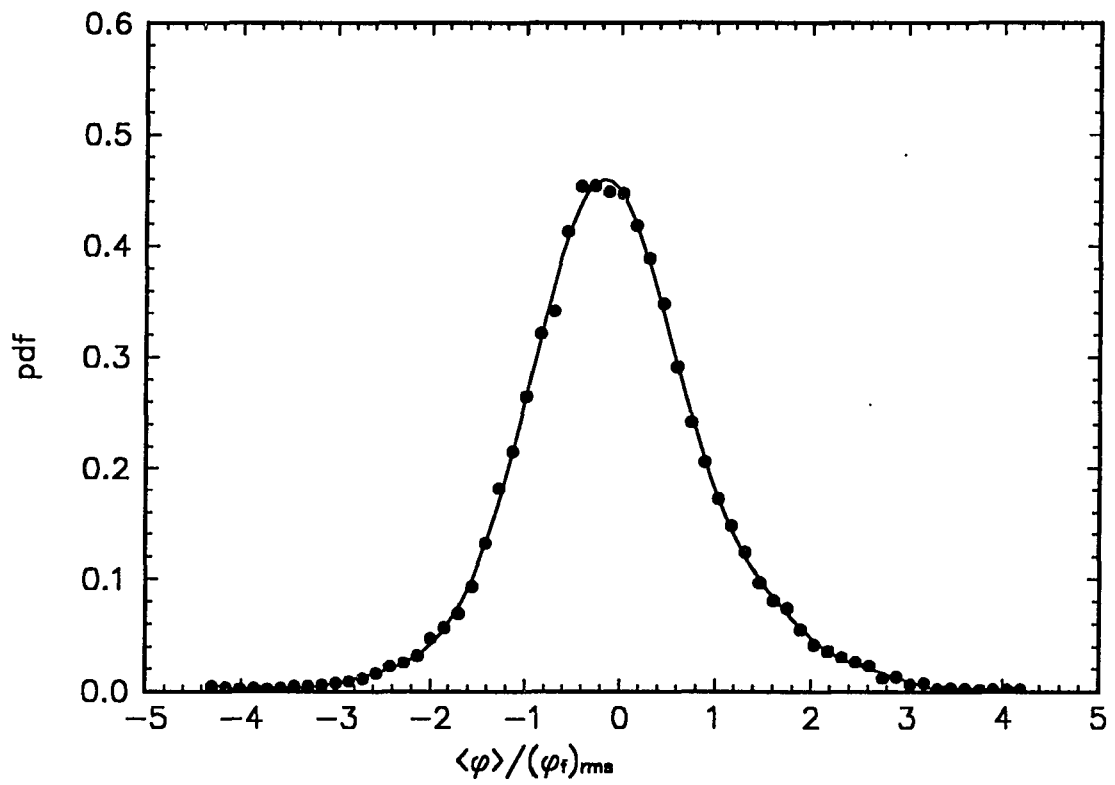


Figure 6.3.11. Probability density function of flow angle ϕ_f measure at the center of probe 1.

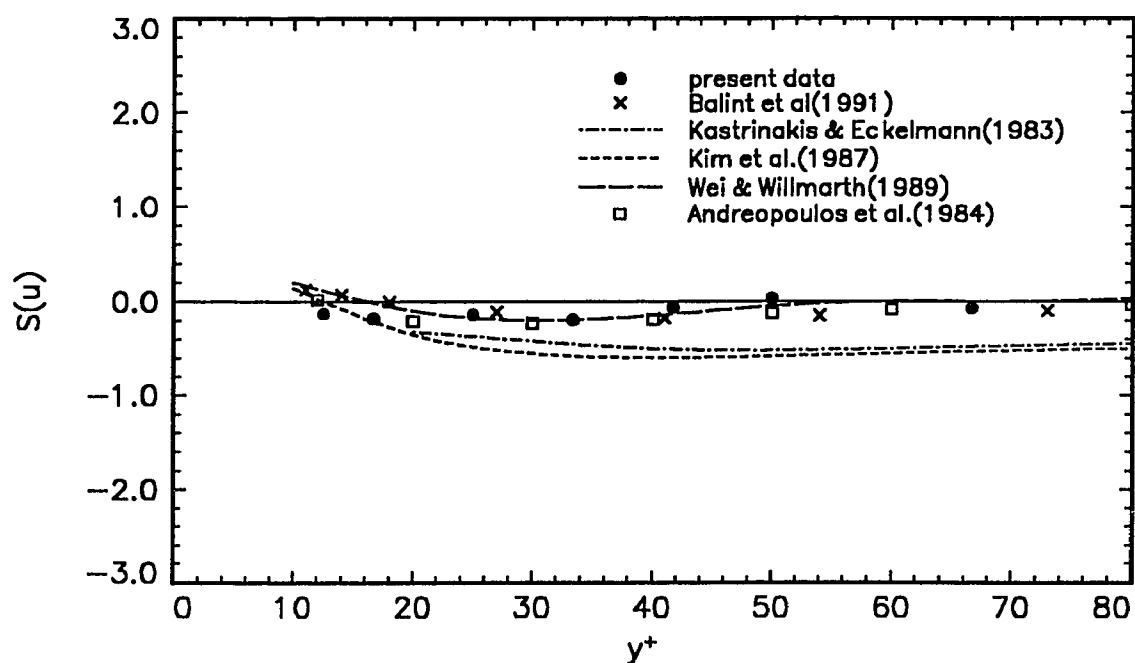


Figure 6.3.12. Skewness factor of velocity component u and compared with other simulated and measured datasets.

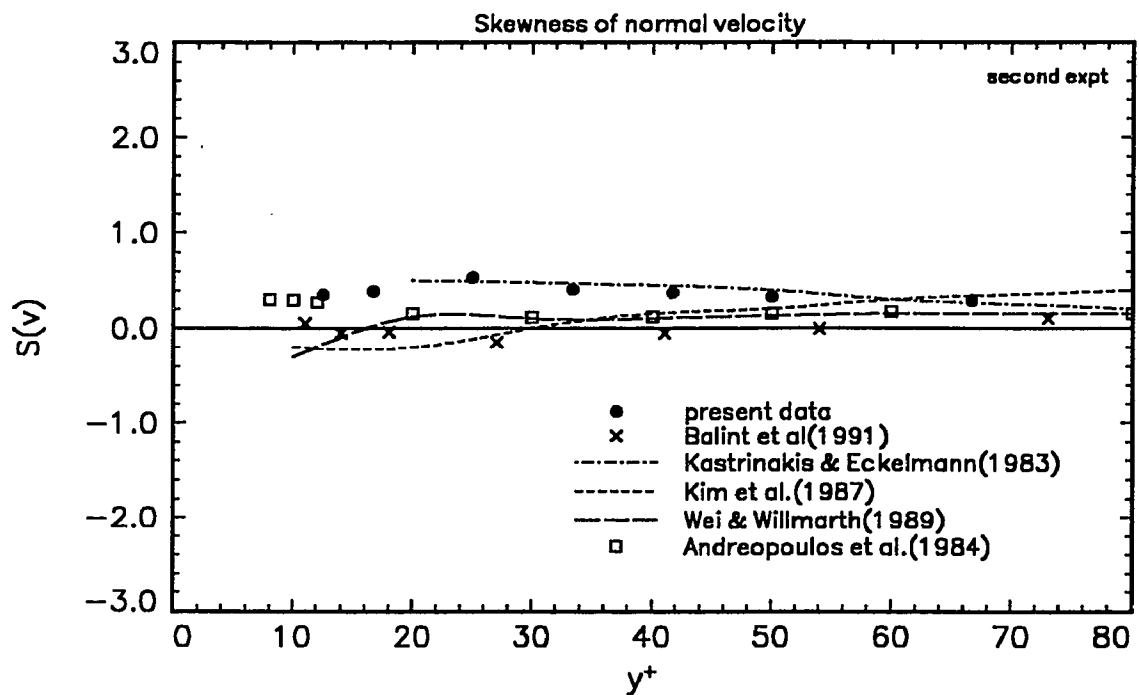


Figure 6.3.13. Skewness factor of velocity component v and compared with other simulated and measured datasets.

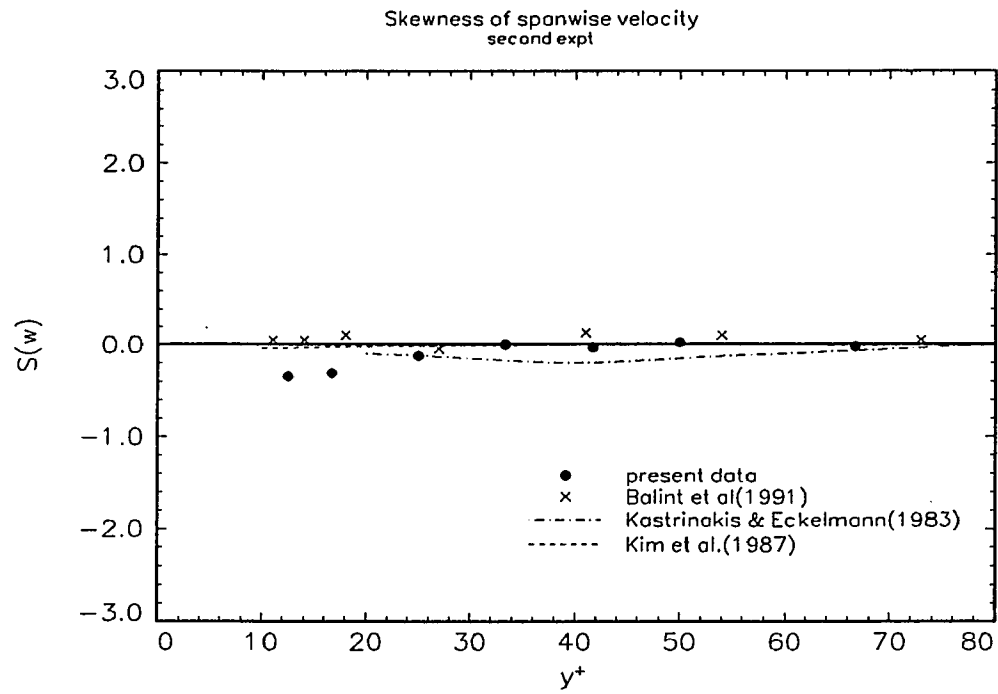


Figure 6.3.14. Skewness factor of velocity component w and compared with other simulated and measured datasets.

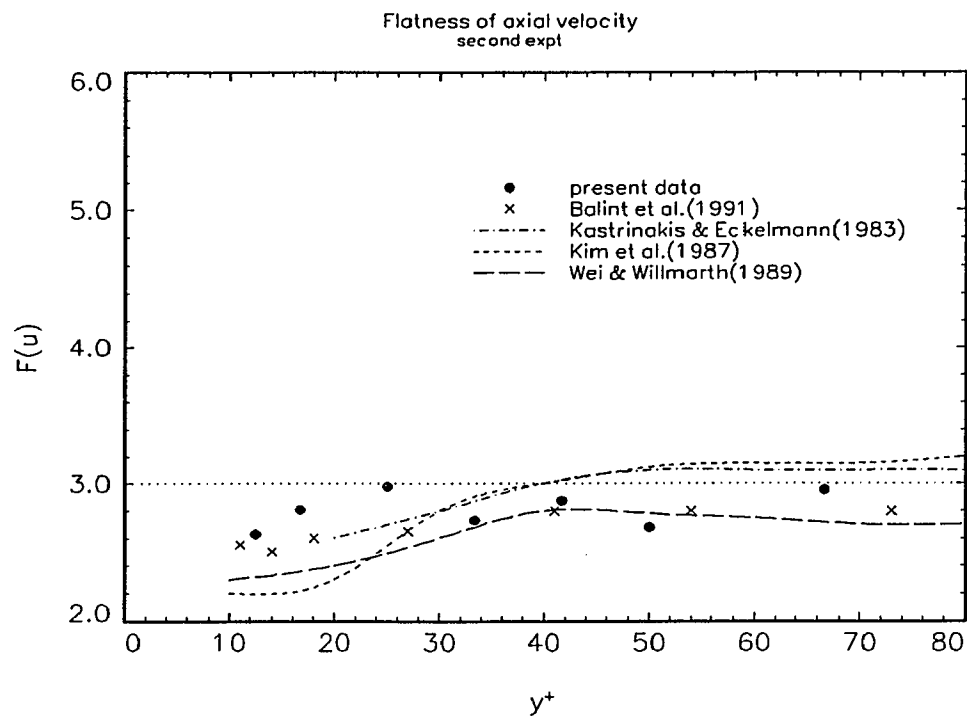


Figure 6.3.15. Flatness factor of velocity component u and compared with other simulated and measured datasets.

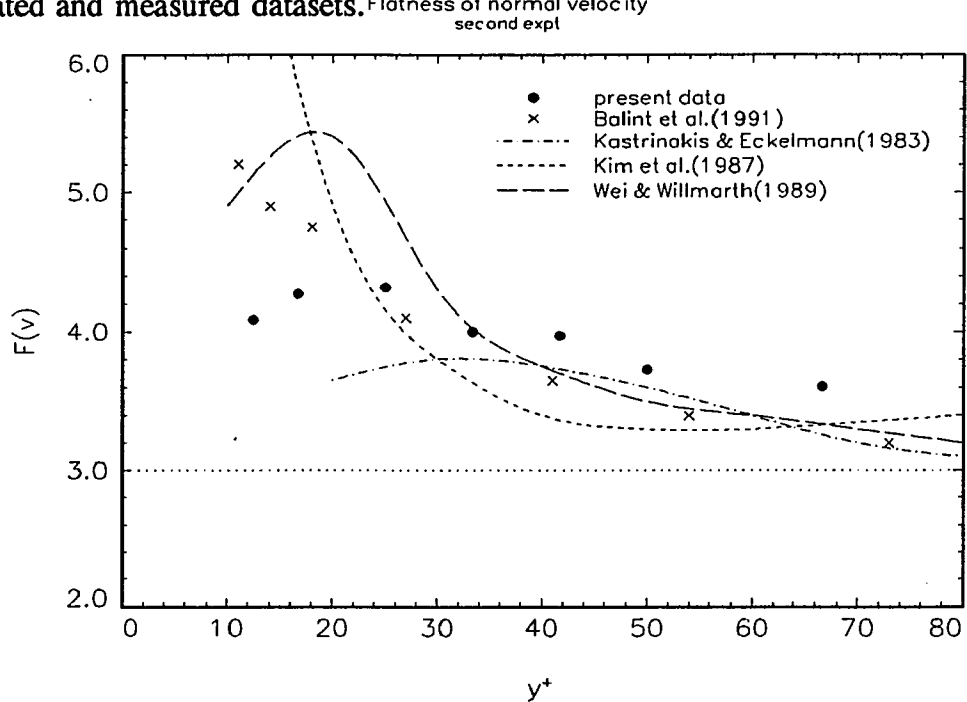


Figure 6.3.16. Flatness factor of velocity component v and compared with other simulated and measured datasets.

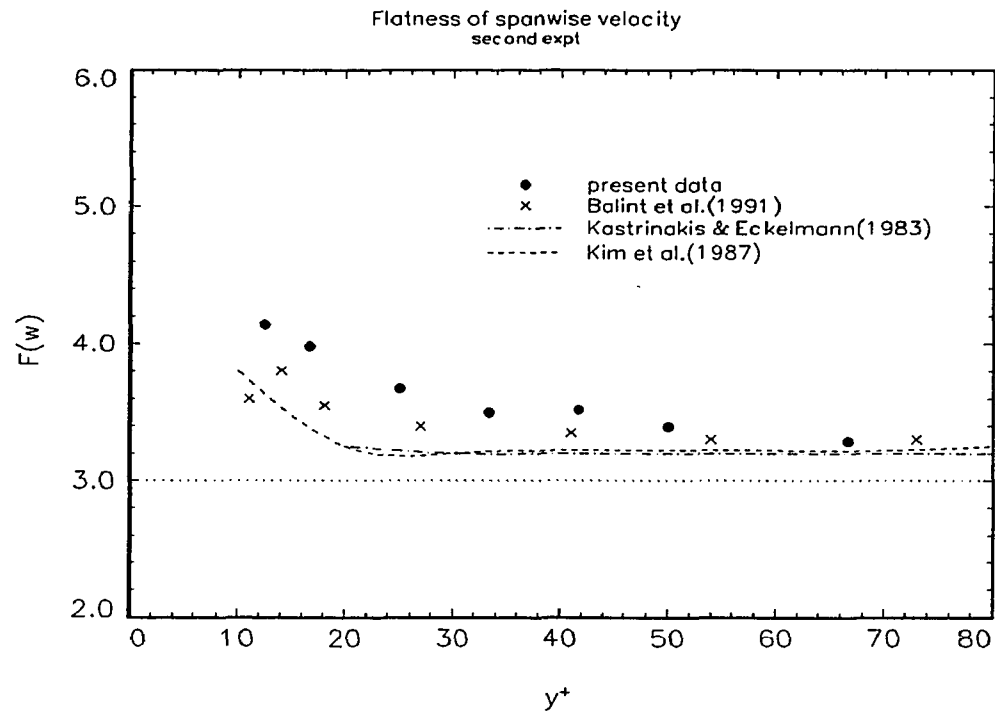


Figure 6.3.17. Flatness factor of velocity component w and compared with other simulated and measured datasets.

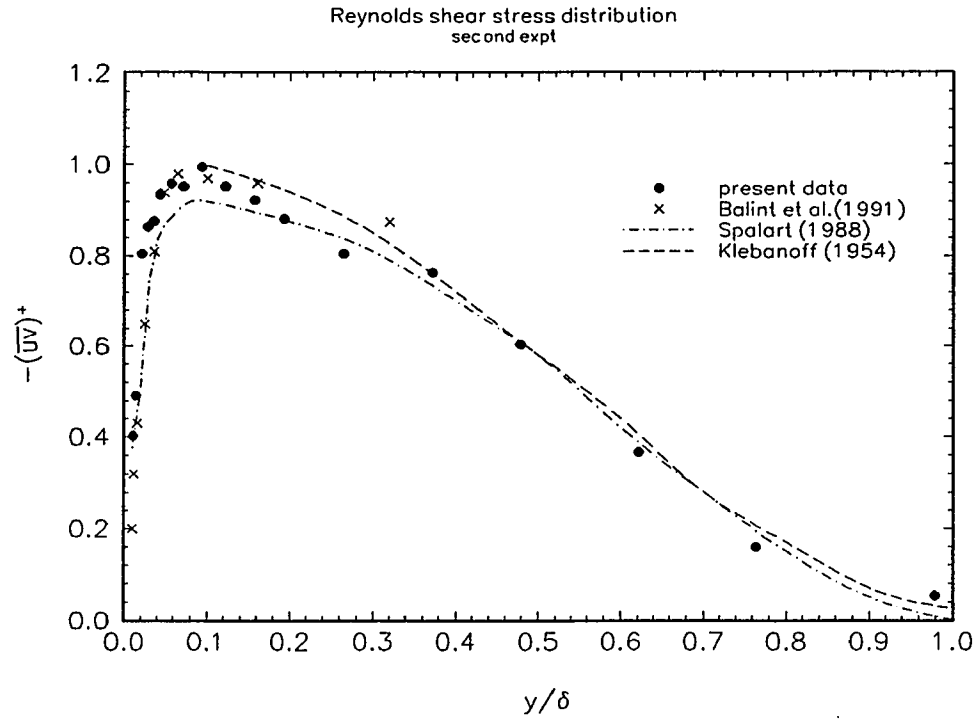


Figure 6.3.18. Normalized Reynolds shear stress $-\overline{uv}$ across the boundary layer.

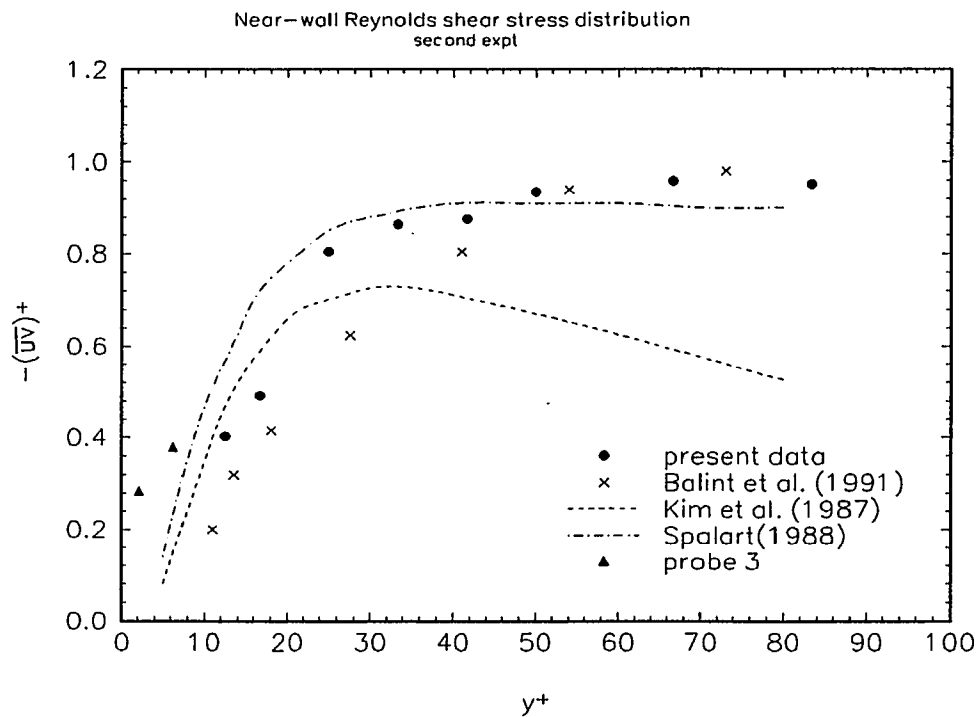


Figure 6.3.19. Normalized Reynolds shear stress $-\overline{uv}$ in the near wall region.

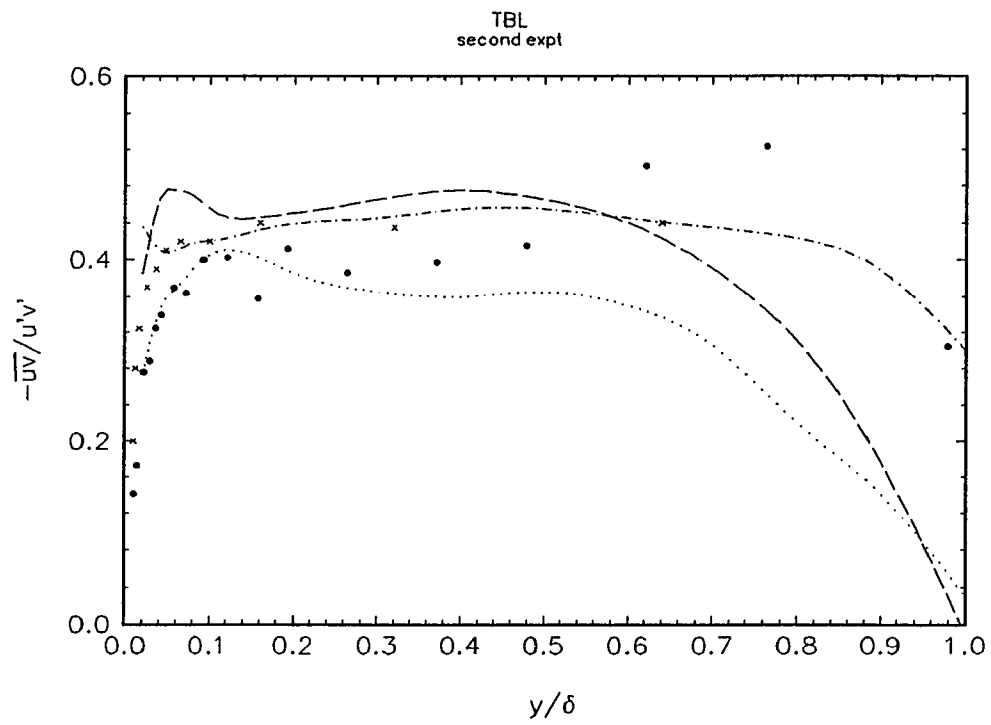


Figure 6.3.20. Measured correlation coefficient distribution across the boundary layer.

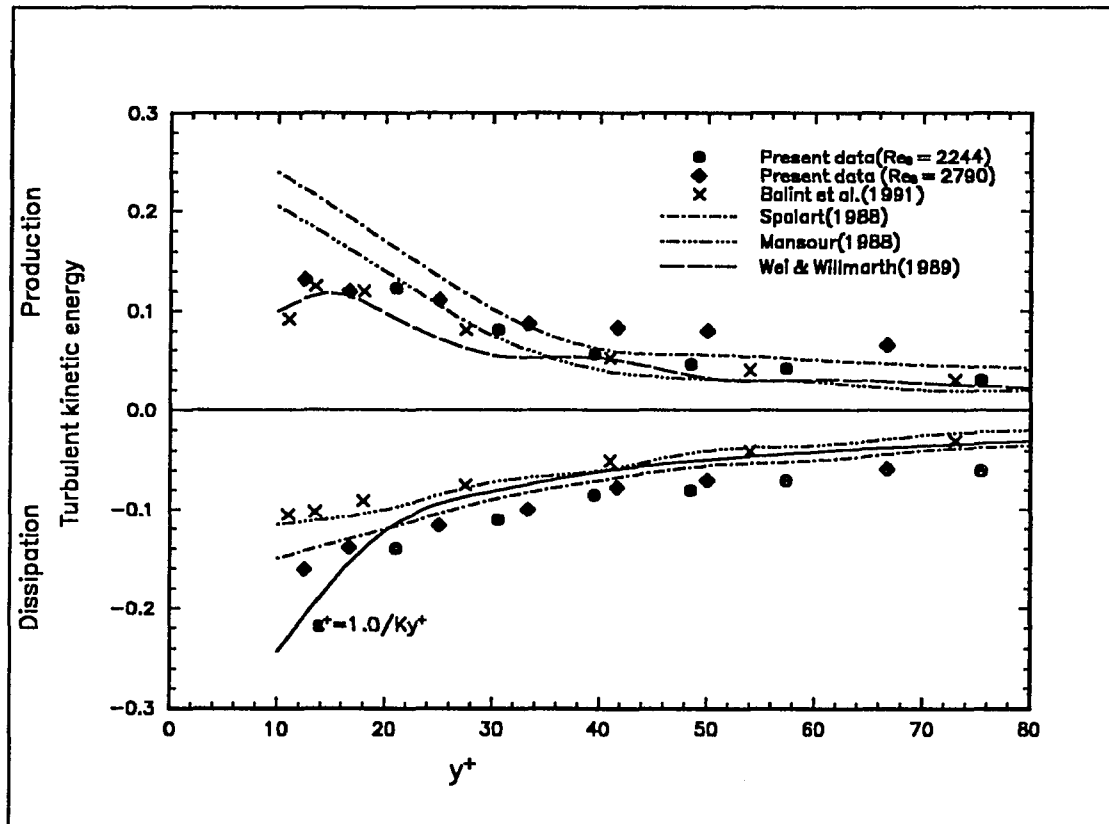


Figure 6.3.21 Computed turbulent kinetic energy production and dissipation rates weighted by the wall variables u_τ and ν at $y^+ = 12.5$.

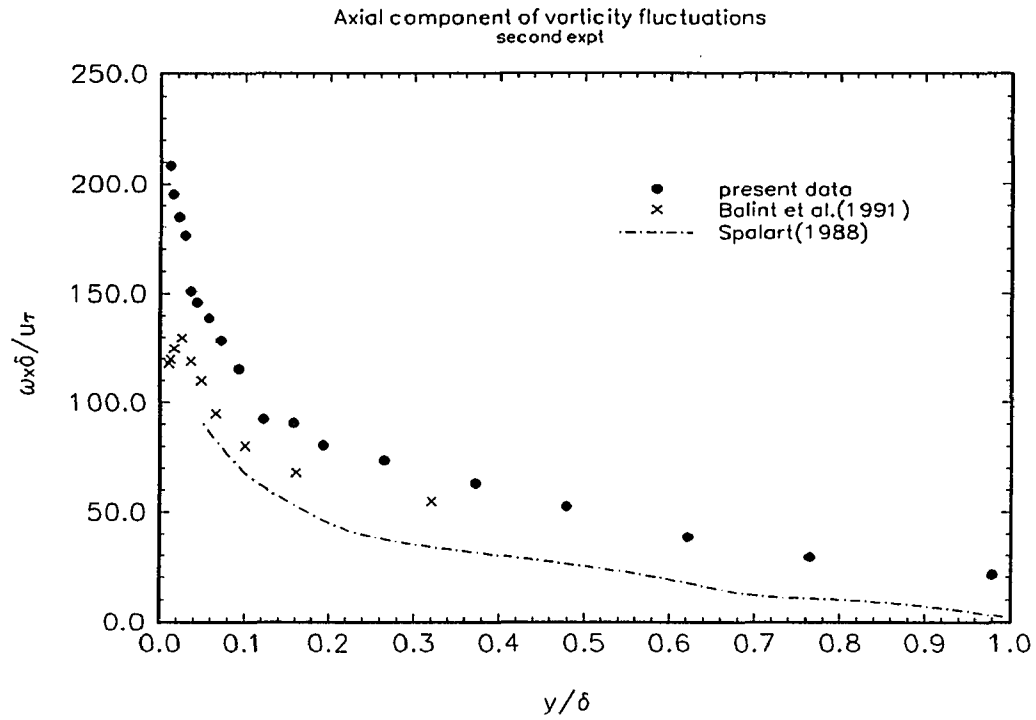


Figure 6.3.22. R.m.s. axial vorticity fluctuations ω'_x normalized by outer variables u_τ and δ .

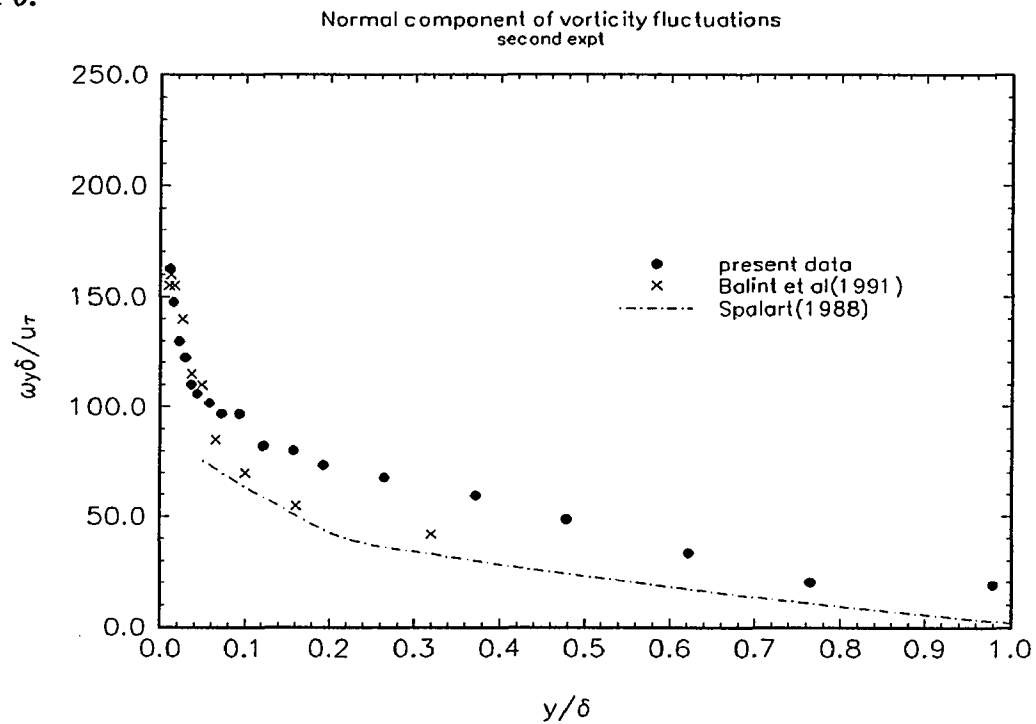


Figure 6.3.23. R.m.s. normal vorticity fluctuations ω'_y normalized by outer variables u_τ and δ .

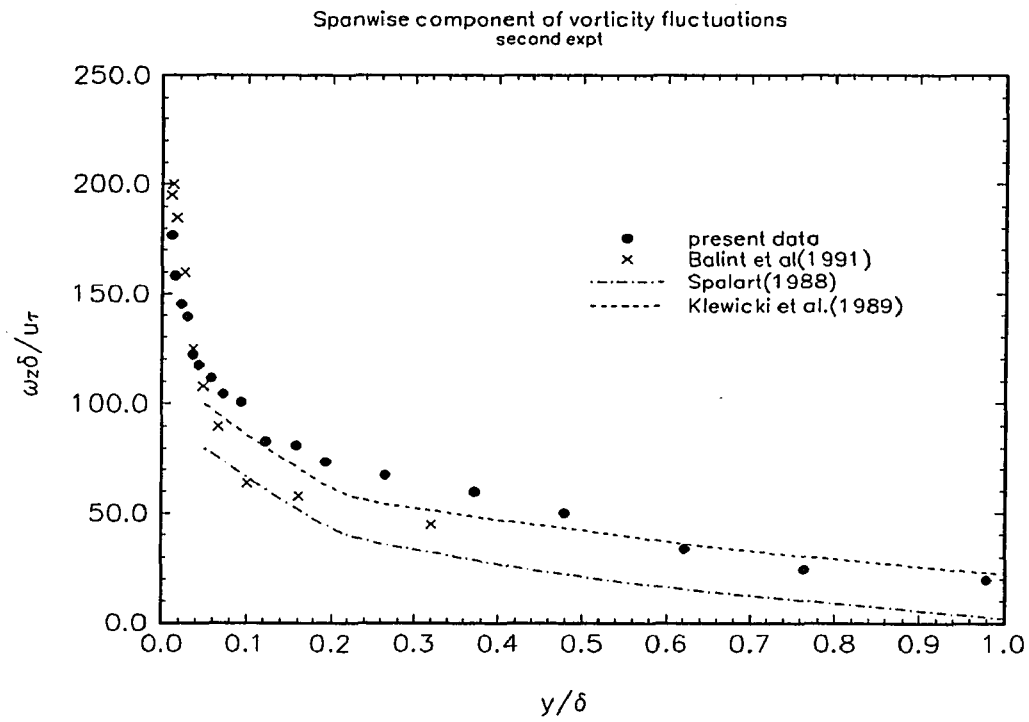


Figure 6.3.24. R.m.s. spanwise vorticity fluctuations ω'_z normalized by outer variables u_τ and δ .

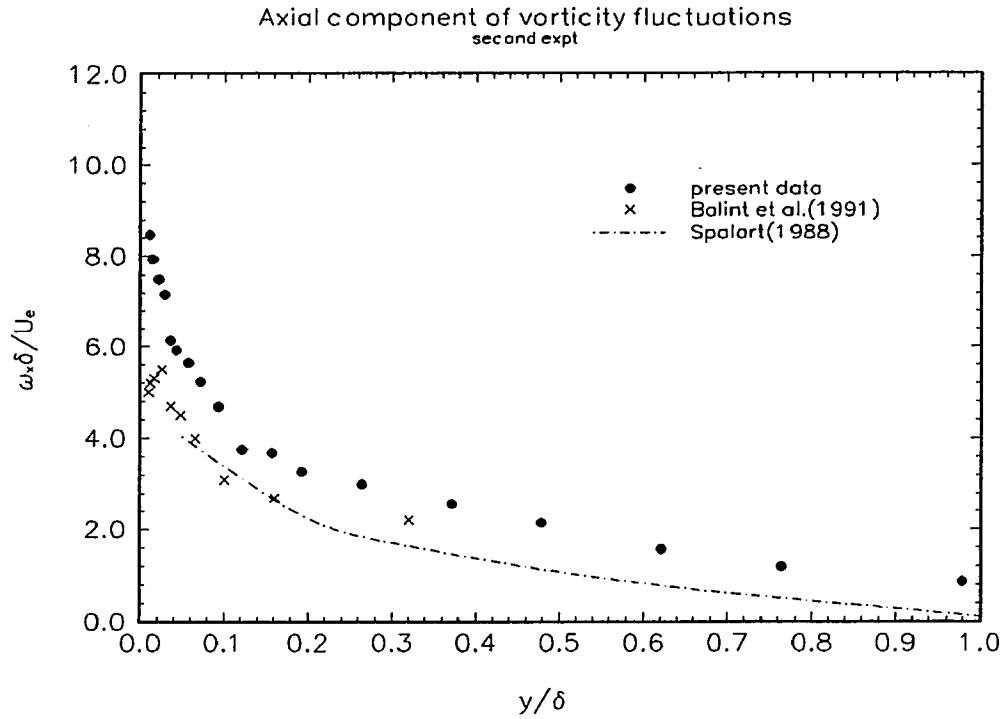


Figure 6.3.25. R.m.s. axial vorticity fluctuations ω'_x scaled by variables U_∞ and δ .

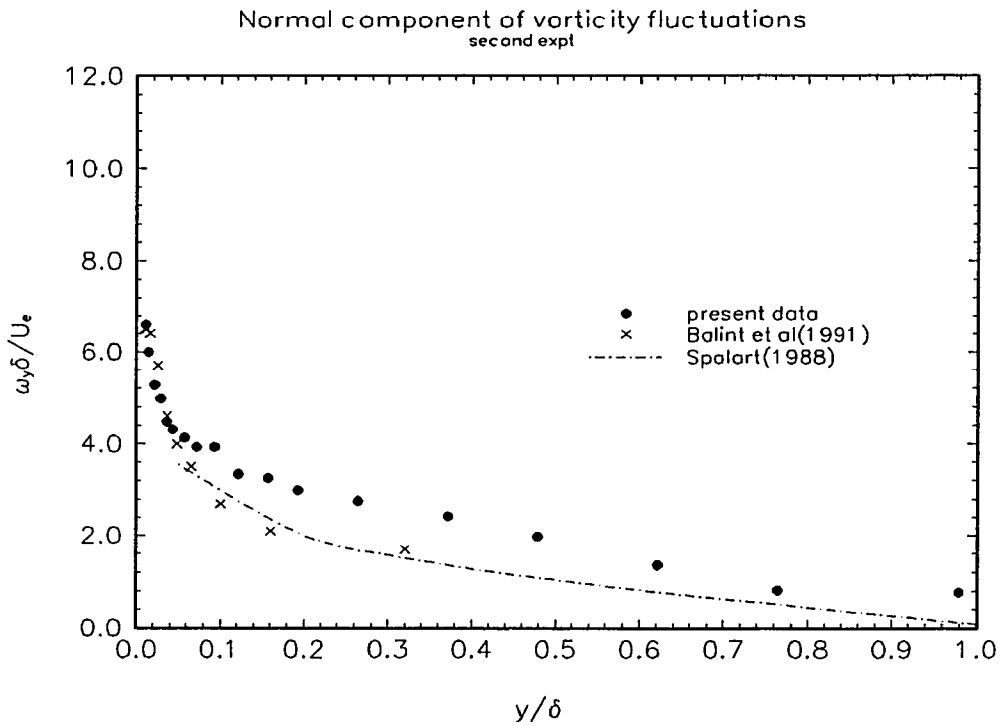


Figure 6.3.26. R.m.s. normal vorticity fluctuations ω'_y scaled by variables U_∞ and δ .

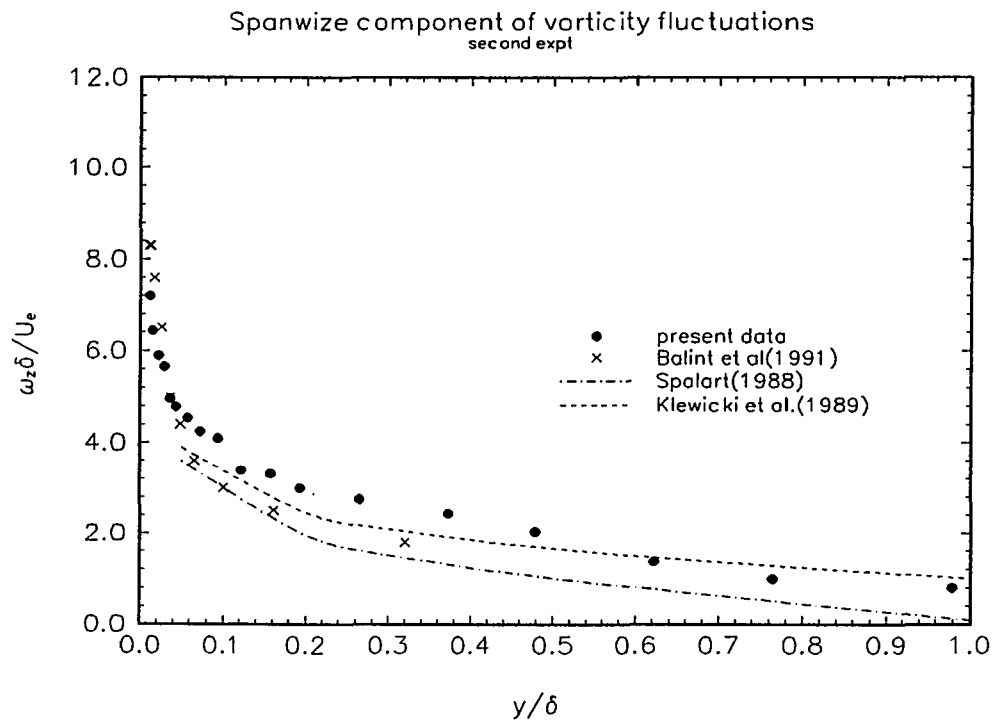


Figure 6.3.27. R.m.s. spanwise vorticity fluctuations ω'_z scaled by variables U_∞ and δ .

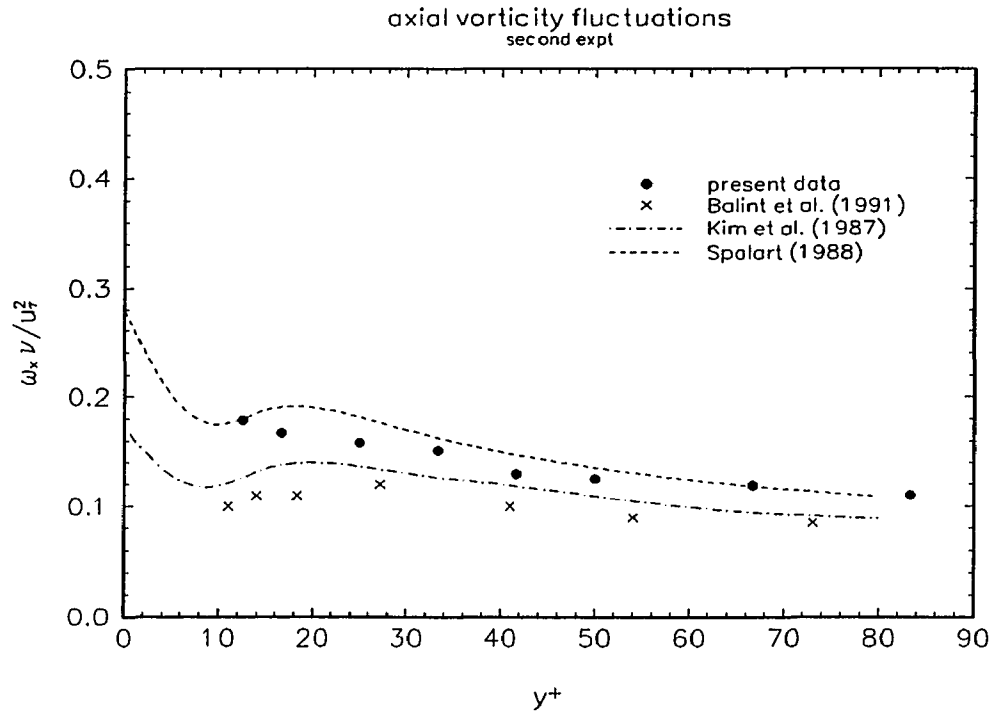


Figure 6.3.28. Near-wall axial vorticity fluctuations ω'_x normalized by inner variables u_τ and ν .

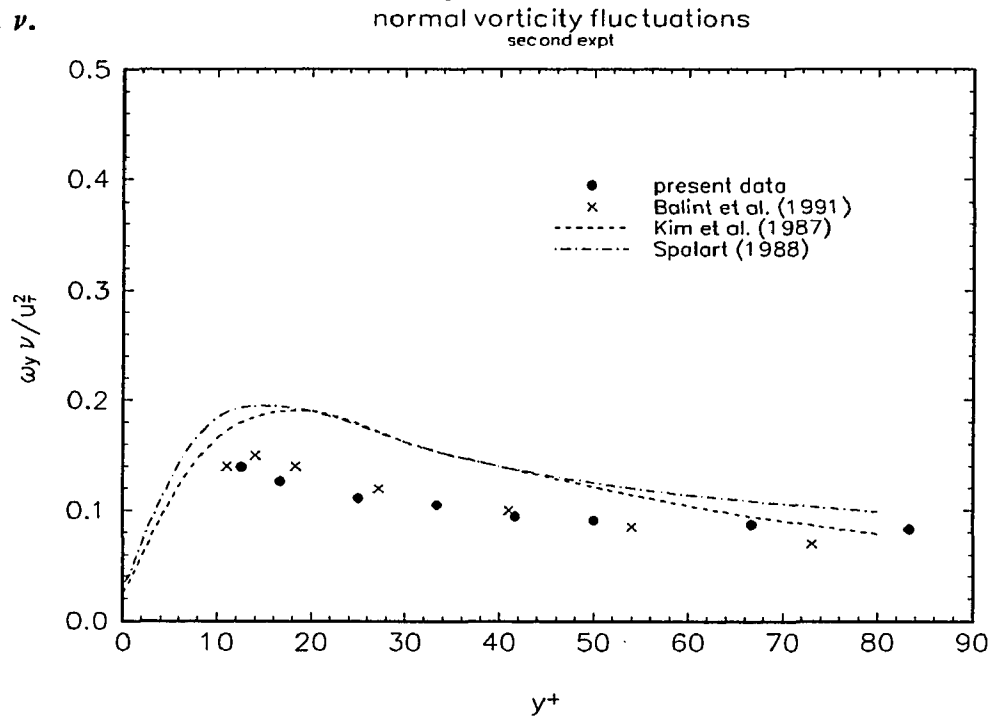


Figure 6.3.29. Near-wall normal vorticity fluctuations ω'_y normalized by inner variables u_τ and ν .

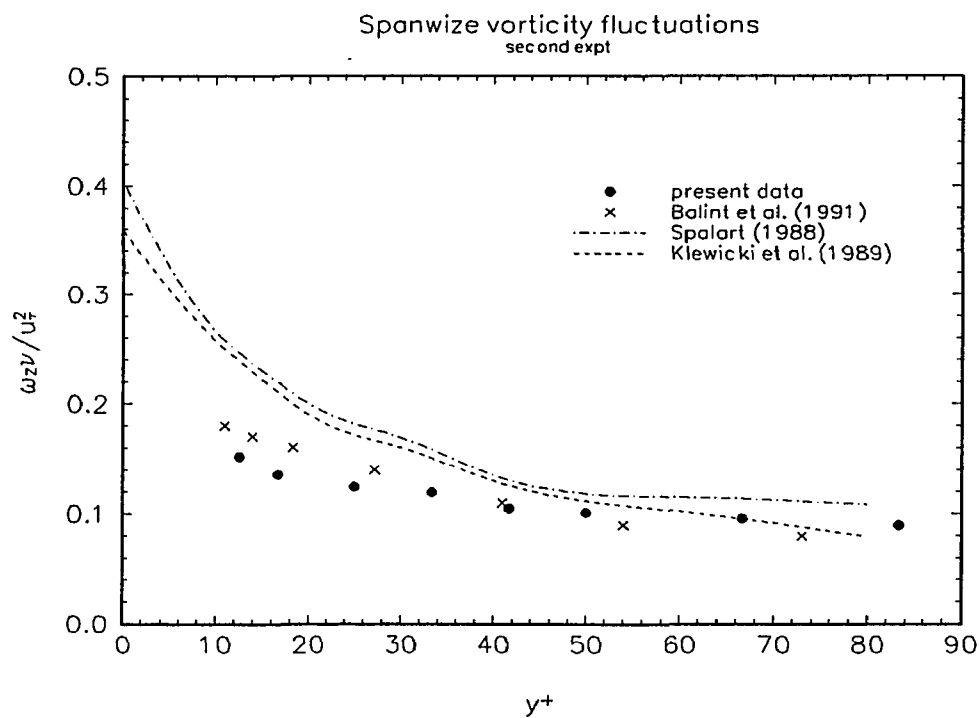


Figure 6.3.30. Near-wall spanwise vorticity fluctuations ω'_z normalized by inner variables u_τ and ν .

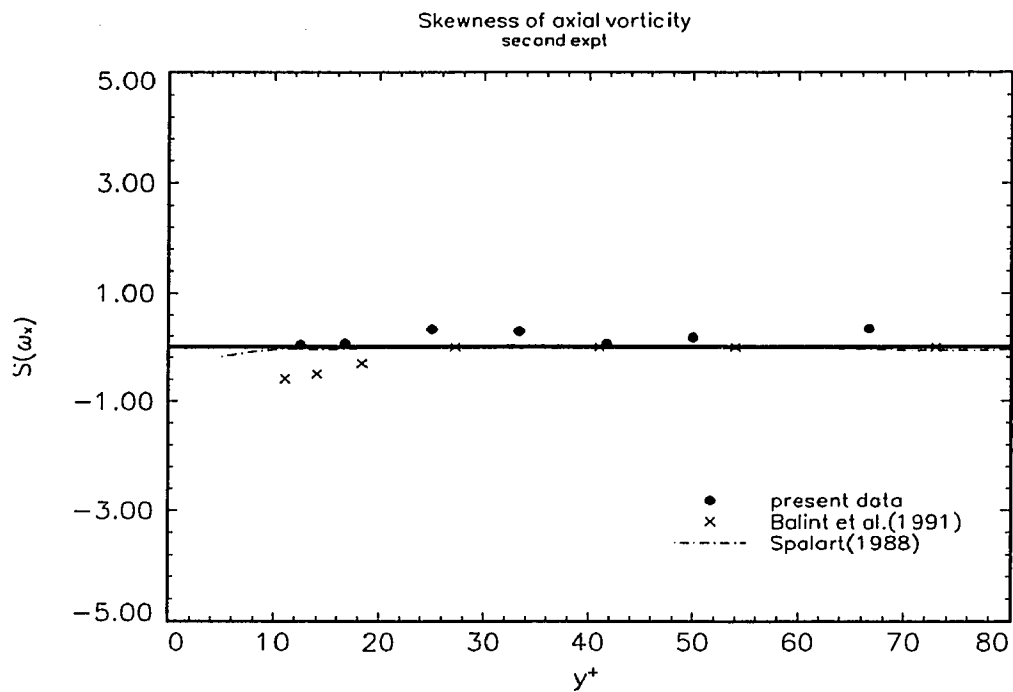


Figure 6.3.31. Skewness factor of vorticity component ω_x and compared with other simulated and measured datasets.

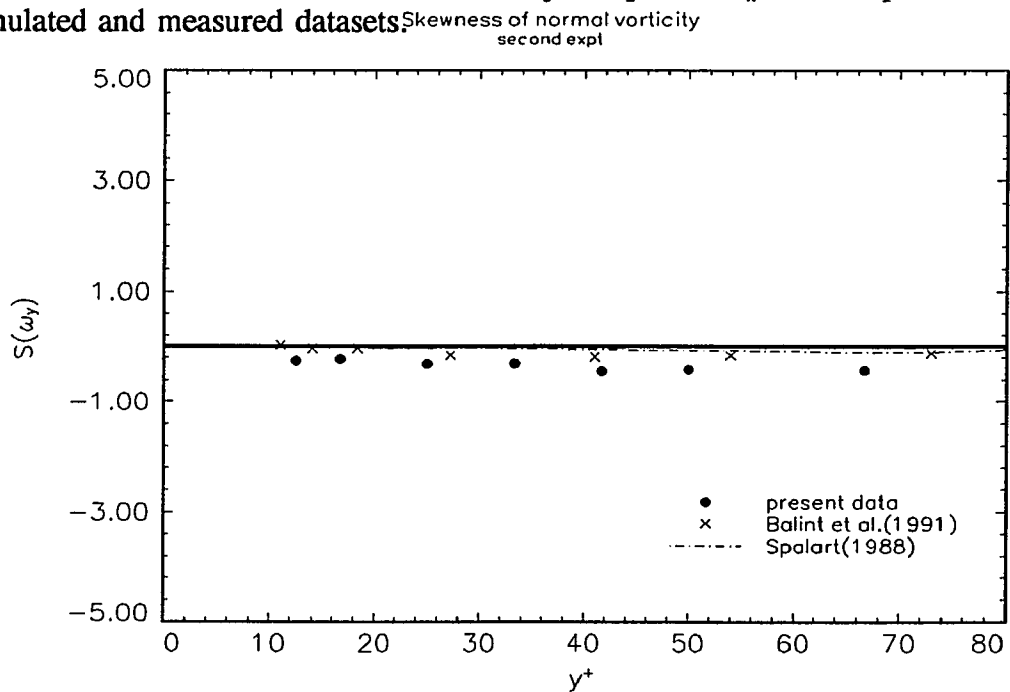


Figure 6.3.32. Skewness factor of vorticity component ω_y and compared with other simulated and measured datasets.

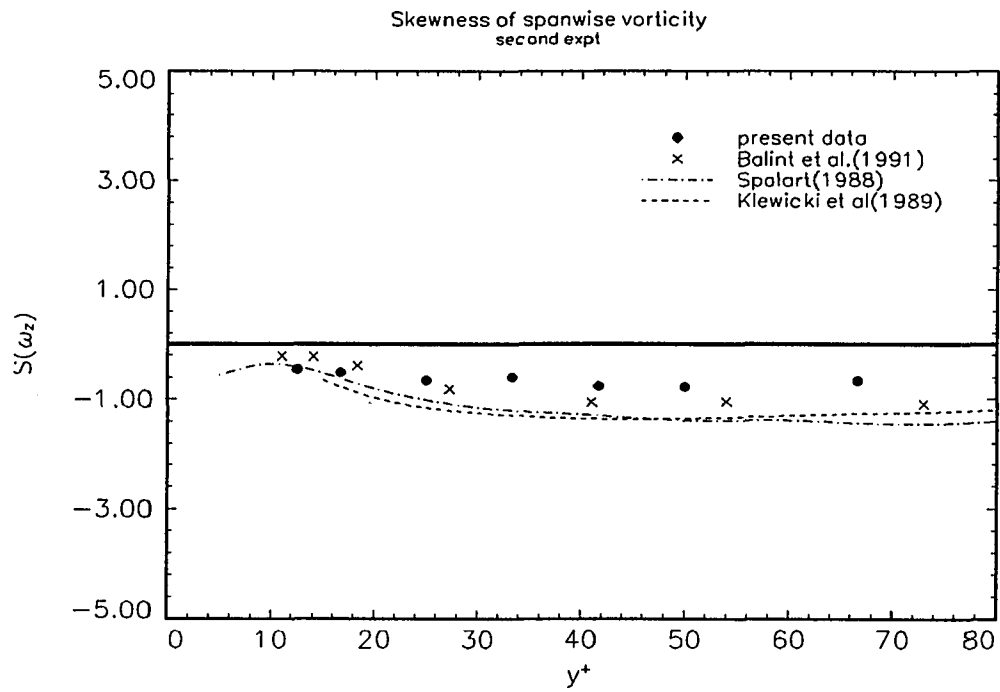


Figure 6.3.33. Skewness factor of vorticity component ω_z and compared with other simulated and measured datasets.

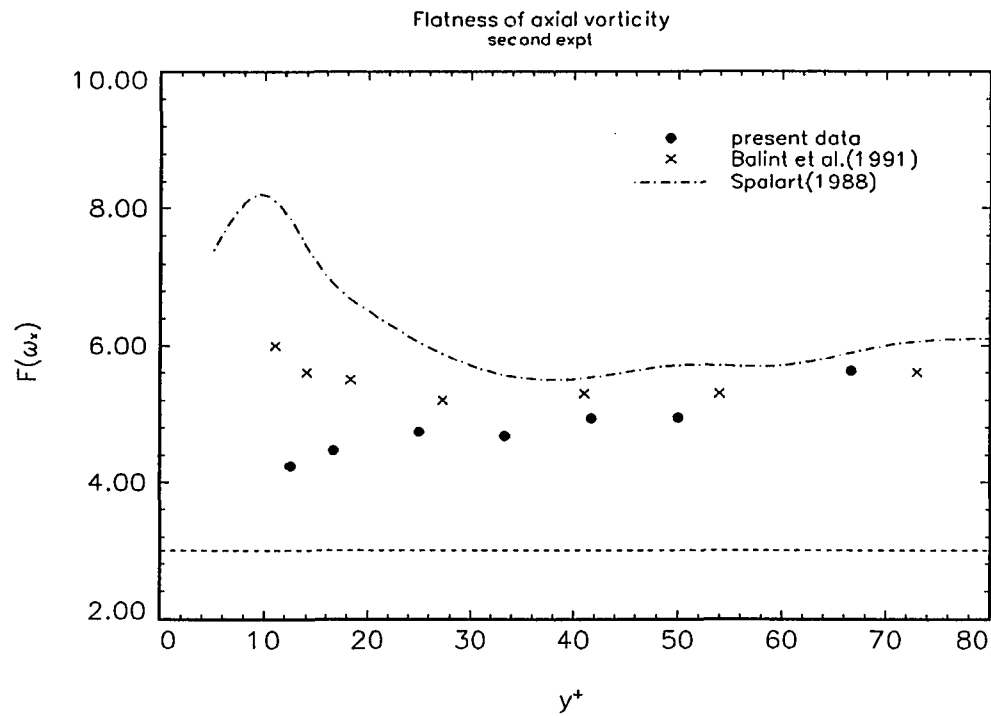


Figure 6.3.34. Flatness factor of vorticity component ω_x and compared with other simulated and measured datasets.

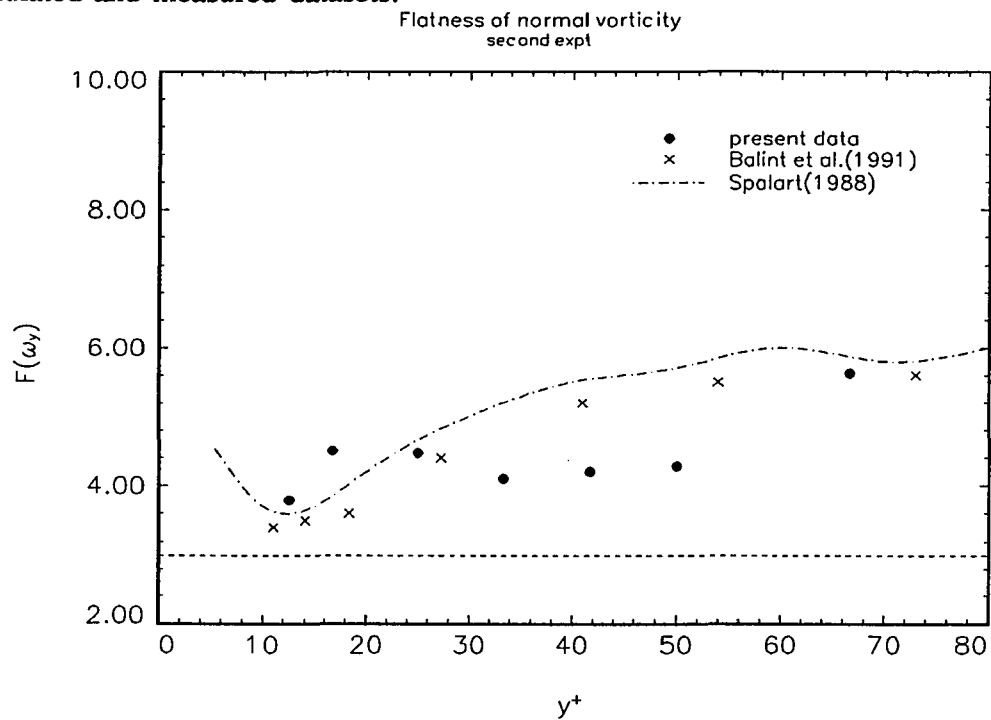


Figure 6.3.35. Flatness factor of vorticity component ω_y and compared with other simulated and measured datasets.

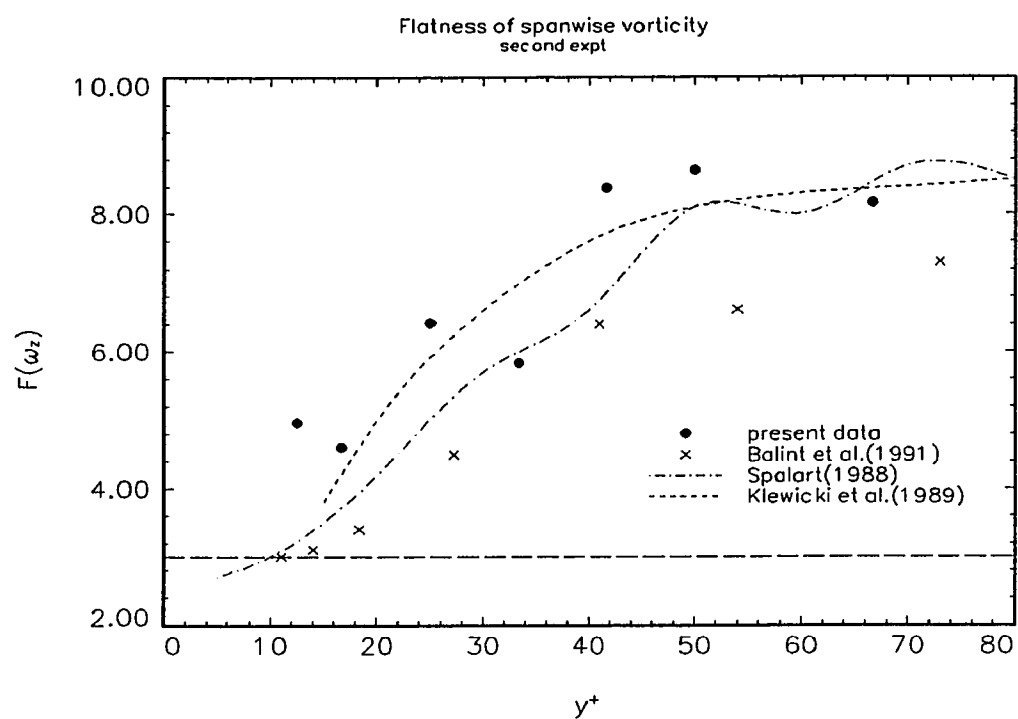


Figure 6.3.36. Flatness factor of vorticity component ω_z and compared with other simulated and measured datasets.

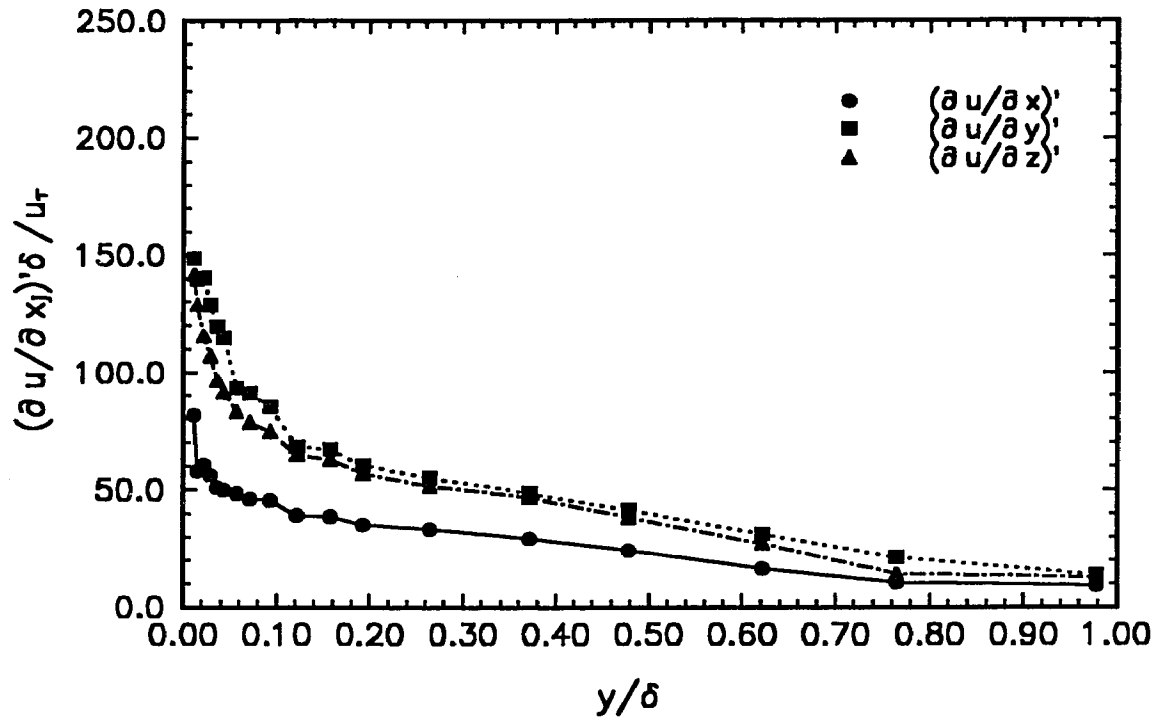


Figure 6.3.37. Measured r.m.s. distributions of spatial derivatives of streamwise velocity normalized by outer variables u_τ and δ .

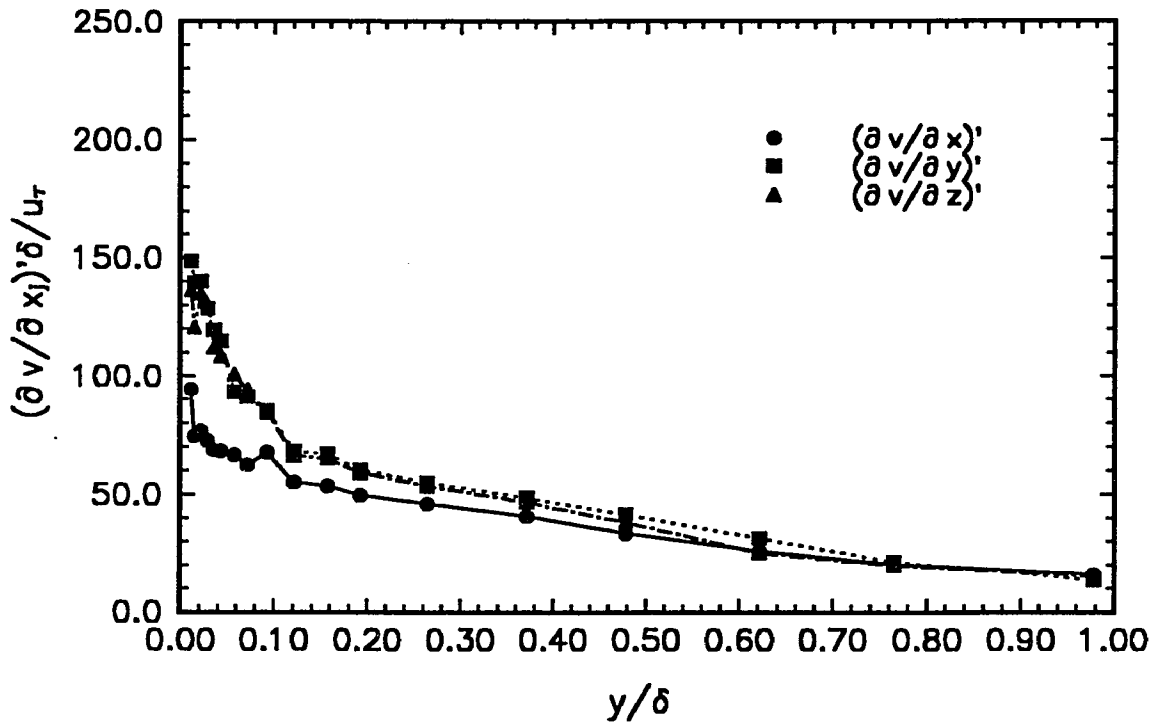


Figure 6.3.38. Measured r.m.s. distributions of spatial derivatives of normal velocity scaled by outer variables u_τ and δ .

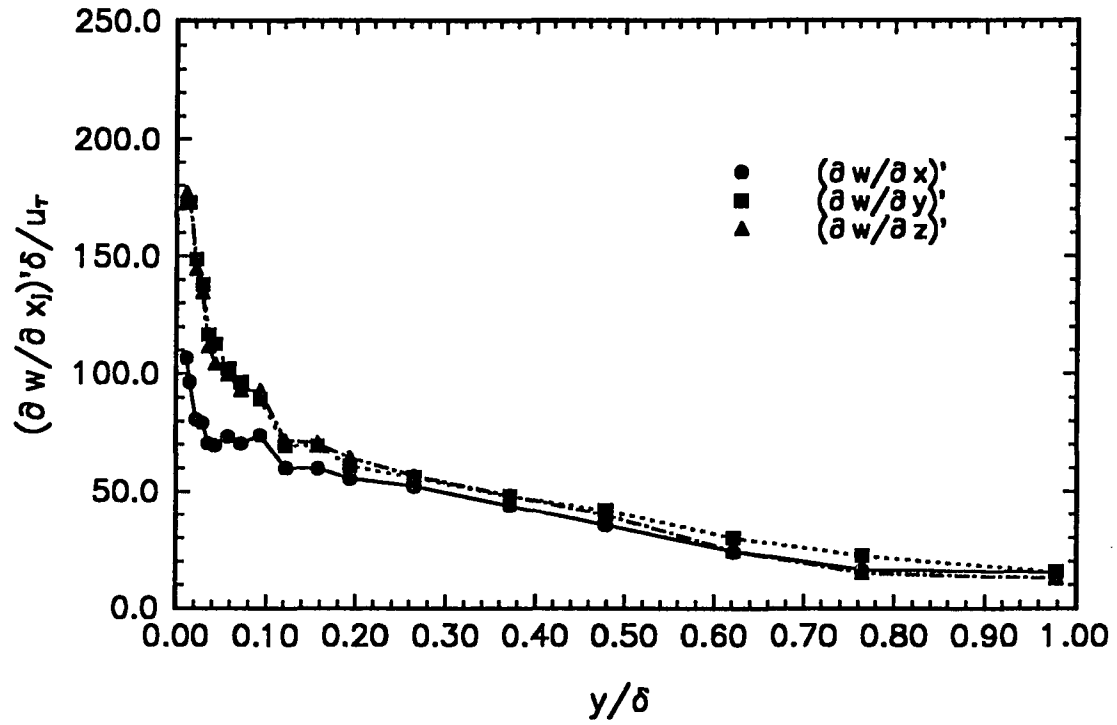


Figure 6.3.39. Measured r.m.s. distributions of spatial derivatives of spanwise velocity normalized by outer variables u_τ and δ .

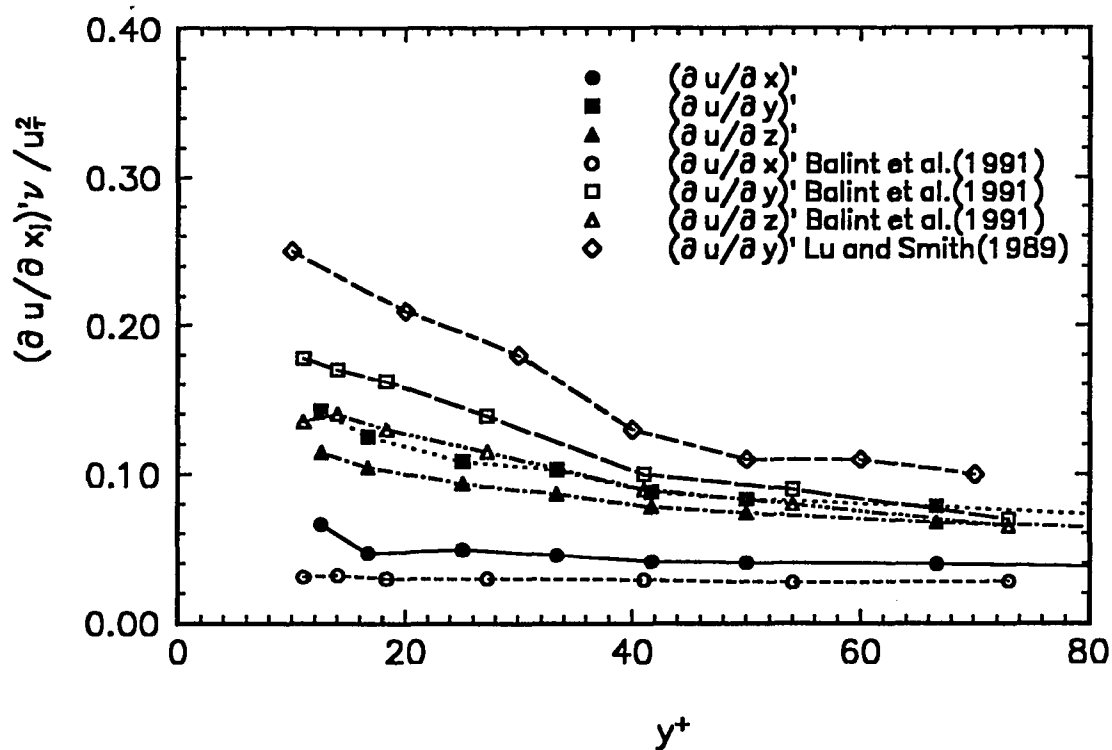


Figure 6.3.40. Near-wall r.m.s. distributions of spatial derivatives of streamwise velocity normalized by inner variables u_τ and ν .

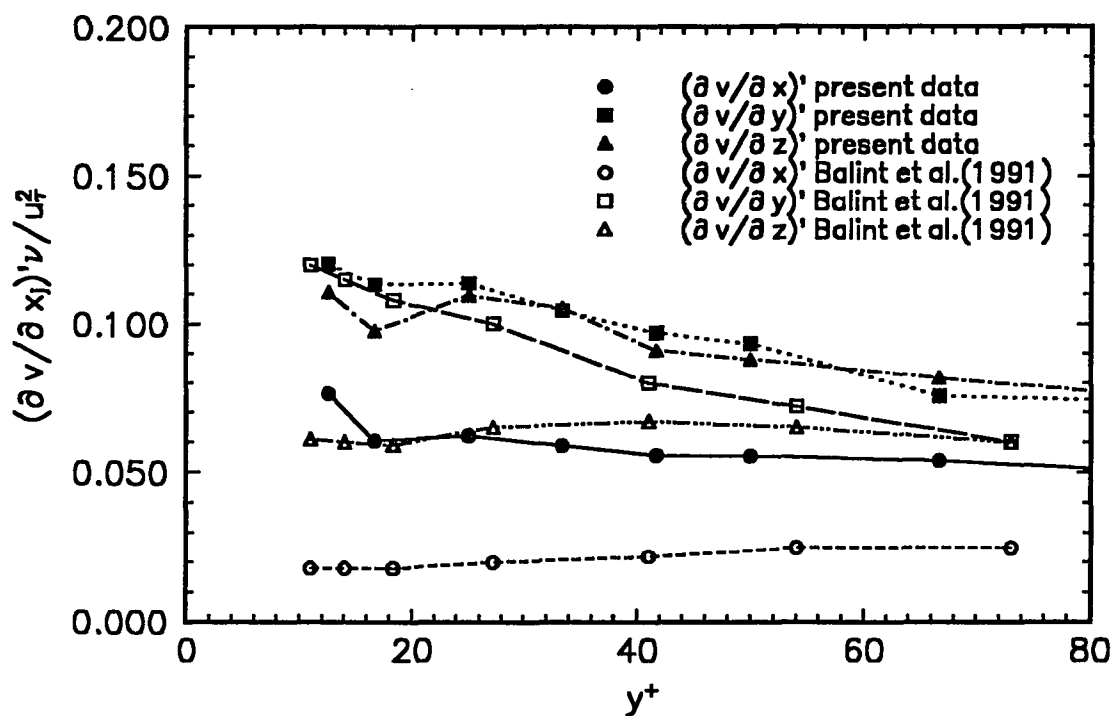


Figure 6.3.41. Near-wall r.m.s. distributions of spatial derivatives of normal velocity scaled by inner variables u_τ and ν .

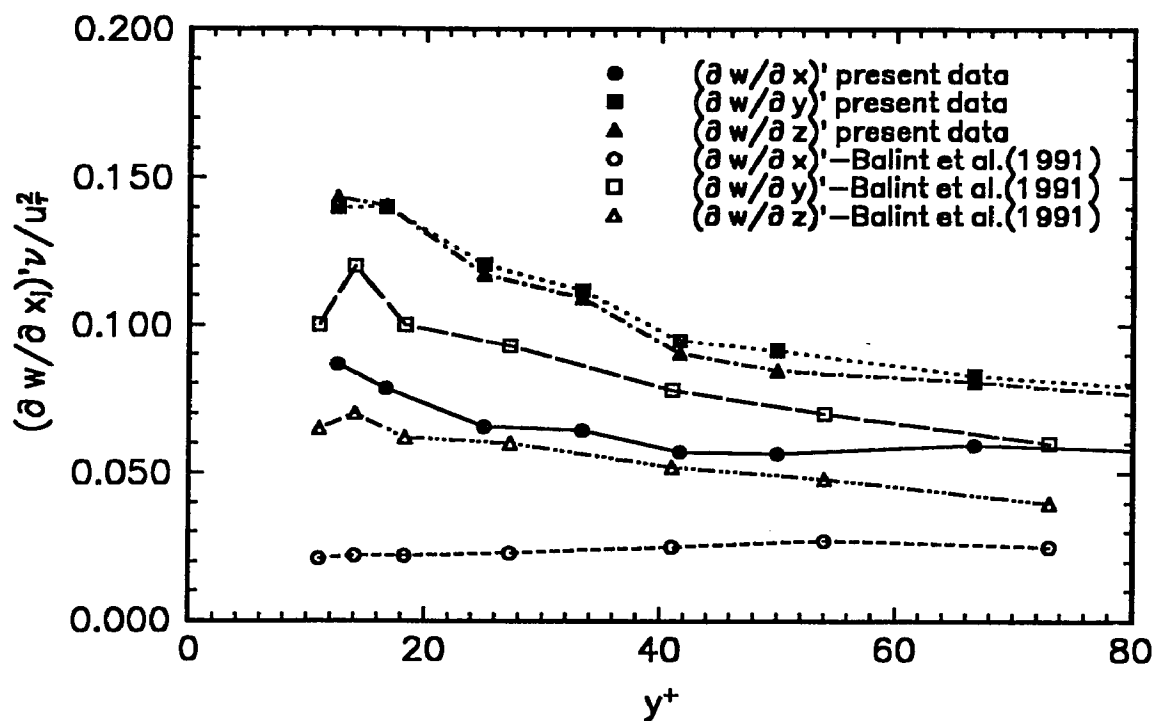


Figure 6.3.42. Near-wall r.m.s. distributions of spatial derivatives of spanwise velocity normalized by inner variables u_τ and ν .

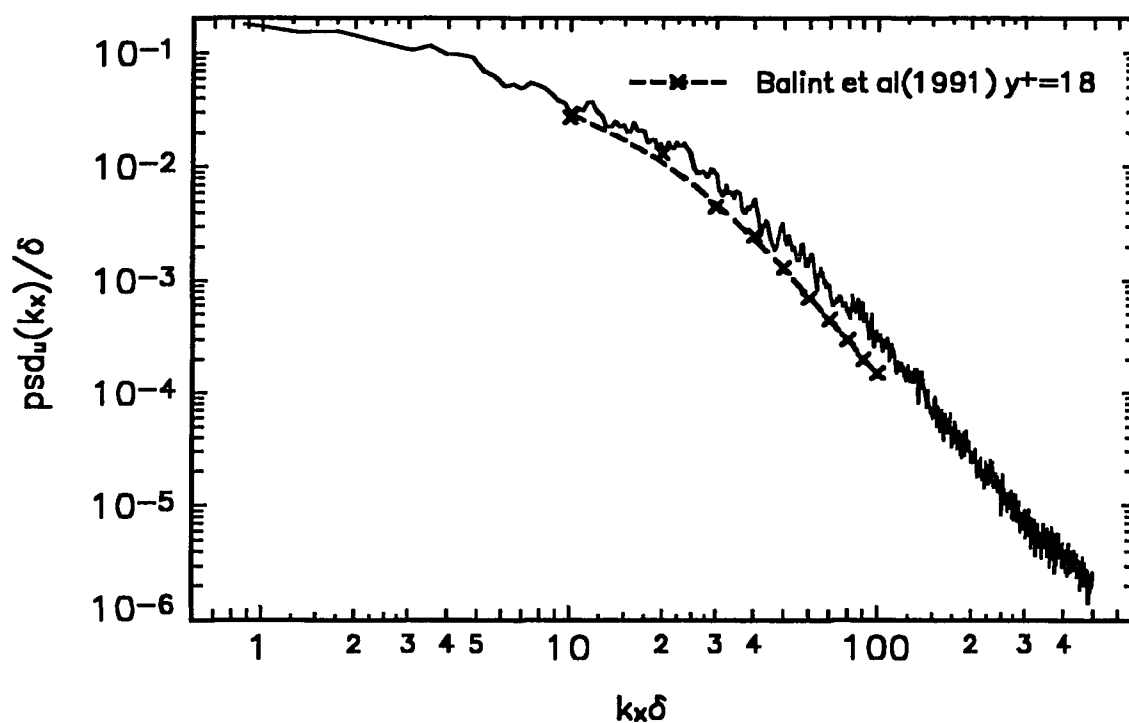


Figure 6.3.43. Power spectral density of axial velocity computed at $y^+ = 12.5$.

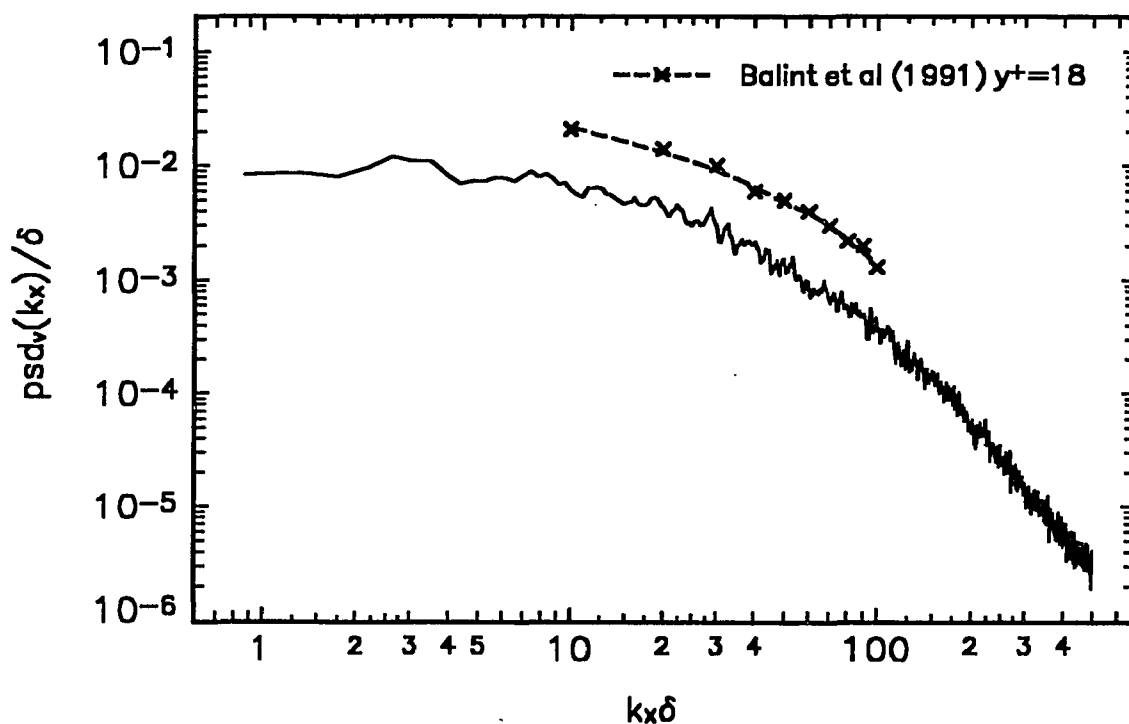


Figure 6.3.44. Power spectral density of normal velocity computed at $y^+ = 12.5$.

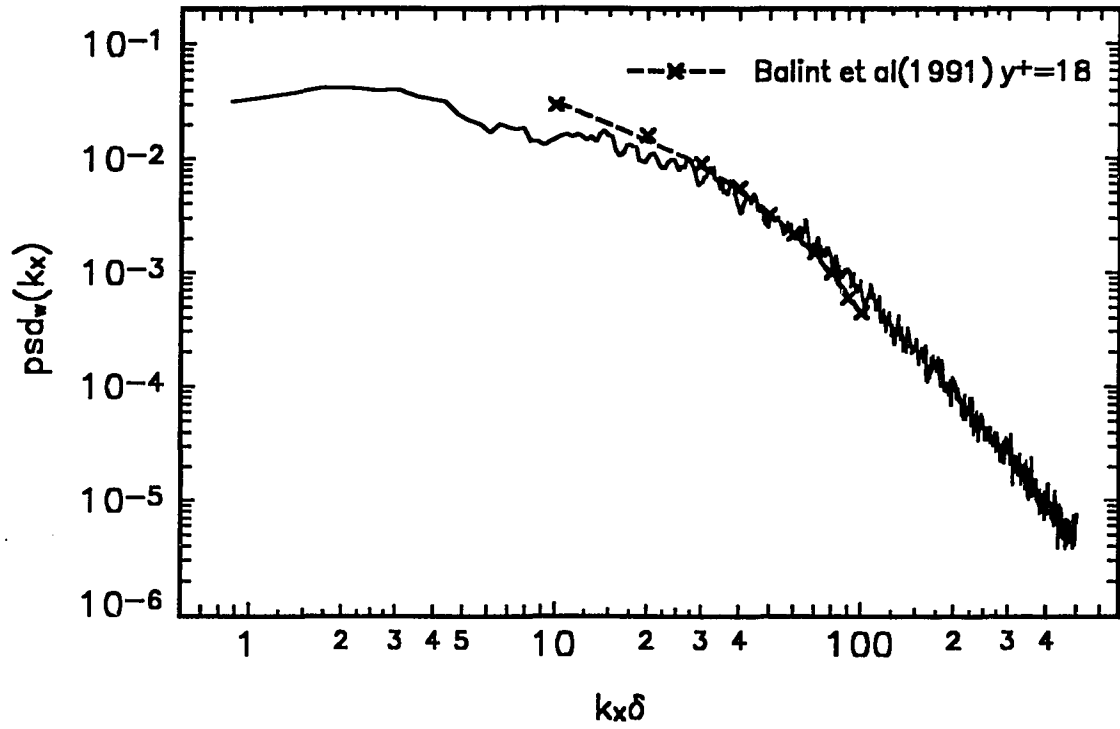


Figure 6.3.45. Power spectral density of spanwise velocity computed at $y^+ = 12.5$.

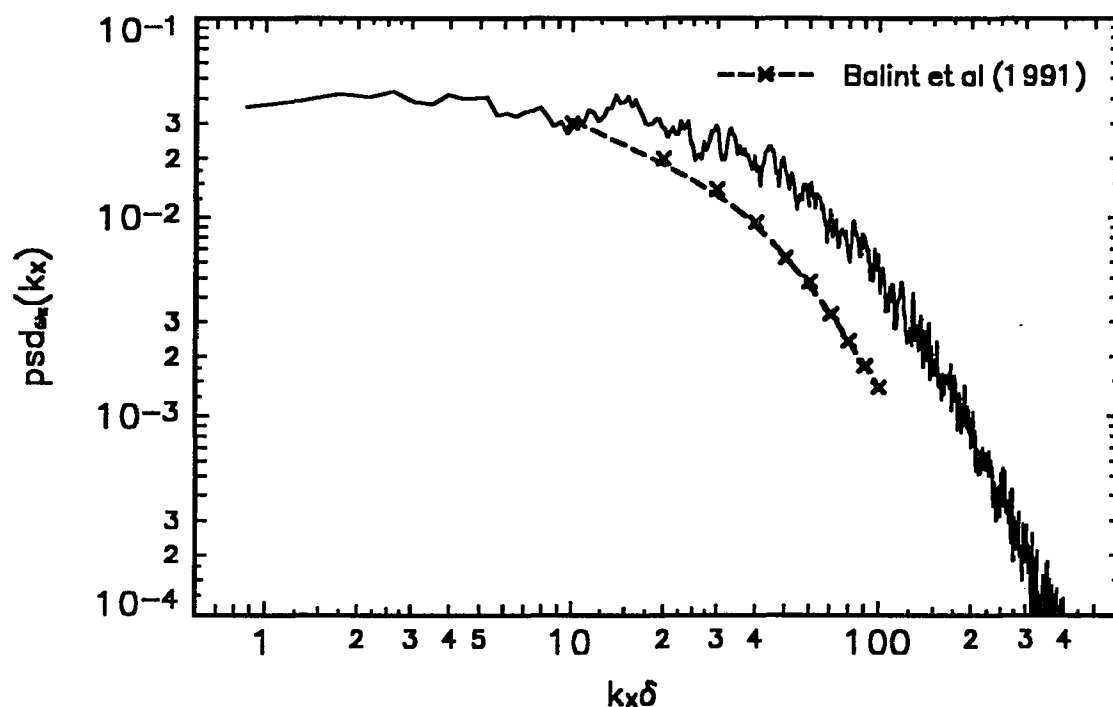


Figure 6.3.46. One dimensional spectral density of fluctuating axial vorticity computed at $y^+ = 12.5$, normalized by wavenumber and boundary layer thickness.

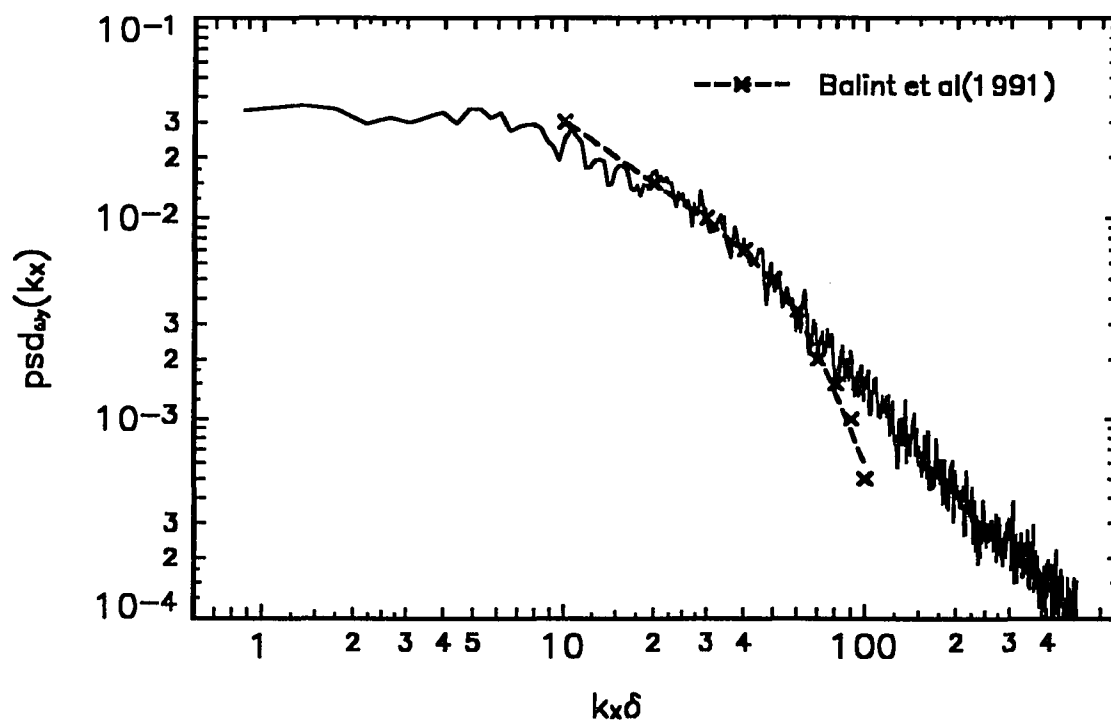


Figure 6.3.47. One dimensional spectral density of fluctuating normal vorticity computed at $y^+ = 12.5$, normalized by wavenumber and boundary layer thickness..

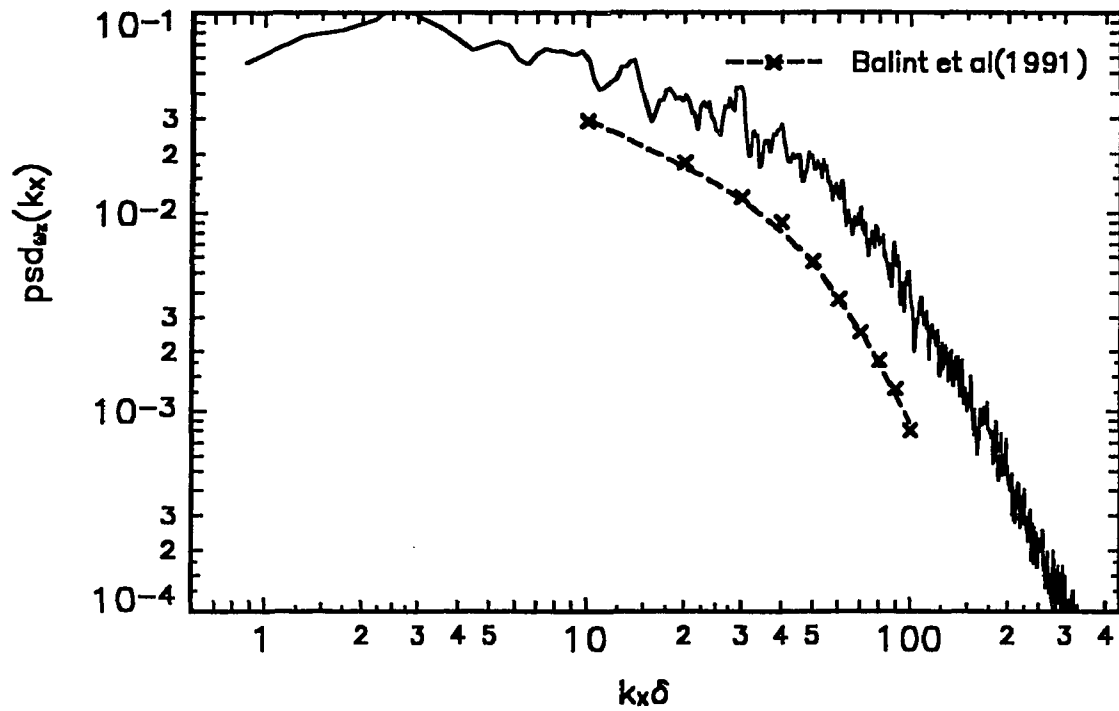


Figure 6.3.48. One dimensional spectral density of fluctuating spanwise vorticity component computed at $y^+ = 12.5$, normalized by wavenumber k_x and boundary layer thickness δ .

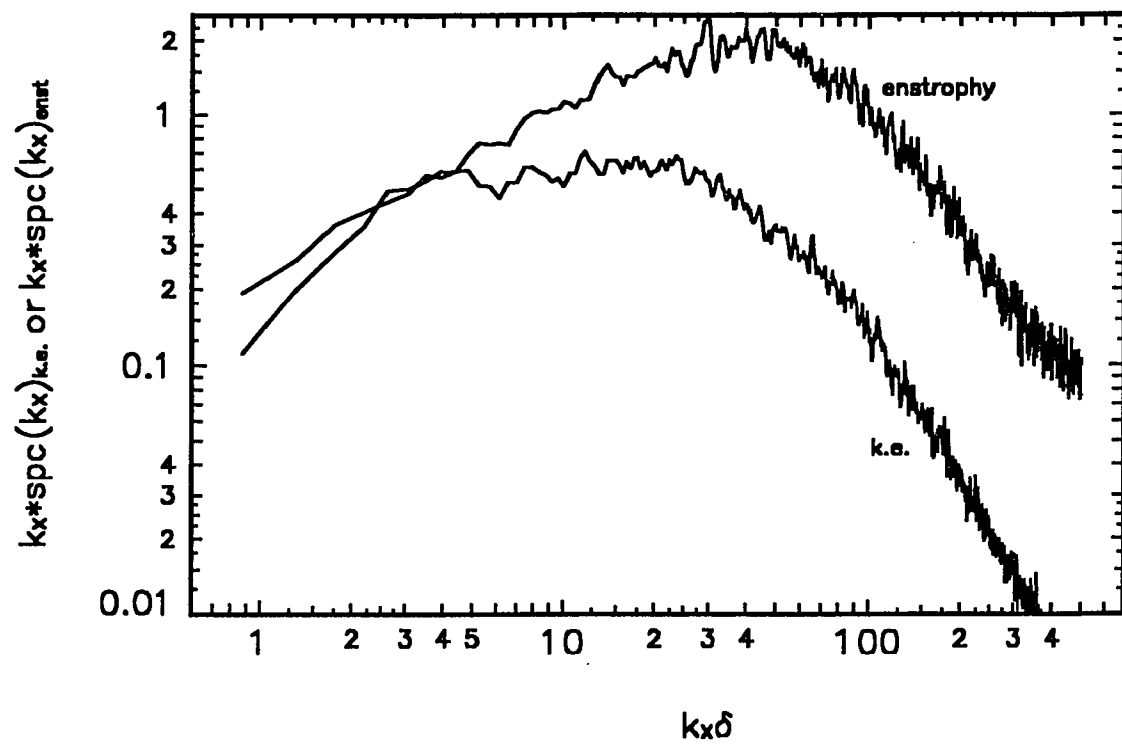


Figure 6.3.49 Spectra of enstrophy and kinetic energy weighted by the wavenumber and computed at $y^+ = 12.5$.

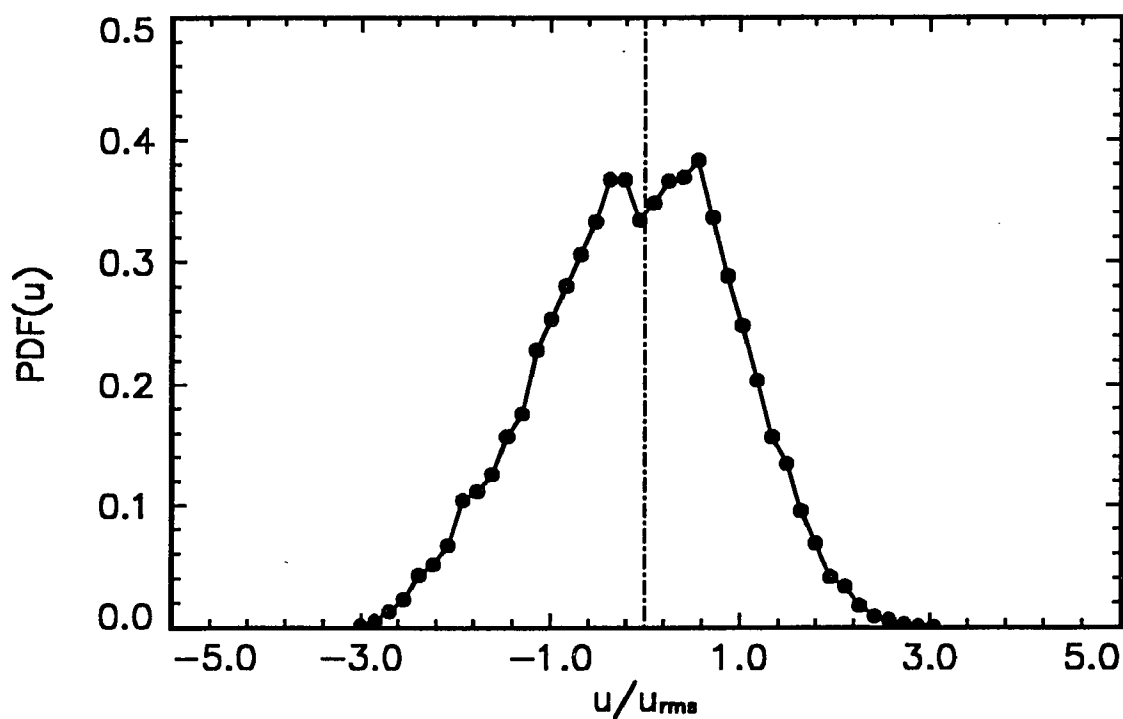


Figure 6.3.50. Probability distribution function of axial component of fluctuating velocity as measured at $y^+ = 12.5$.

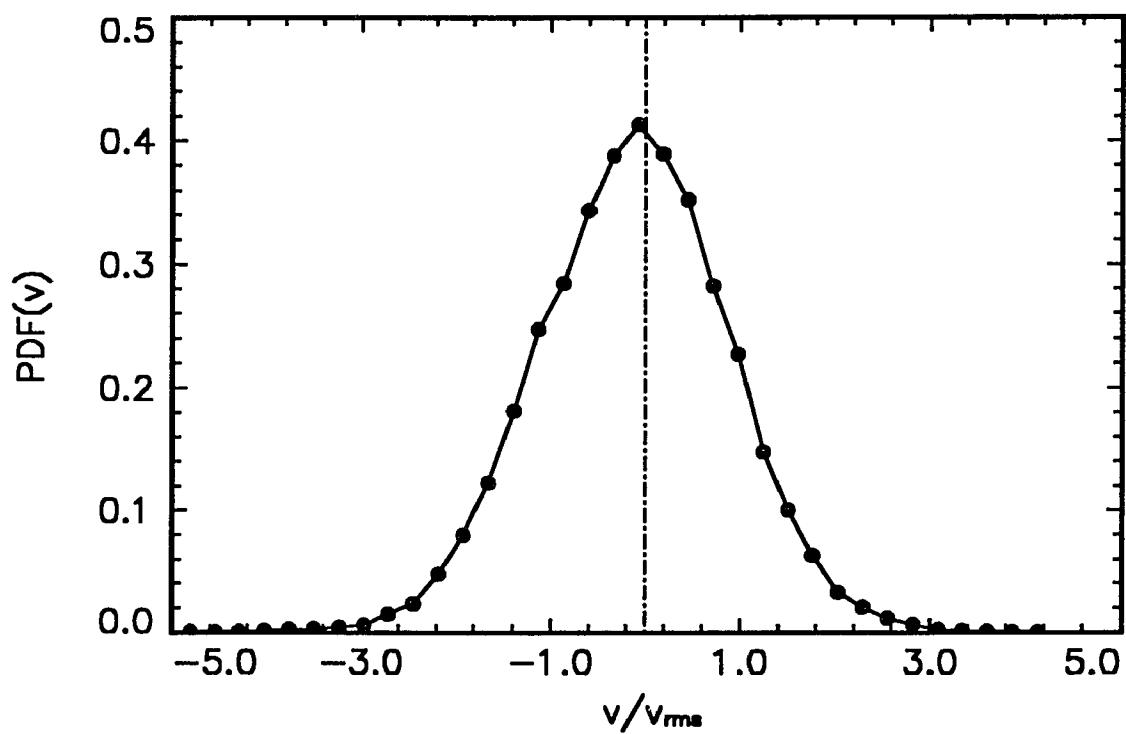


Figure 6.3.51. Probability distribution function of normal component of fluctuating velocity as measured at $y^+ = 12.5$.

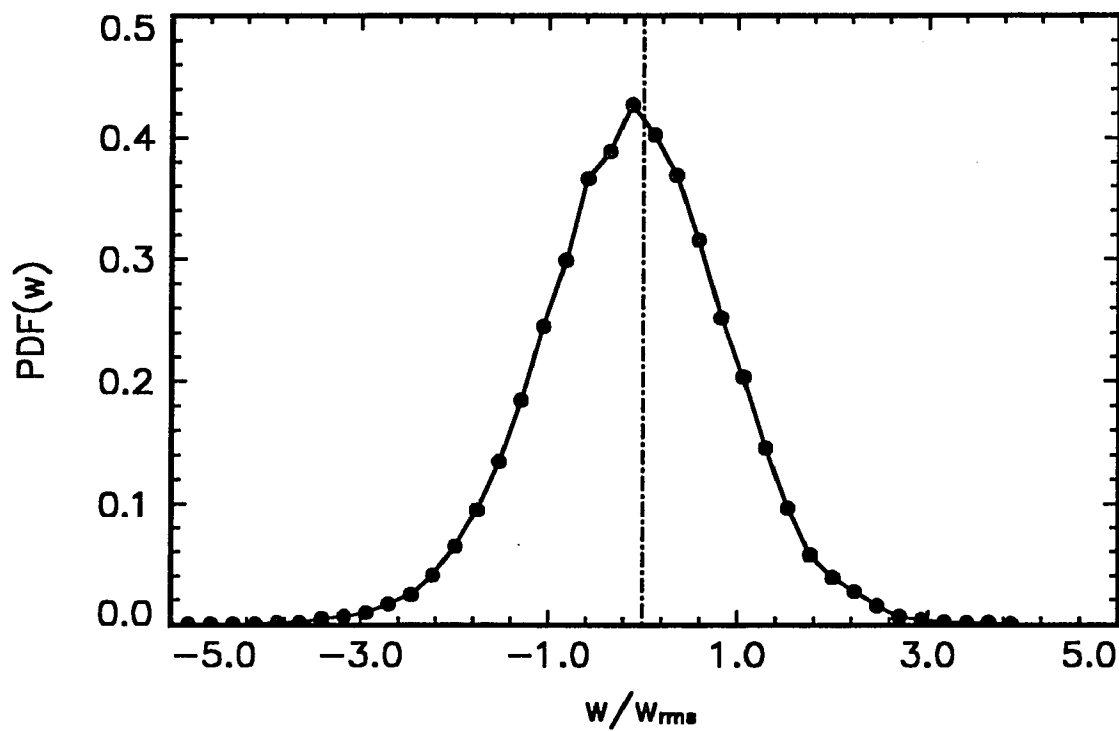


Figure 6.3.52. Probability distribution function of spanwise component of fluctuating velocity as measured at $y^+ = 12.5$.

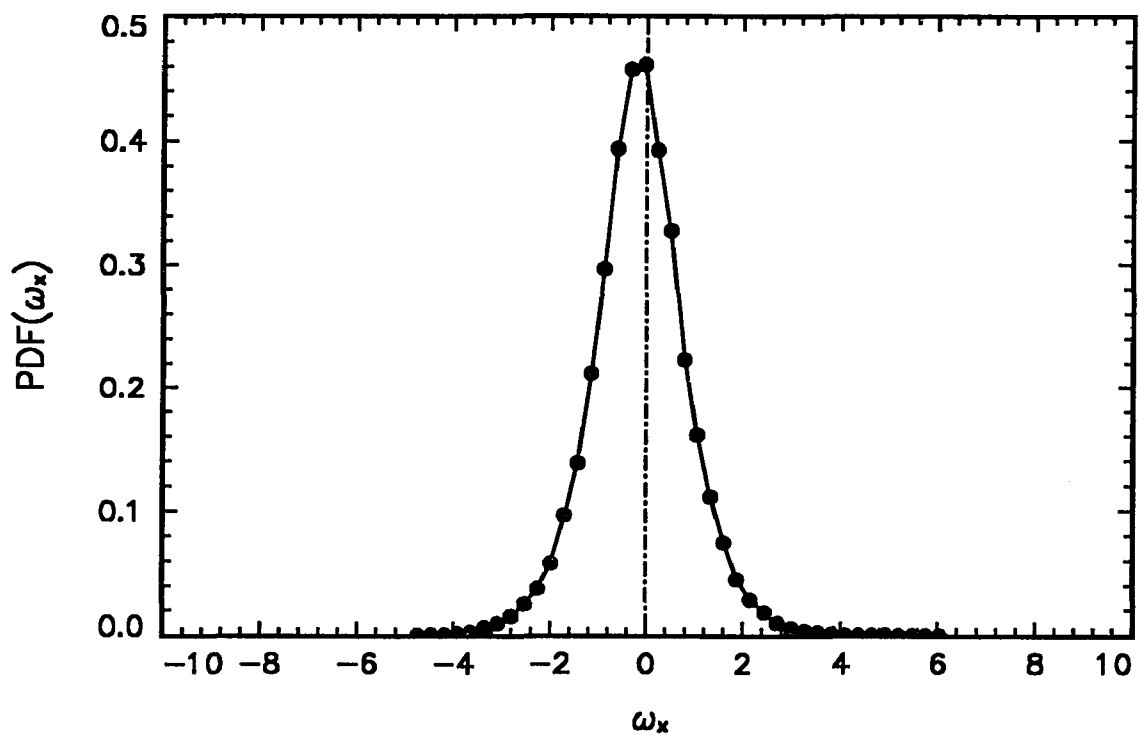


Figure 6.3.53. Probability distribution function of axial component of fluctuating vorticity as measured at $y^+ = 12.5$.

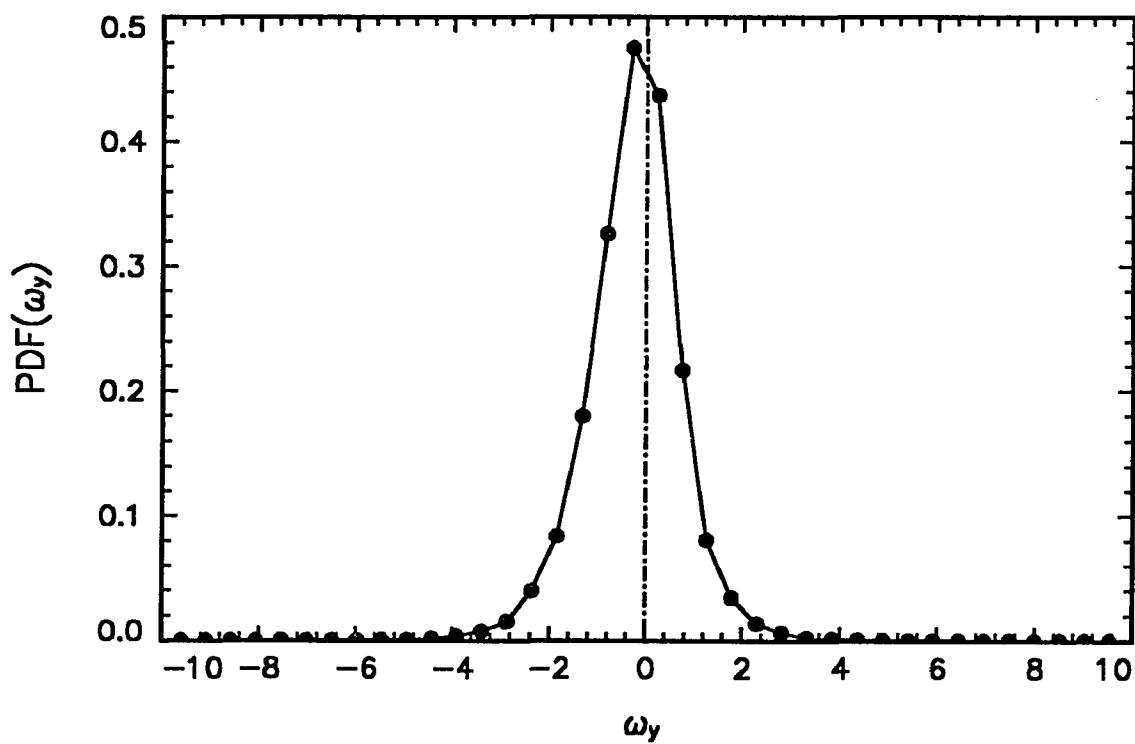


Figure 6.3.54. Probability distribution function of normal component of fluctuating vorticity as measured at $y^+ = 12.5$.

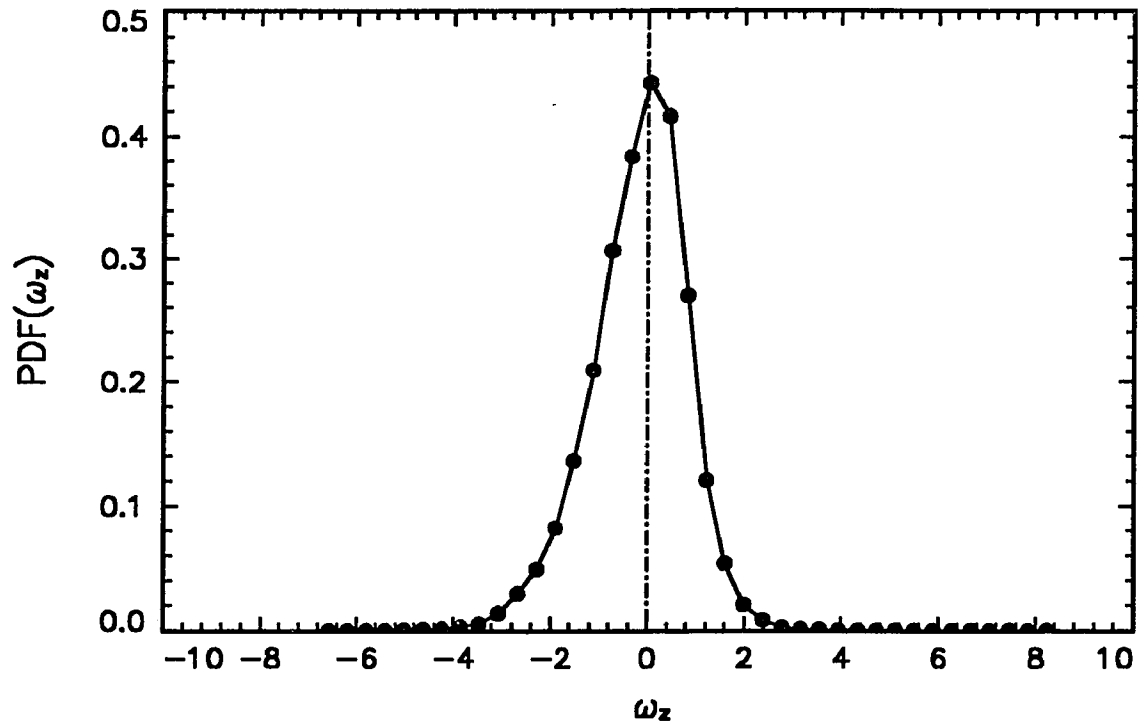


Figure 6.3.55. Probability distribution function of spanwise component of fluctuating vorticity as measured at $y^+ = 12.5$.

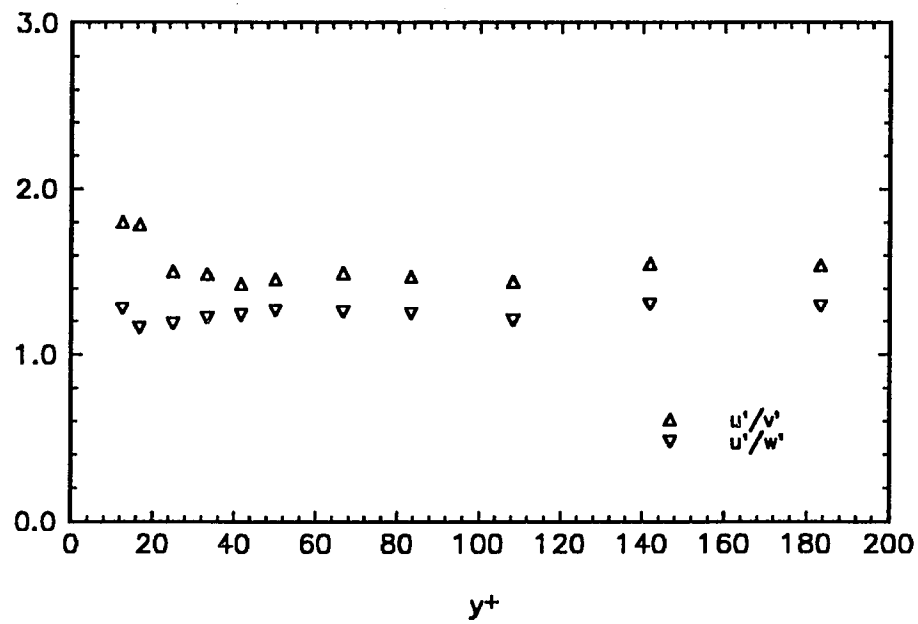


Figure 6.3.56a. Profiles of turbulent intensity ratios u'/v' and u'/w' in the inner layer.

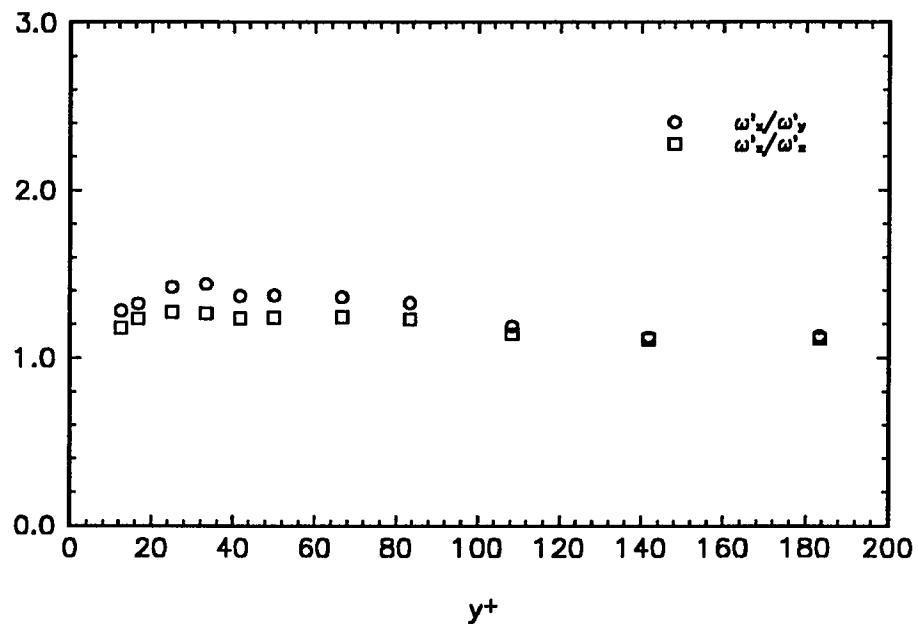


Figure 6.3.56b. Profiles of vorticity fluctuations ratios ω'_x/ω'_y and ω'_x/ω'_z in the inner layer.

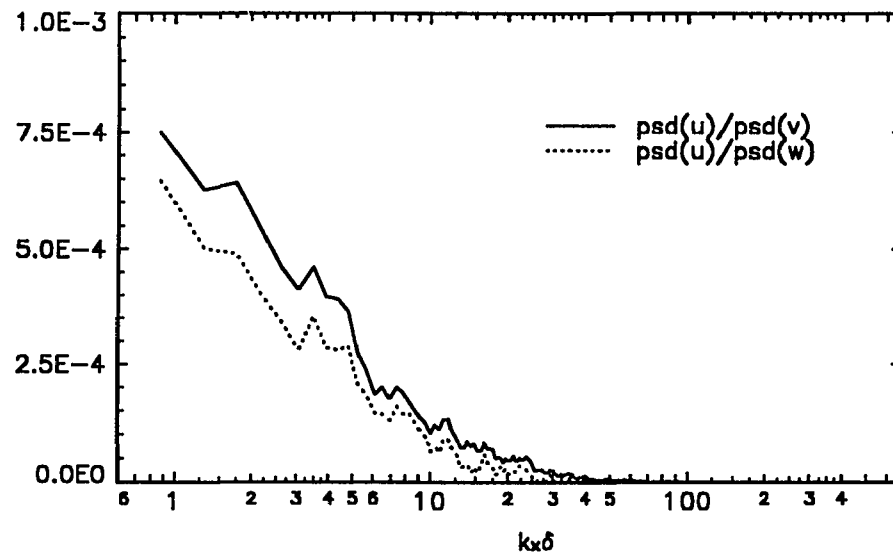


Figure 6.3.57. Log plot of power spectra ratios $\text{psd}(u)/\text{psd}(v)$ and $\text{psd}(u)/\text{psd}(w)$ vs. wavenumber normalized by δ computed at $y^+ = 12.5$.

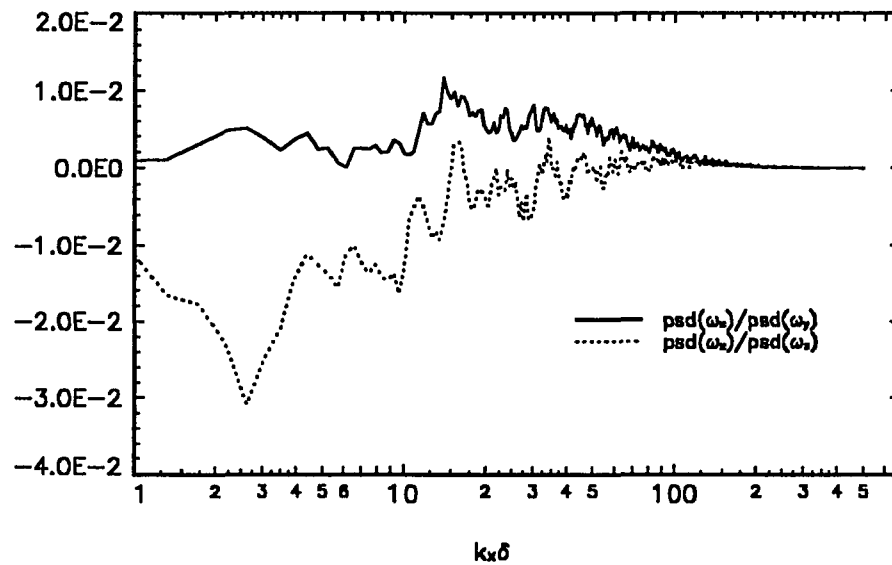


Figure 6.3.58. Log plot of power spectra ratios $\text{psd}(\omega_x)/\text{psd}(\omega_y)$ and $\text{psd}(\omega_x)/\text{psd}(\omega_z)$ vs. wavenumber normalized by δ at $y^+ = 12.5$.

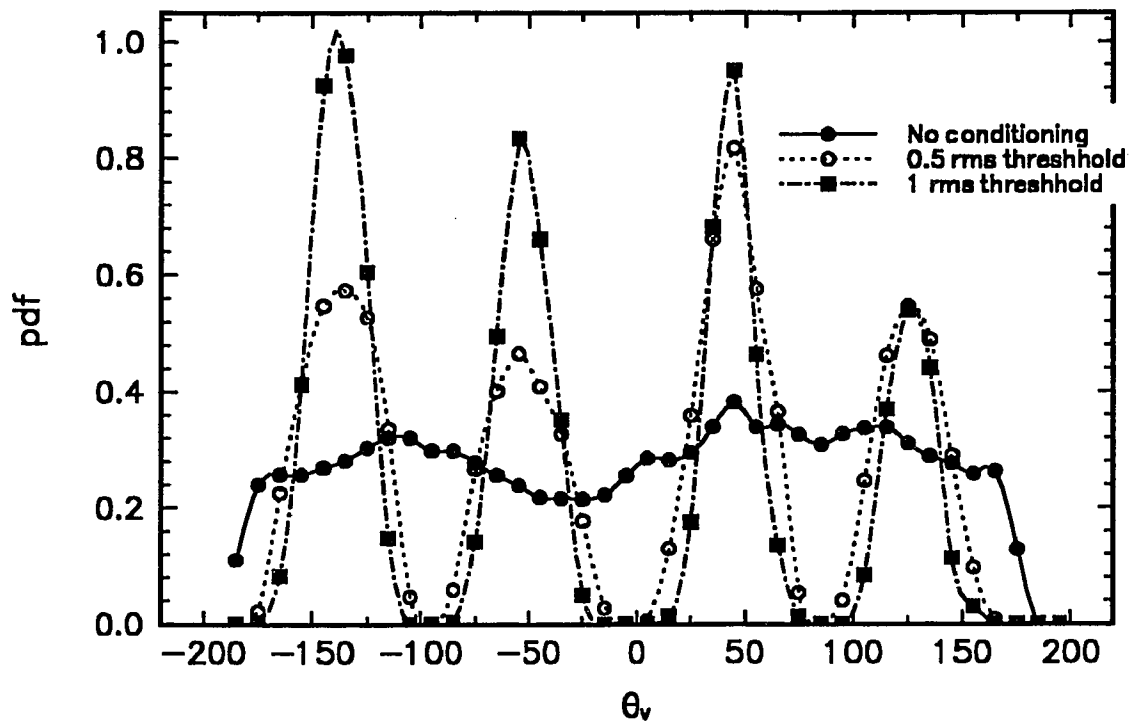


Figure 6.3.59. Probability distribution function of vorticity angle θ_v in x-z plane for threshold level 0, 50% and 100% of the r.m.s. of ω_z .

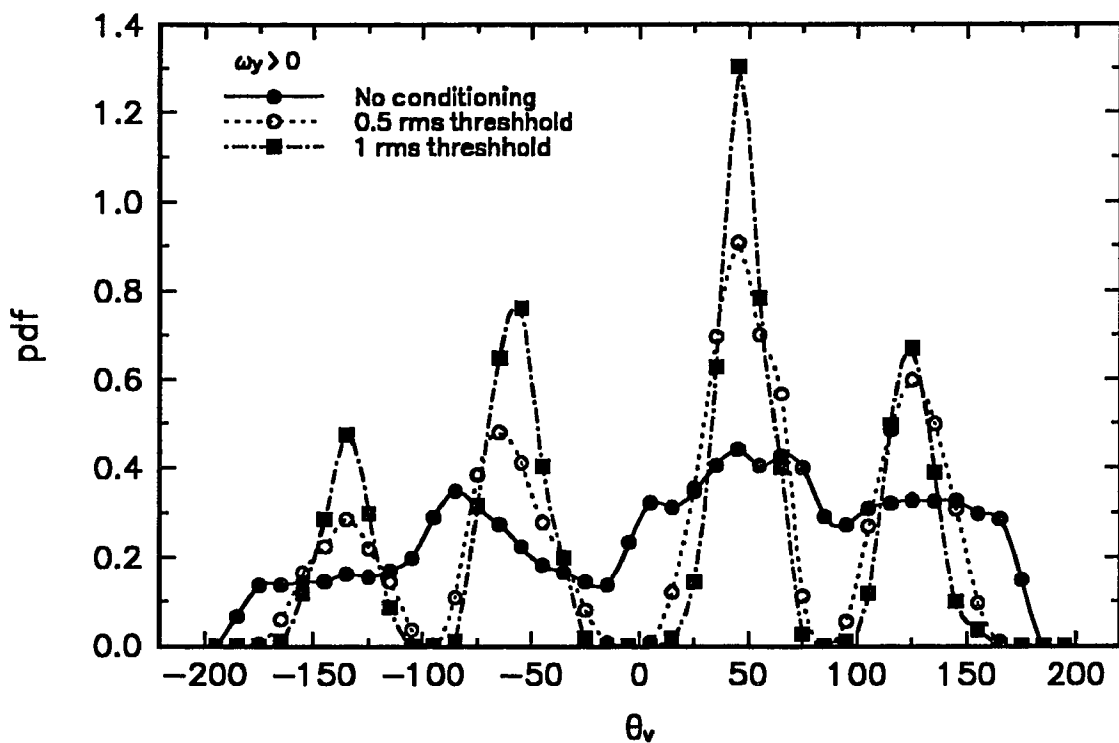


Figure 6.3.60. Probability distribution function of vorticity angle θ_v in x-z plane for threshold level 0, 50% and 100% of the r.m.s. when $\omega_y > 0$.

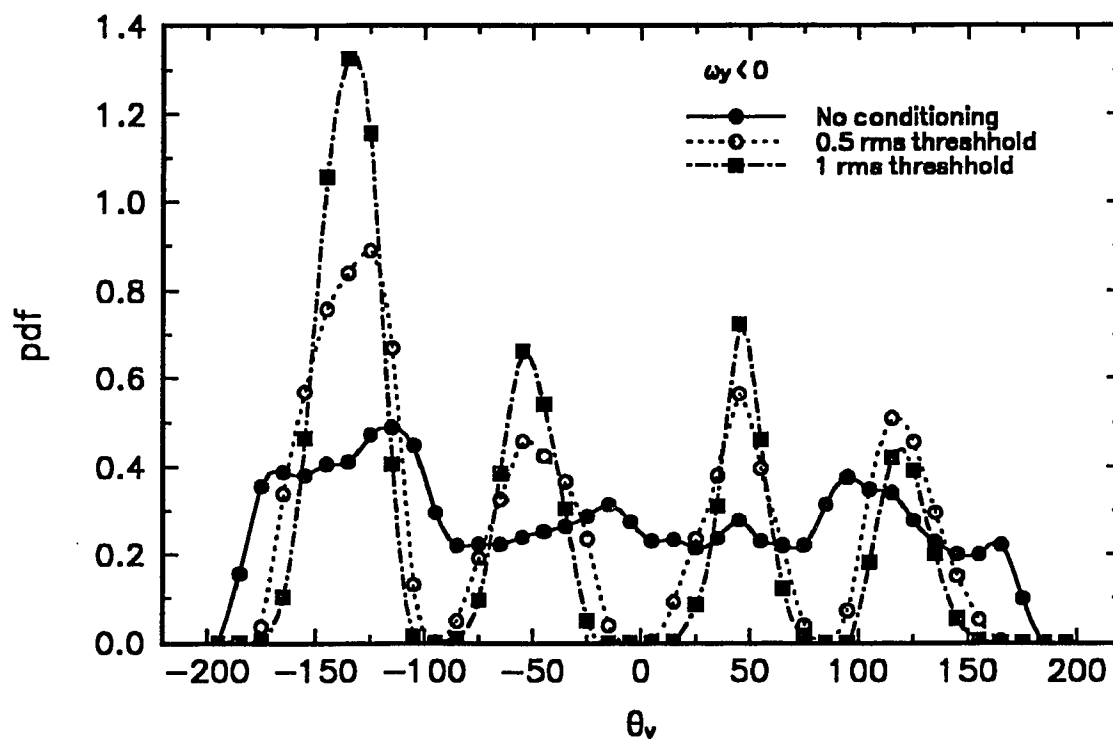


Figure 6.3.61. Probability distribution function of vorticity angle θ_v in x-z plane for threshold level 0, 50% and 100% of the r.m.s. when $\omega_y < 0$.

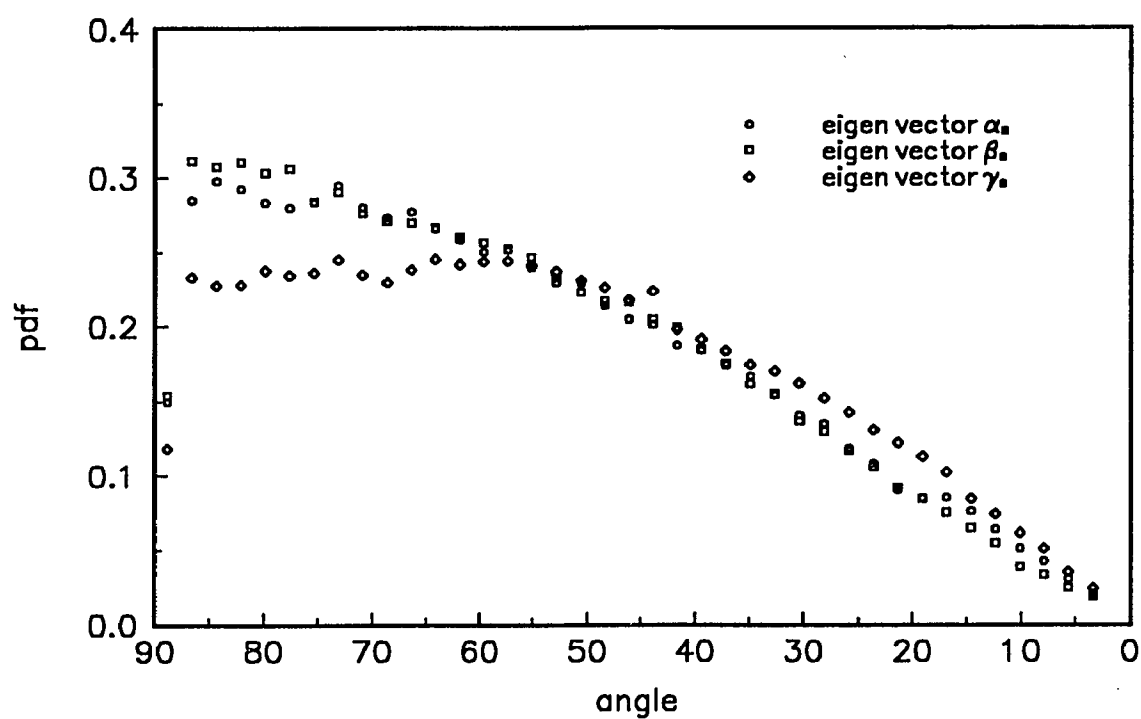


Figure 6.3.62. Probability of the alignment of the vorticity vector with each of the three eigen vectors α_s , β_s , and γ_s associated with the strain rate matrix.

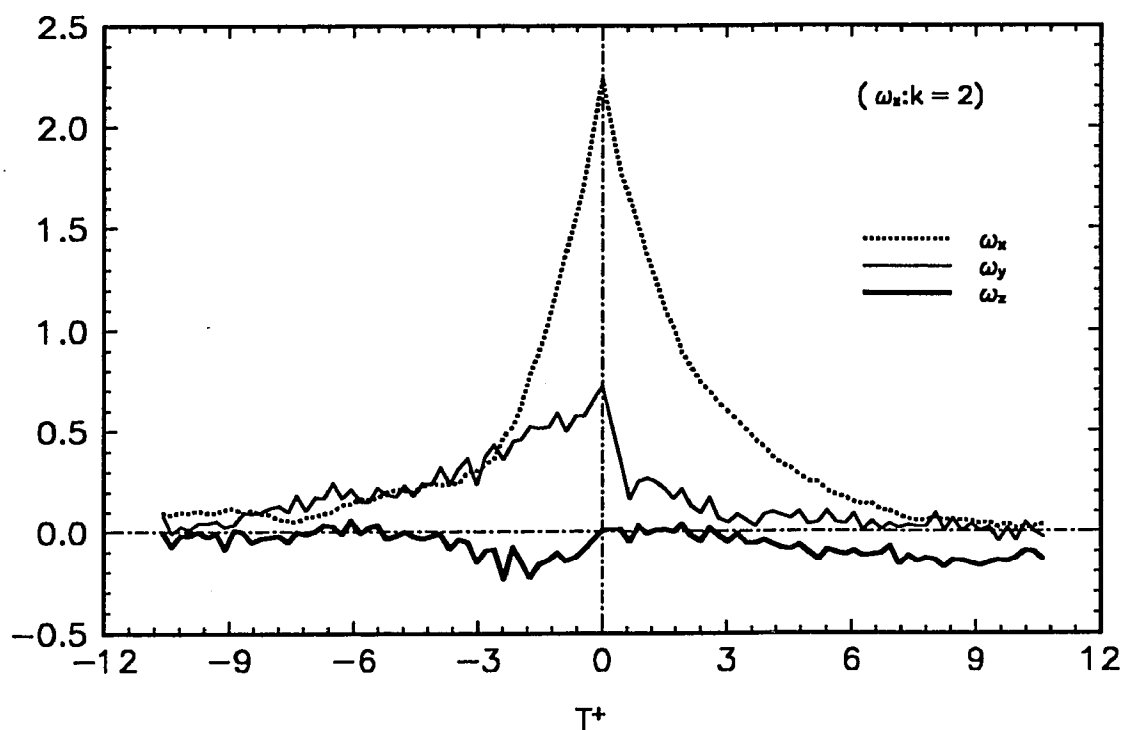


Figure 6.3.63. Relative amplitudes of the events associated with vorticity conditioned on positive ω_x , threshold $k=2$.

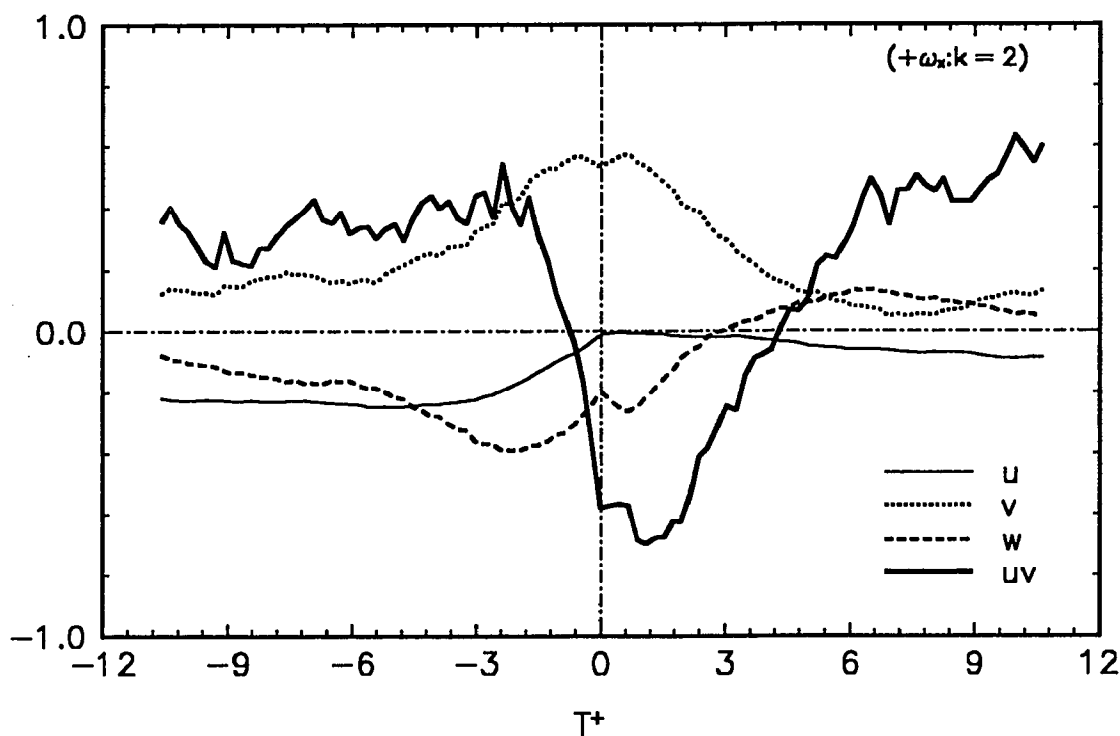


Figure 6.3.64. Relative amplitudes of the events associated with velocity conditioned on positive ω_x , threshold $k=2$.

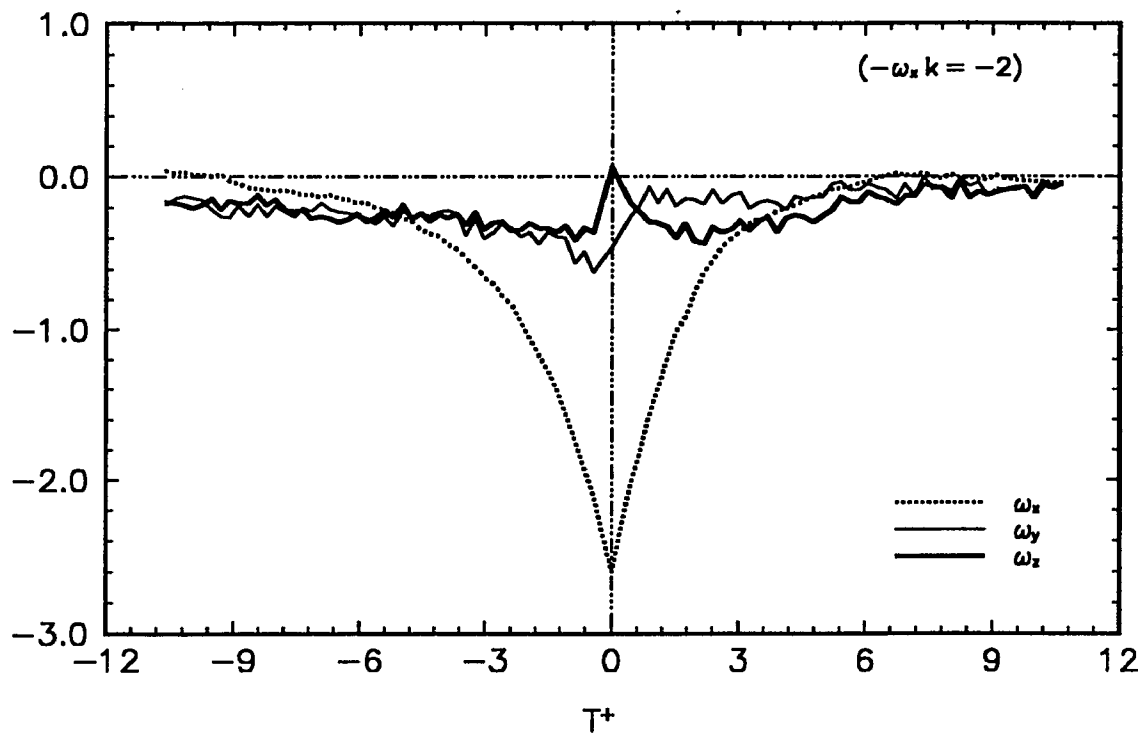


Figure 6.3.65. Relative amplitudes of the events associated with vorticity conditioned on negative ω_x , threshold $k=-2$.

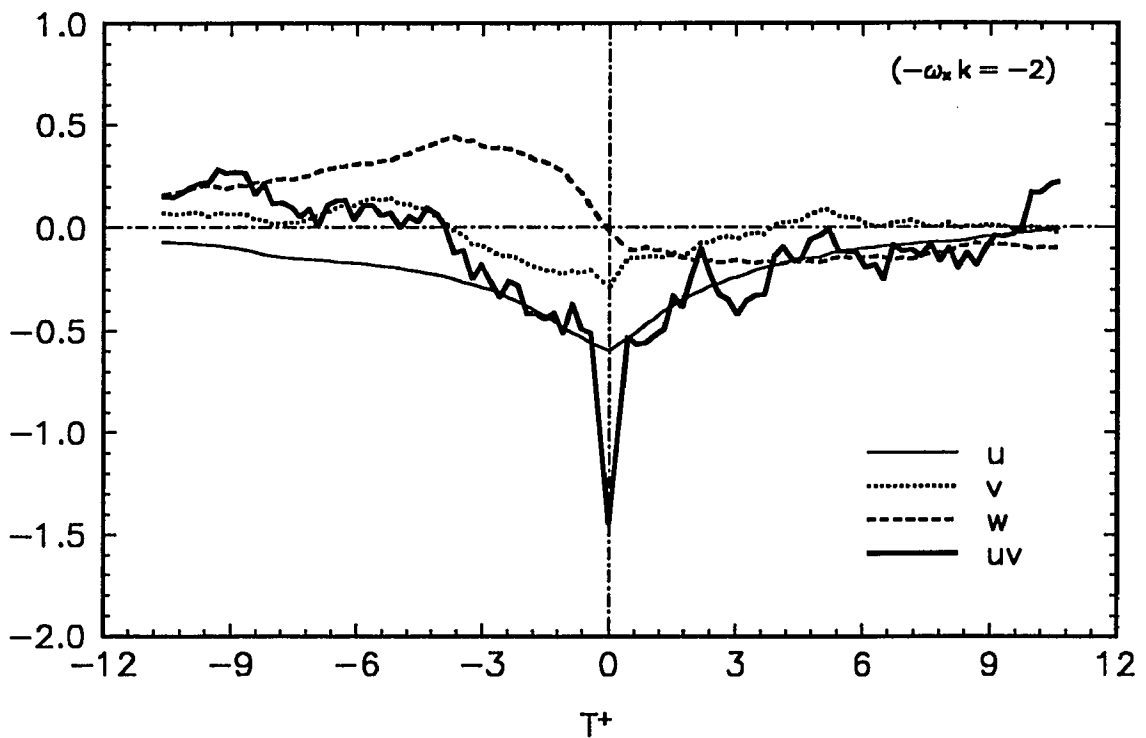


Figure 6.3.66. Relative amplitudes of the events associated with velocity conditioned on negative ω_x , threshold $k=-2$.

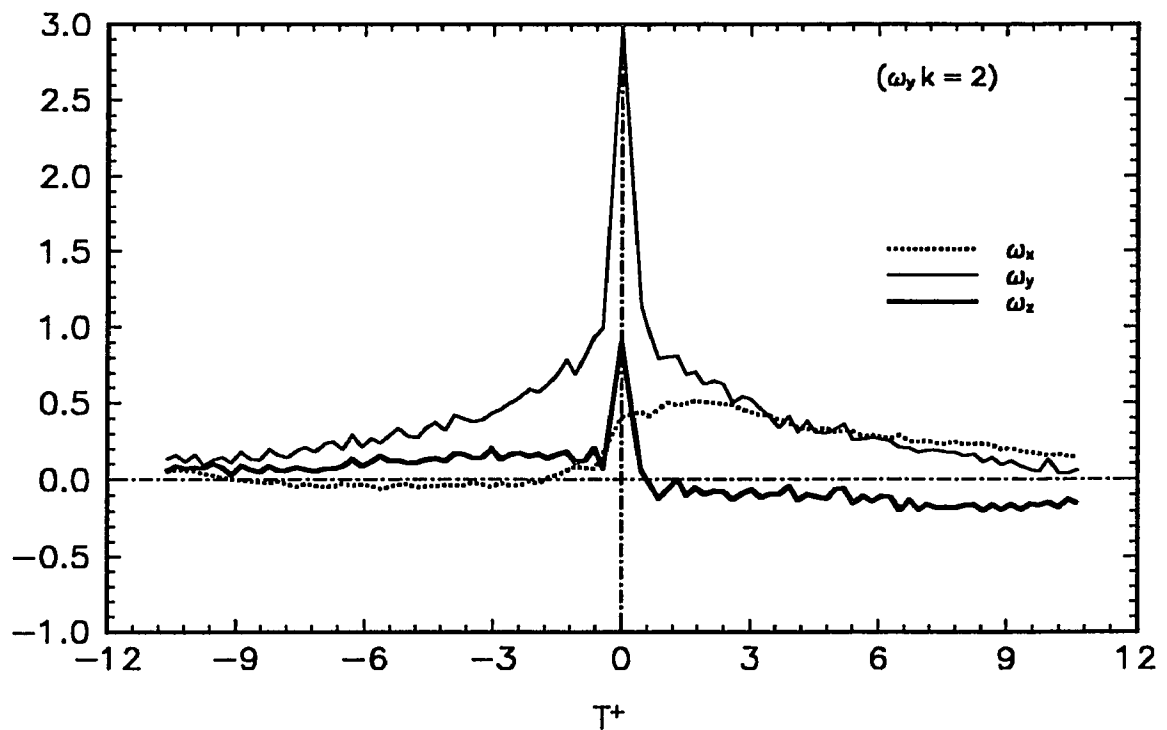


Figure 6.3.67. Relative amplitudes of the events associated with vorticity conditioned on positive ω_y , threshold $k=2$.

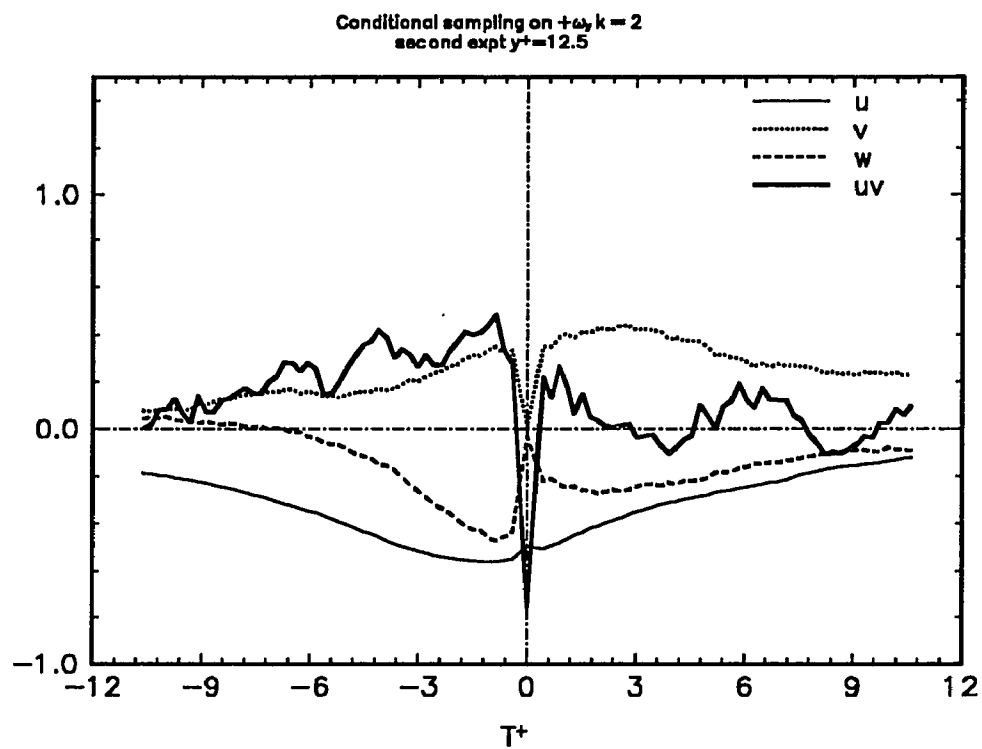


Figure 6.3.68. Relative amplitudes of the events associated with velocity conditioned on positive ω_y , threshold $k=2$.

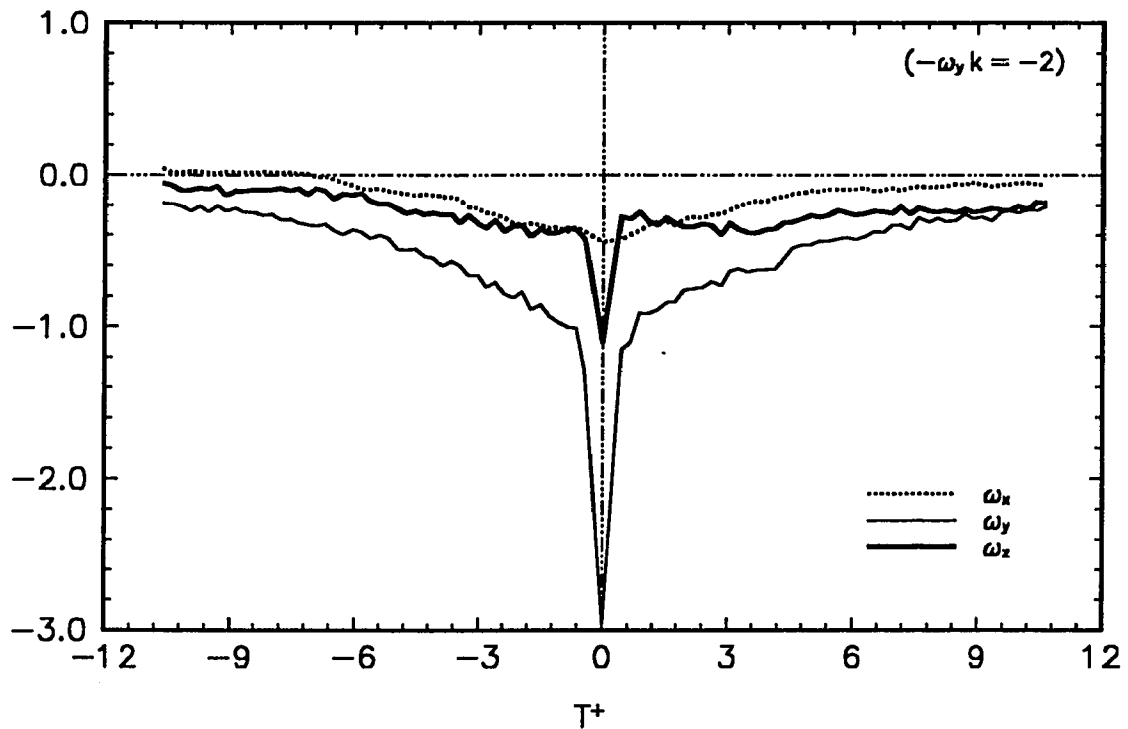


Figure 6.3.69. Relative amplitudes of the events associated with vorticity conditioned on negative ω_y , threshold $k=-2$.

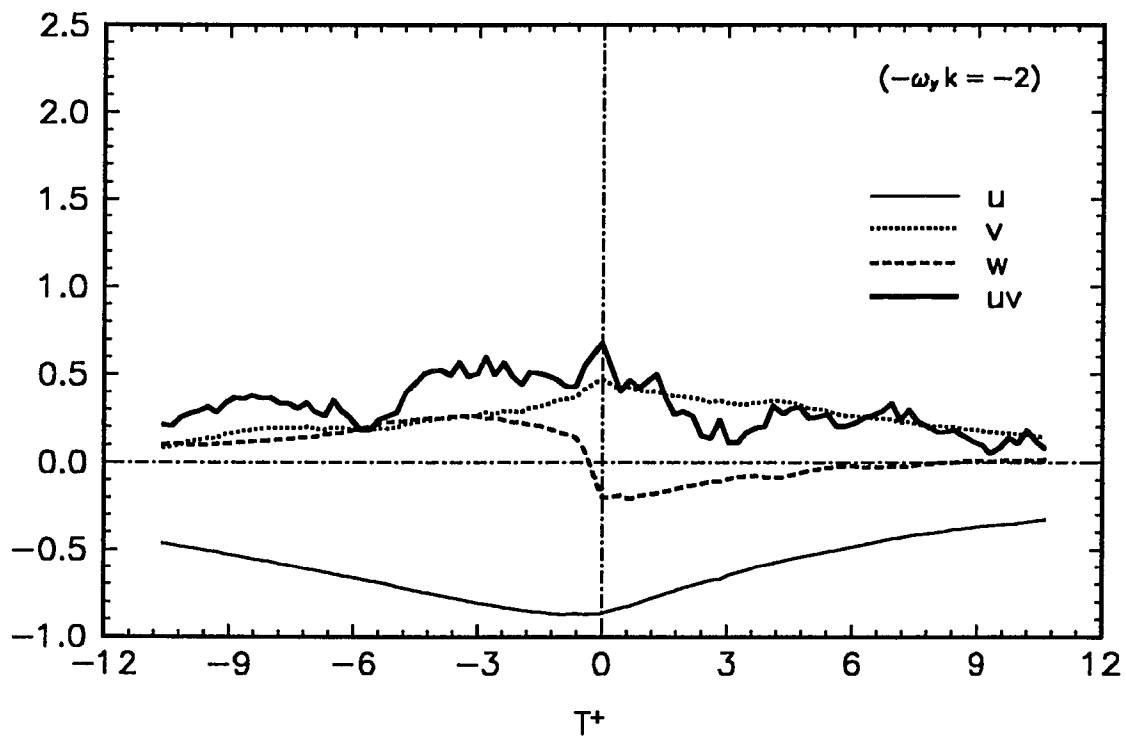


Figure 6.3.70. Relative amplitudes of the events associated with velocity conditioned on negative ω_y , threshold $k=-2$.

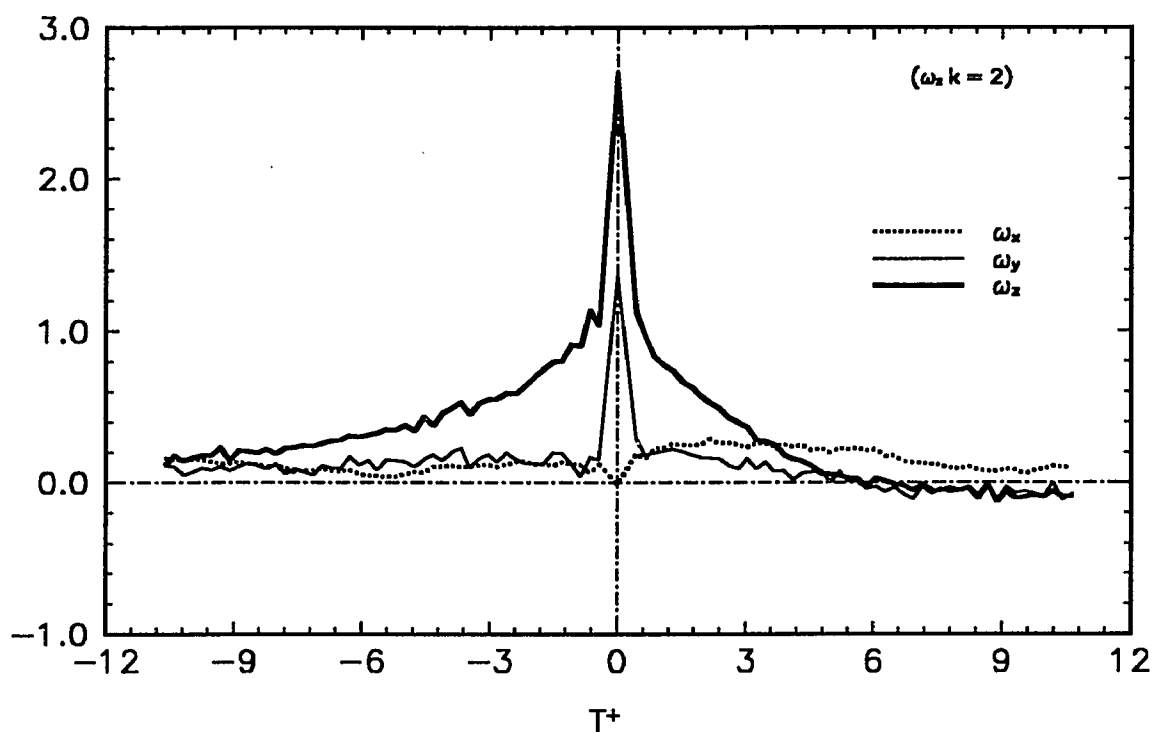


Figure 6.3.71. Relative amplitudes of the events associated with vorticity conditioned on positive ω_z , threshold $k=2$.

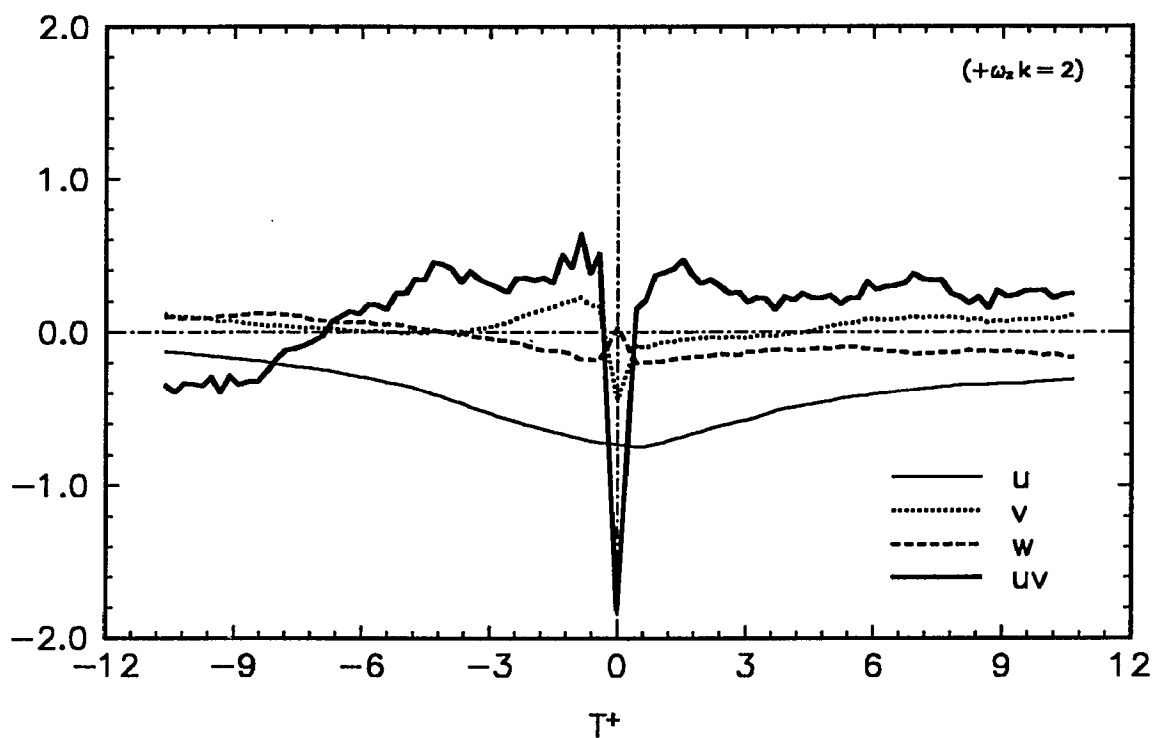


Figure 6.3.72. Relative amplitudes of the events associated with velocity conditioned on positive ω_z , threshold $k=2$.

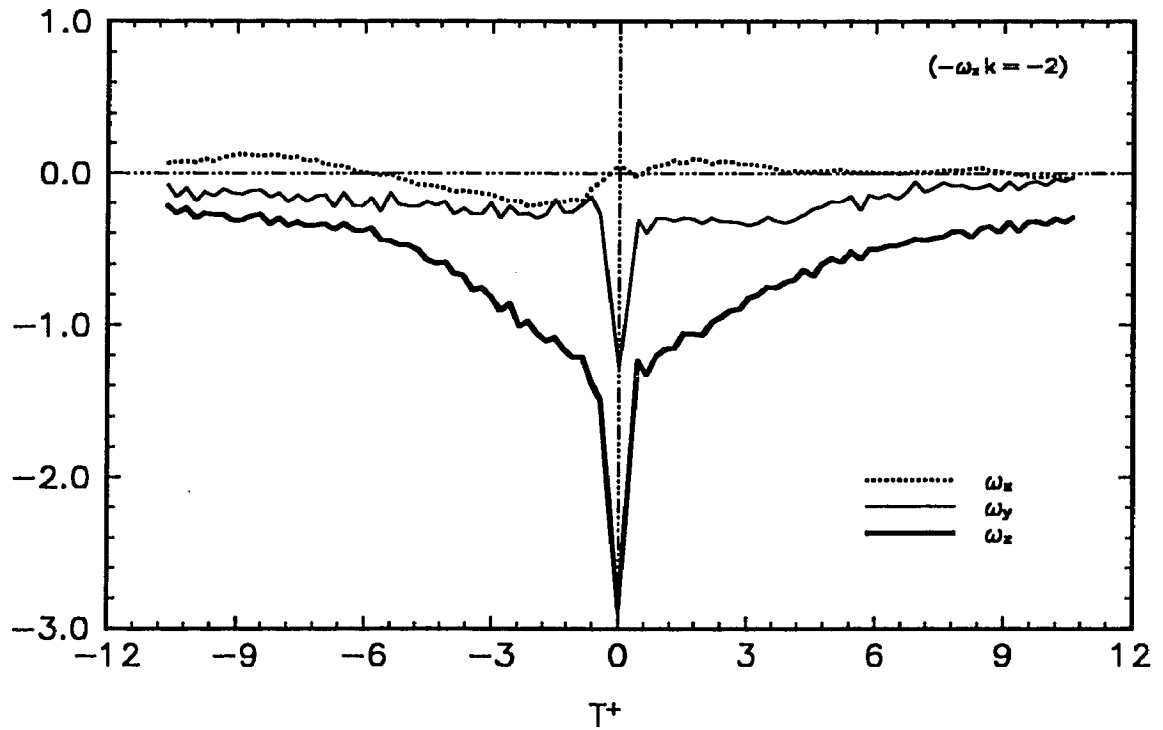


Figure 6.3.73. Relative amplitudes of the events associated with vorticity conditioned on negative ω_z , threshold $k=-2$.

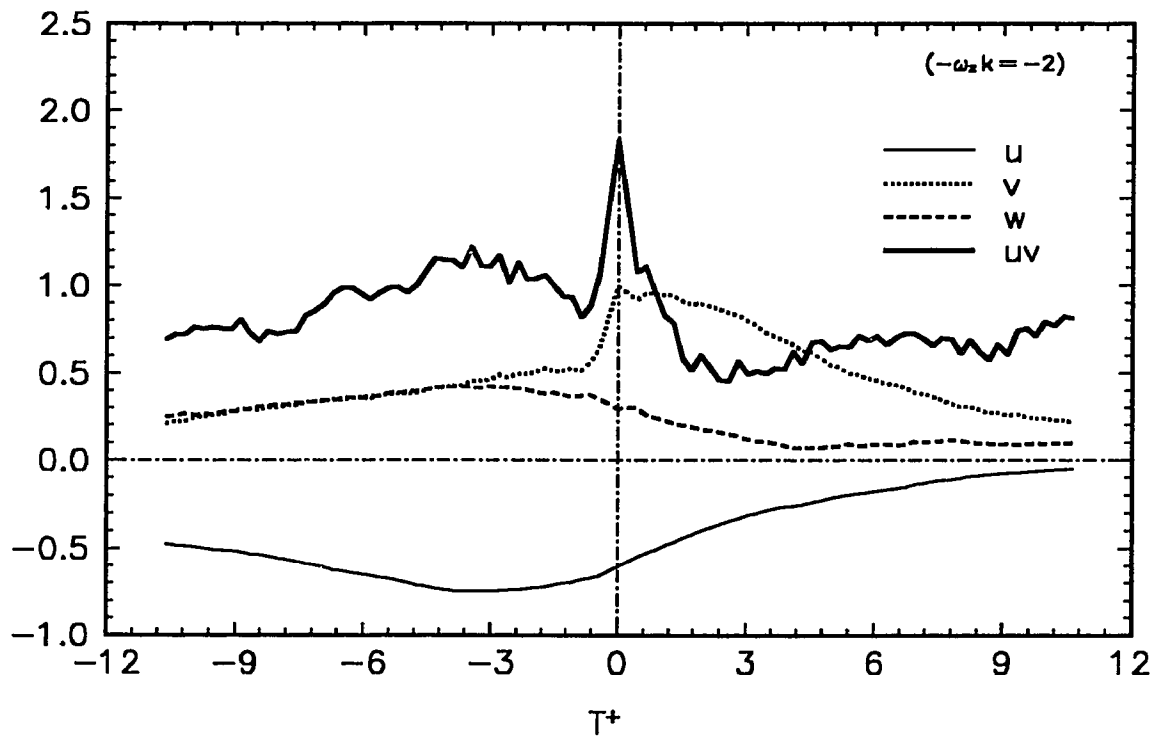


Figure 6.3.74. Relative amplitudes of the events associated with velocity conditioned on negative ω_z , threshold $k=-2$.

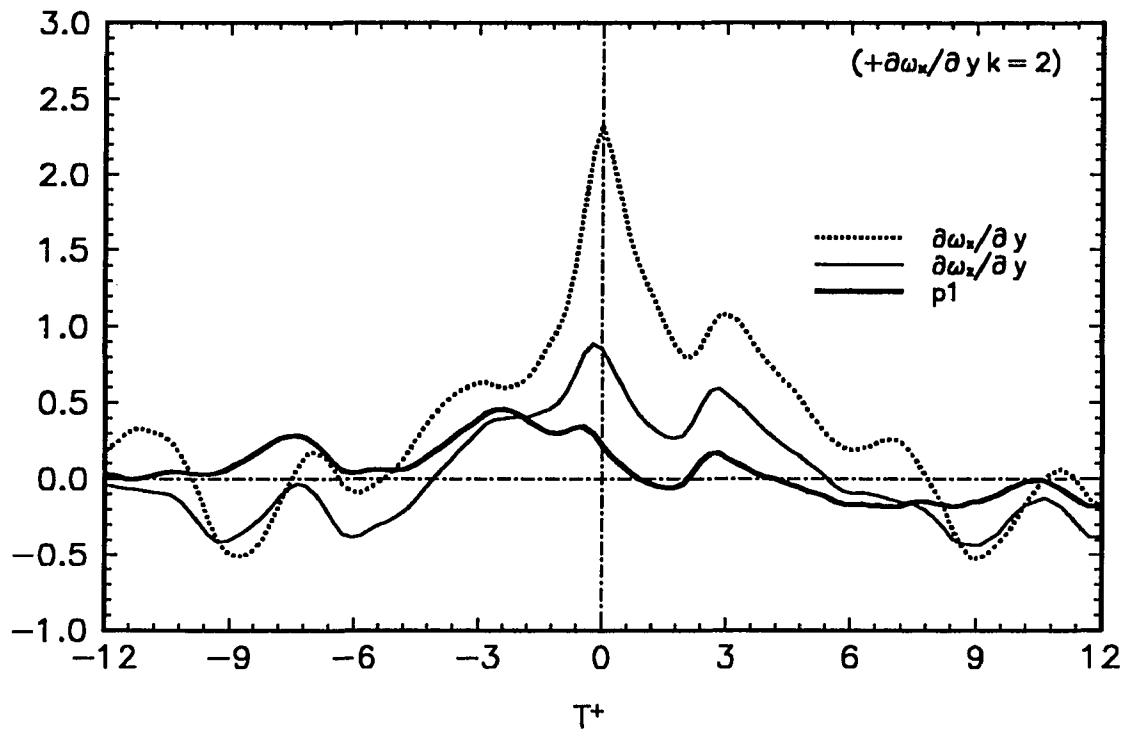


Figure 6.3.75. Relative amplitudes of the events associated with vorticity flux/pressure conditioned on positive $\partial\omega_x/\partial y$, threshold $k=2$.

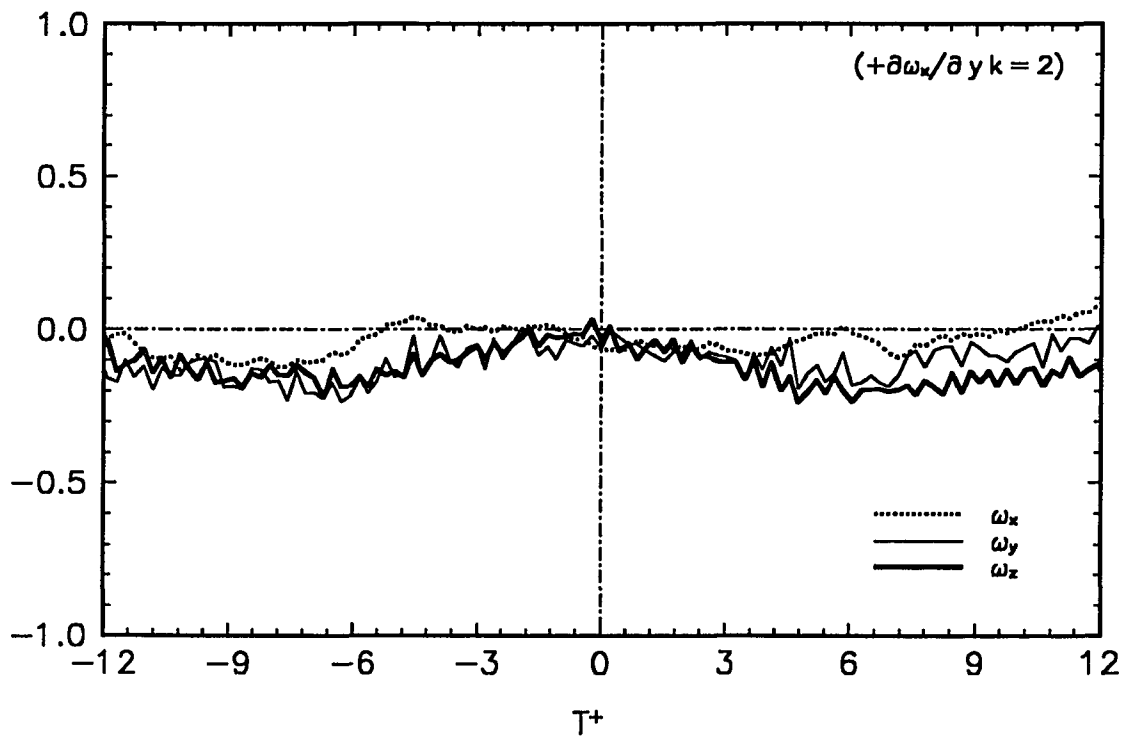


Figure 6.3.76. Relative amplitudes of the events associated with vorticity conditioned on positive $\partial\omega_x/\partial y$, threshold $k=2$.

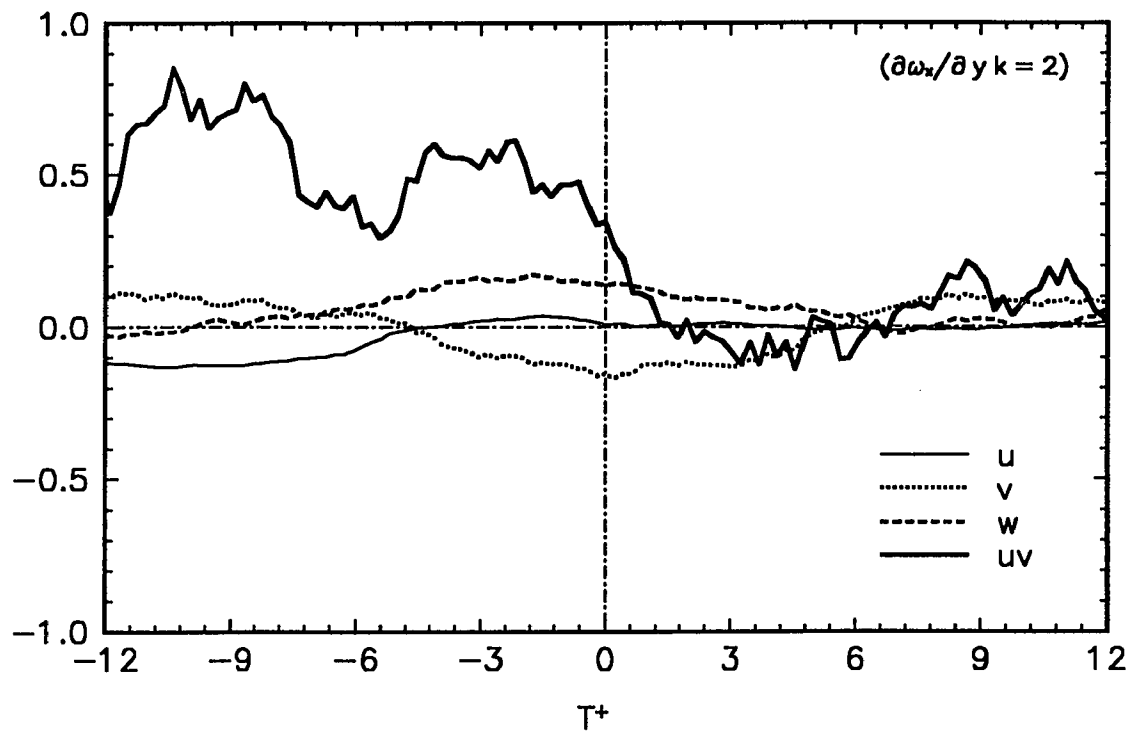


Figure 6.3.77. Relative amplitudes of the events associated with velocity conditioned on positive $\partial \omega_x / \partial y$, threshold $k=2$.

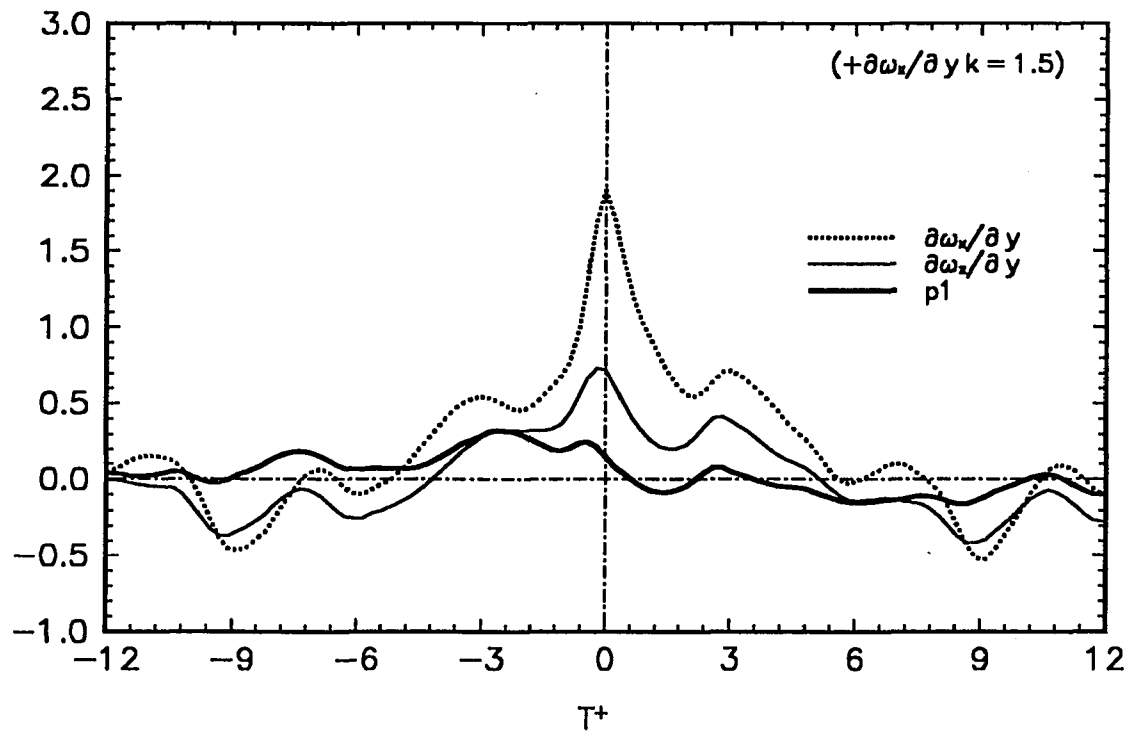


Figure 6.3.78. Relative amplitudes of the events associated with vorticity flux/pressure conditioned on positive $\partial\omega_x/\partial y$, threshold $k=1.5$.

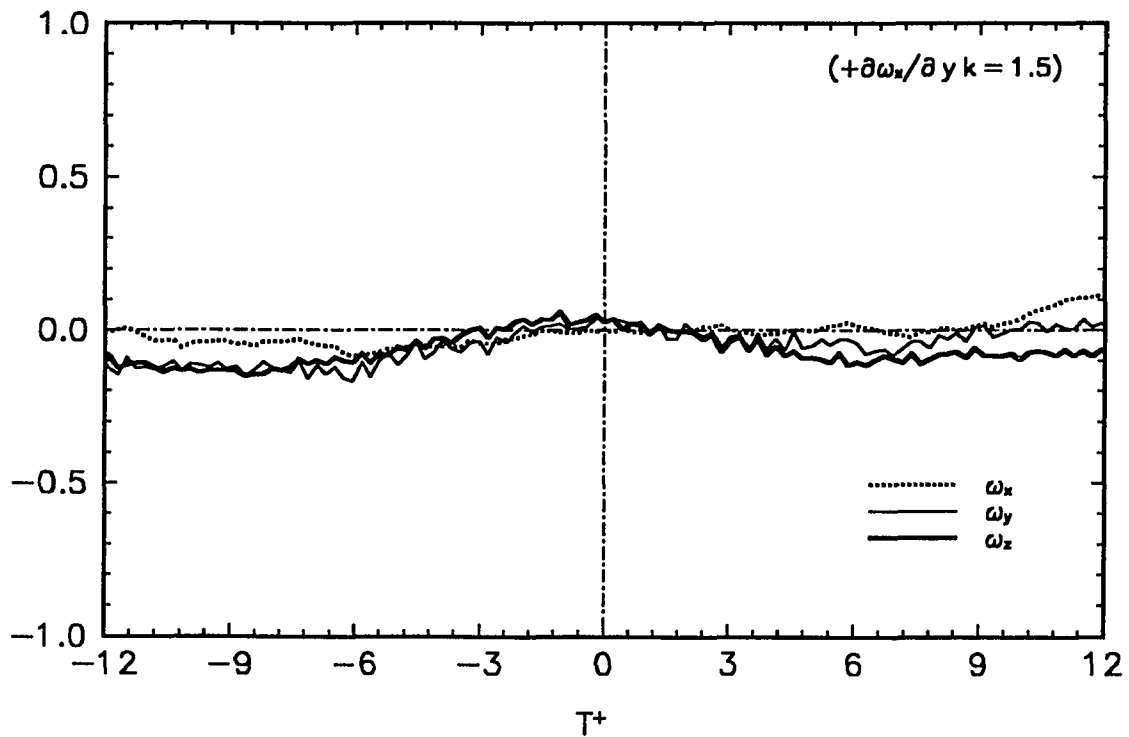


Figure 6.3.79. Relative amplitudes of the events associated with vorticity conditioned on positive $\partial\omega_x/\partial y$, threshold $k=1.5$.

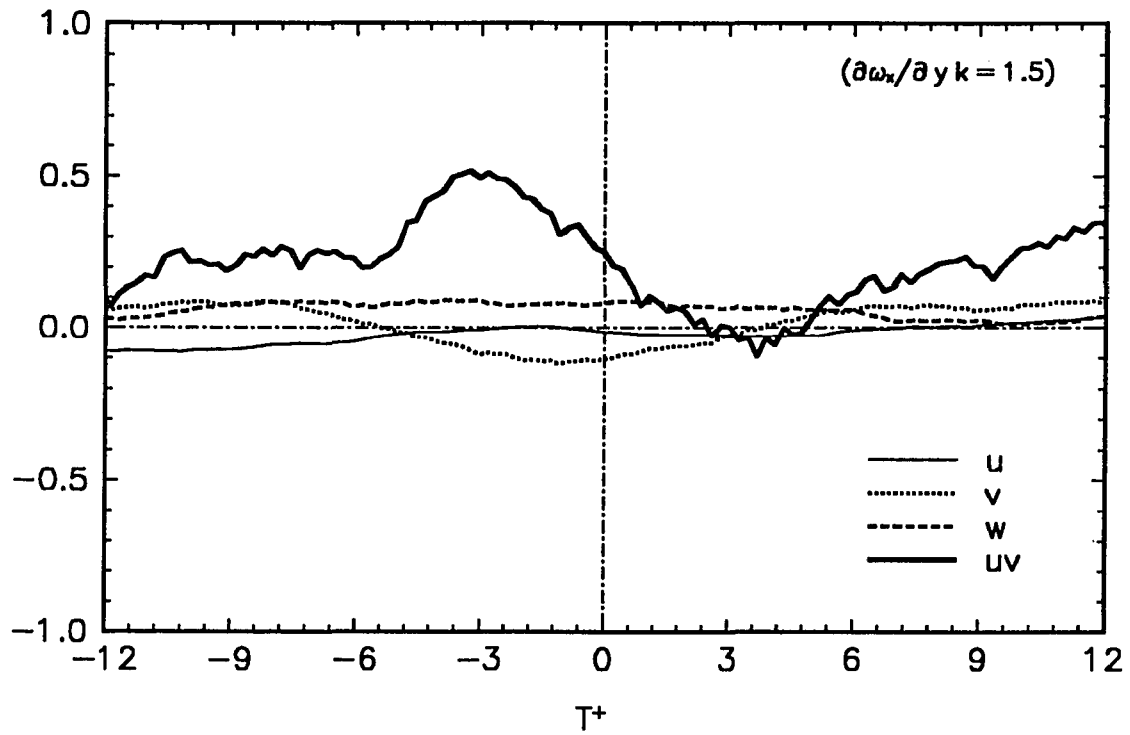


Figure 6.3.80. Relative amplitudes of the events associated with velocity conditioned on positive $\partial\omega_x/\partial y$, threshold $k=1.5$.

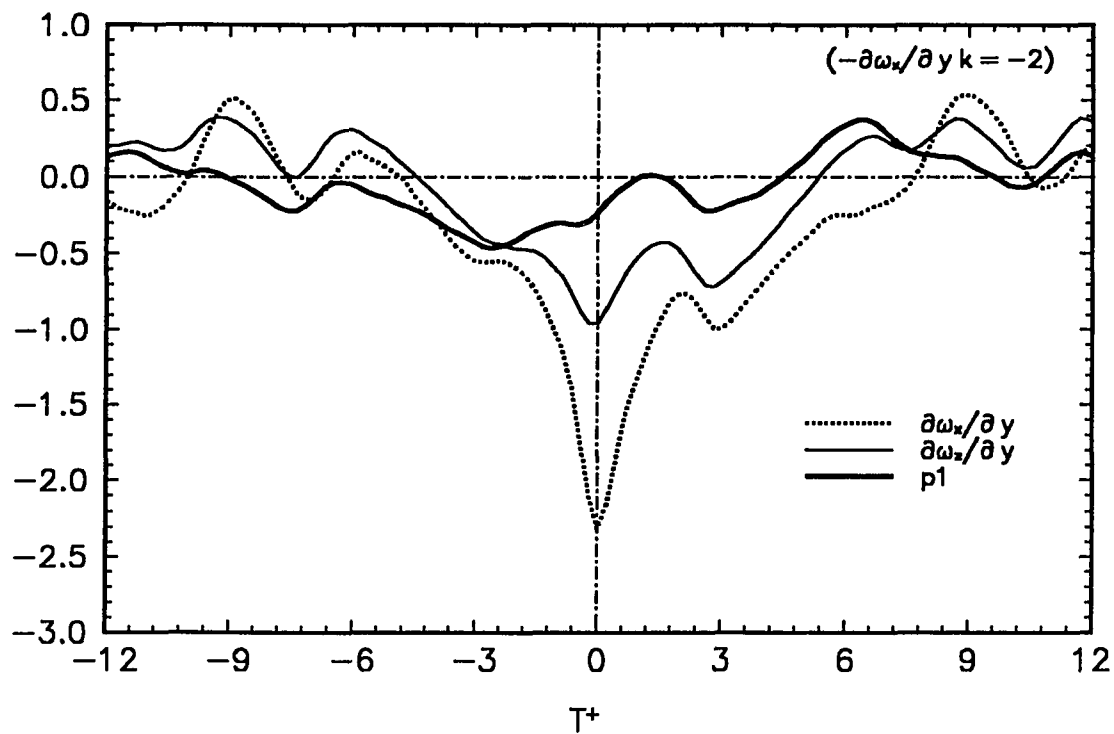


Figure 6.3.81. Relative amplitudes of the events associated with vorticity flux/pressure conditioned on negative $\partial\omega_x/\partial y$, threshold $k=-2$.

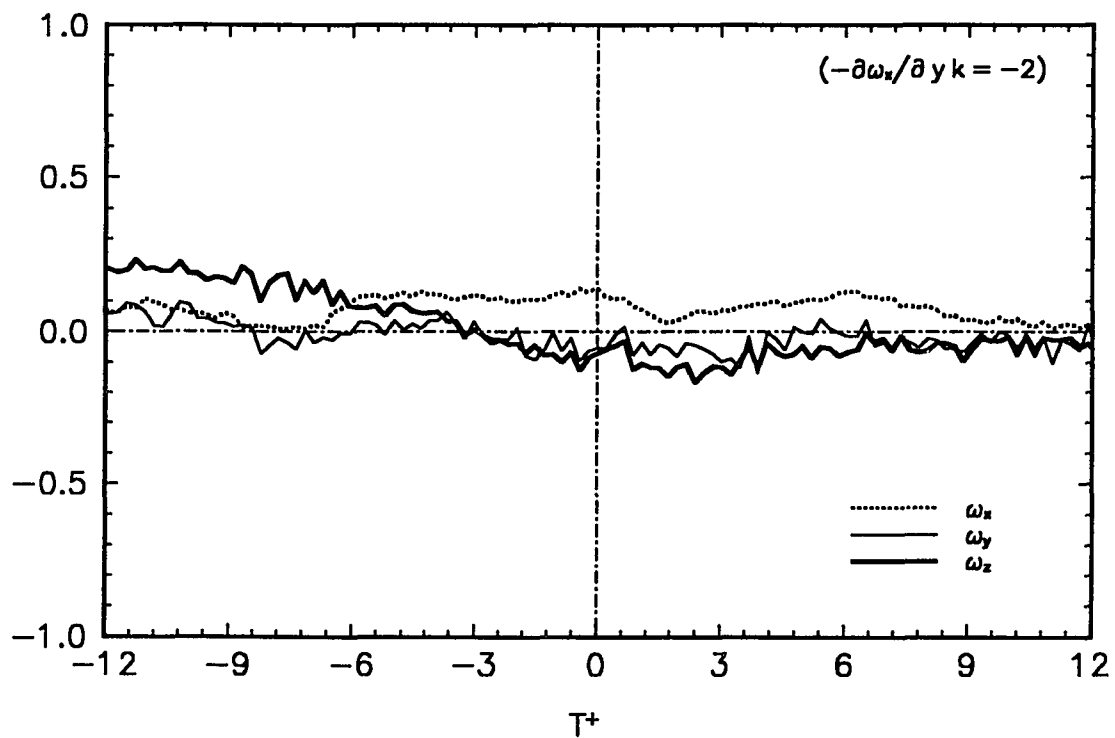


Figure 6.3.82. Relative amplitudes of the events associated with vorticity conditioned on negative $\partial\omega_x/\partial y$, threshold $k=-2$.

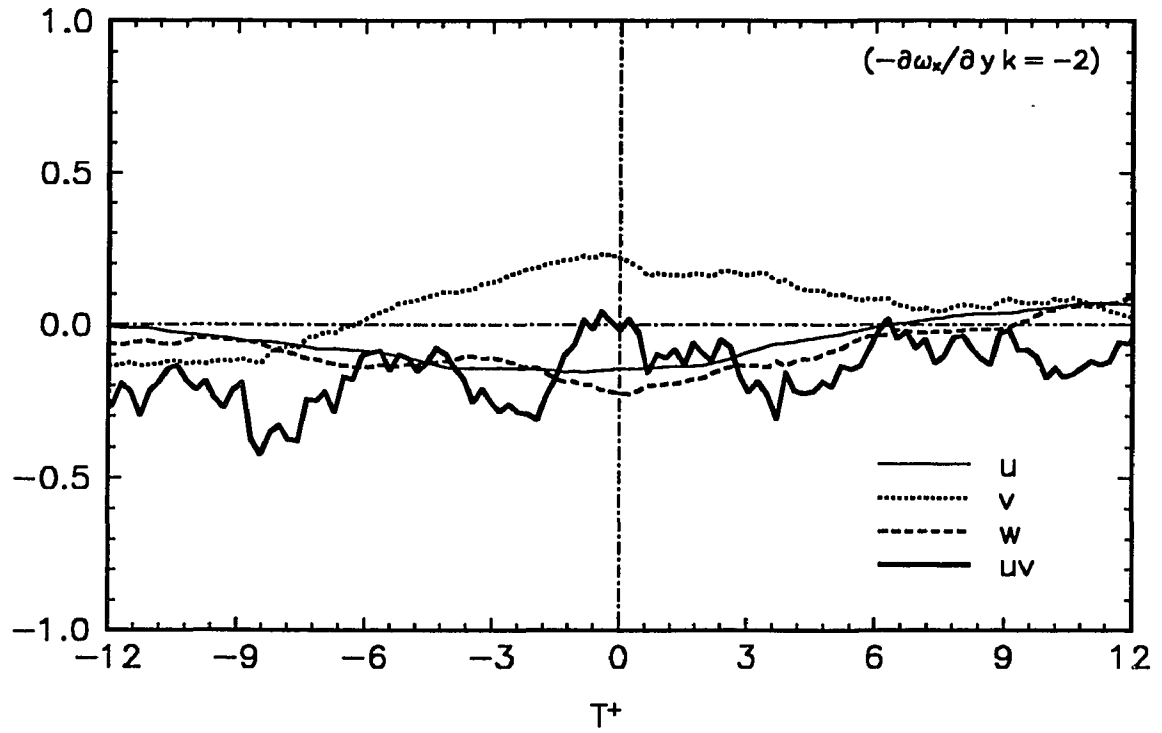


Figure 6.3.83. Relative amplitudes of the events associated with velocity conditioned on negative $\partial\omega_x/\partial y$, threshold $k=-2$.

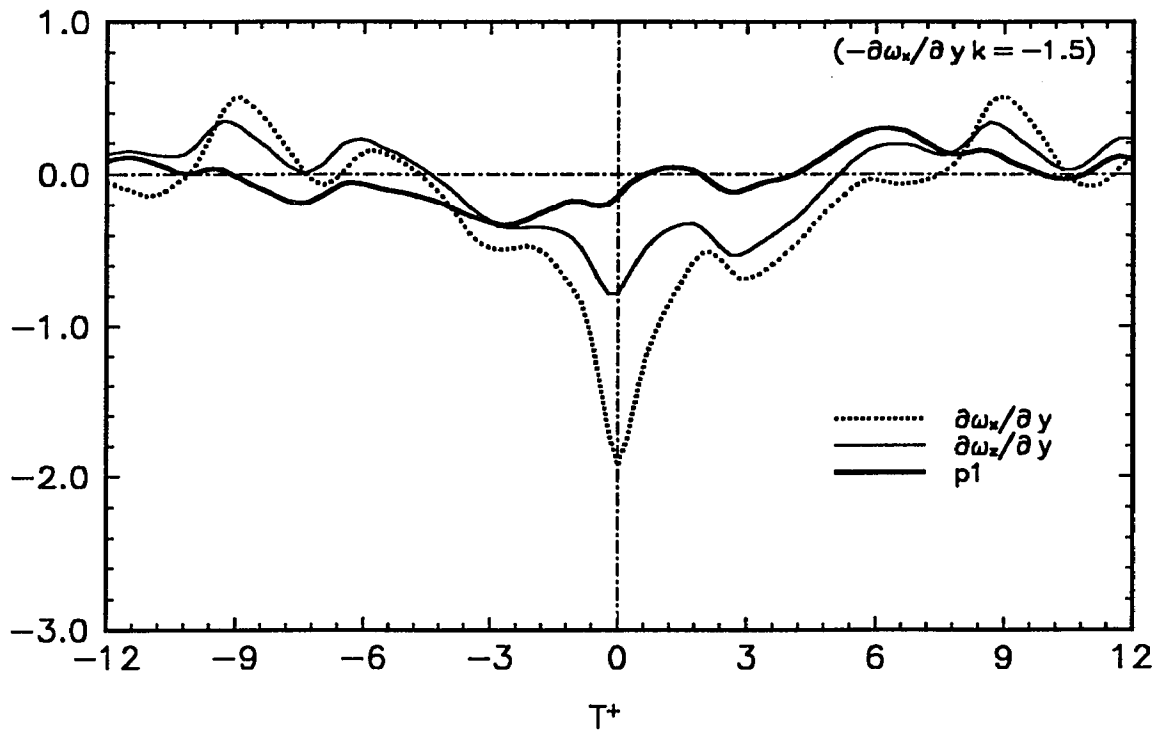


Figure 6.3.84. Relative amplitudes of the events associated with vorticity flux/pressure conditioned on negative $\partial\omega_x/\partial y$, threshold $k=-1.5$.

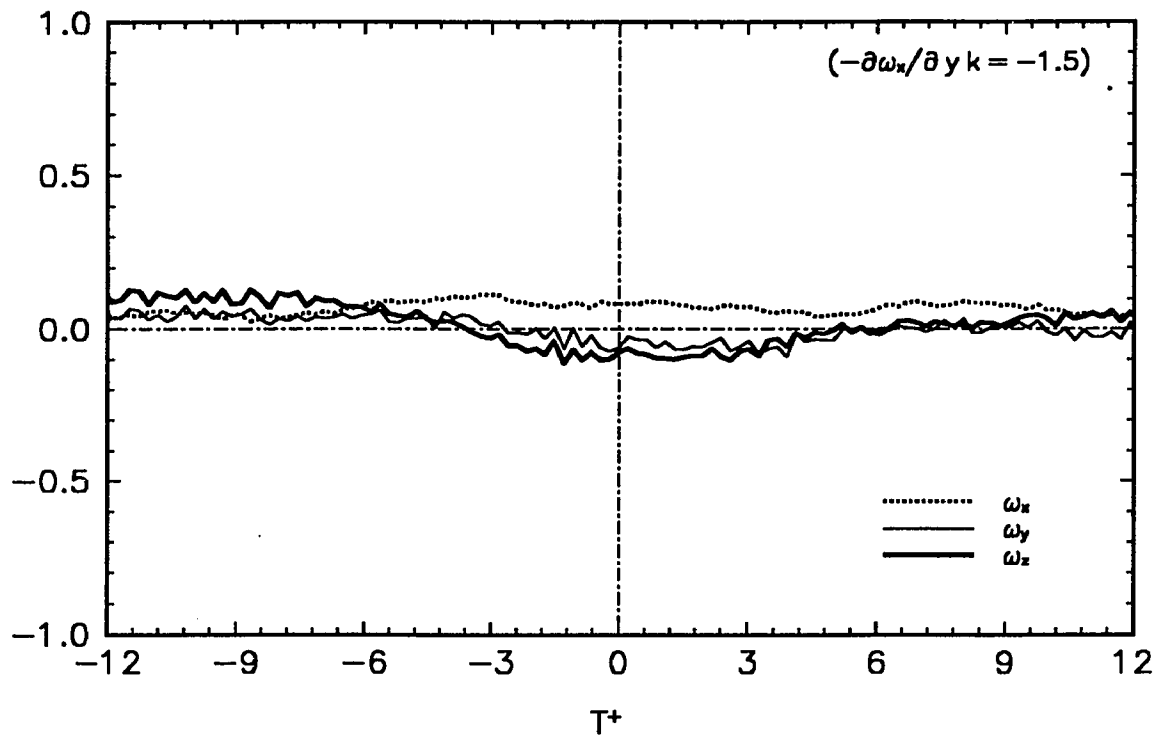


Figure 6.3.85. Relative amplitudes of the events associated with vorticity conditioned on negative $\partial\omega_x/\partial y$, threshold $k=-1.5$.

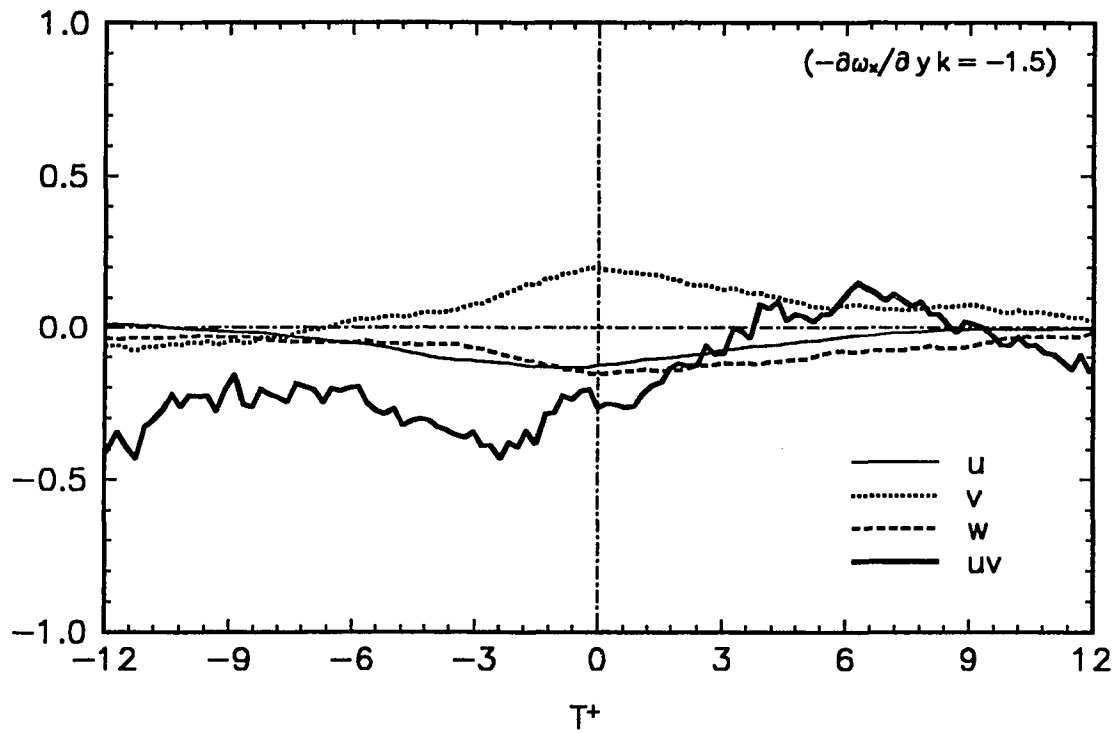


Figure 6.3.86. Relative amplitudes of the events associated with velocity conditioned on negative $\partial\omega_x/\partial y$, threshold $k=-1.5$.

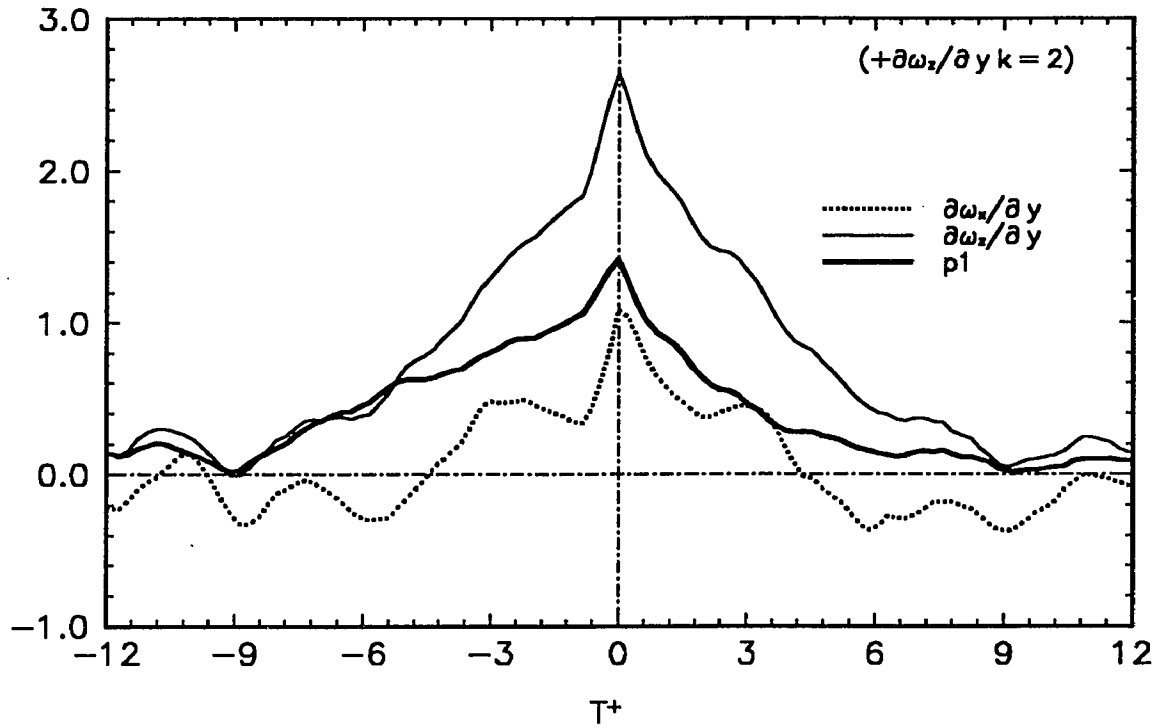


Figure 6.3.87. Relative amplitudes of the events associated with vorticity flux/pressure conditioned on positive $\partial\omega_z/\partial y$, threshold $k=2$.

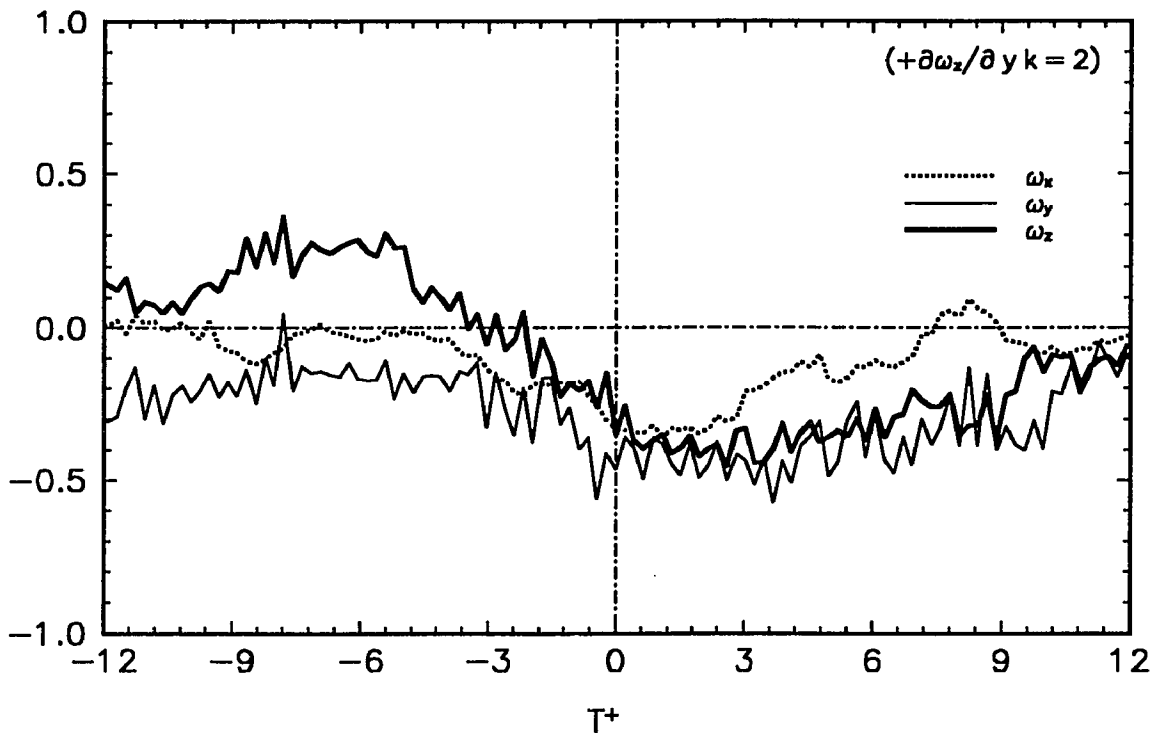


Figure 6.3.88. Relative amplitudes of the events associated with vorticity conditioned on positive $\partial\omega_z/\partial y$, threshold $k=2$.

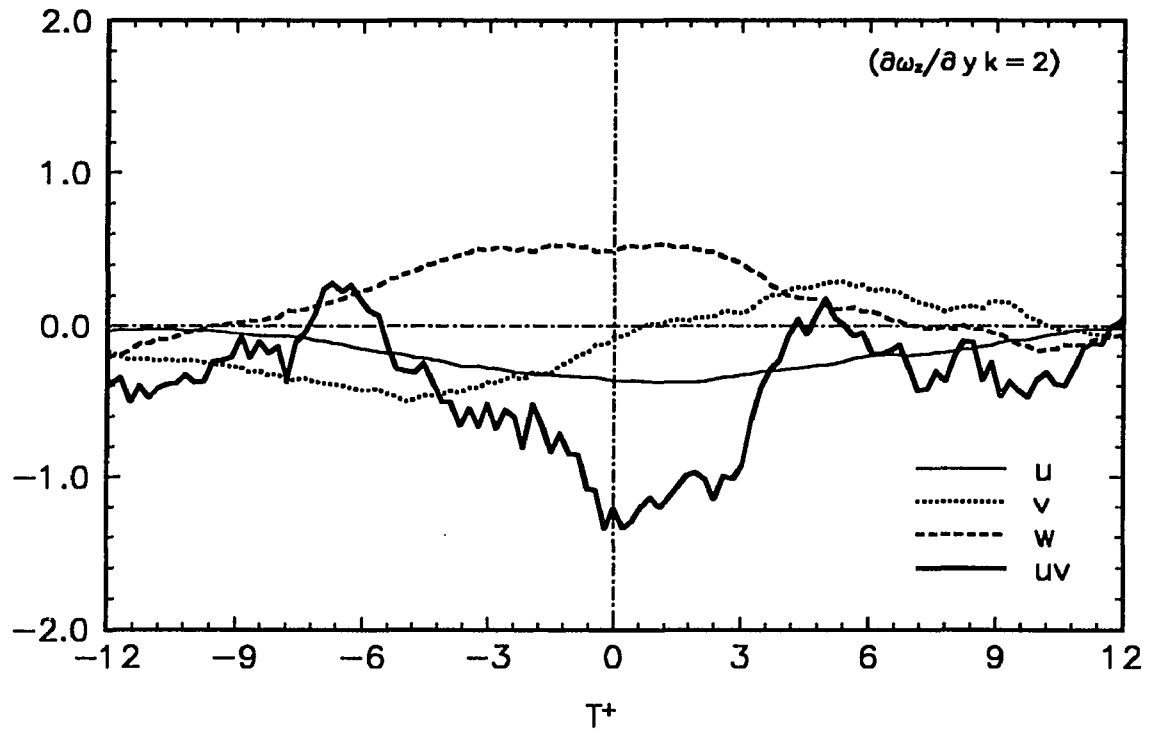


Figure 6.3.89. Relative amplitudes of the events associated with velocity conditioned on positive $\partial\omega_z/\partial y$, threshold $k=2$.

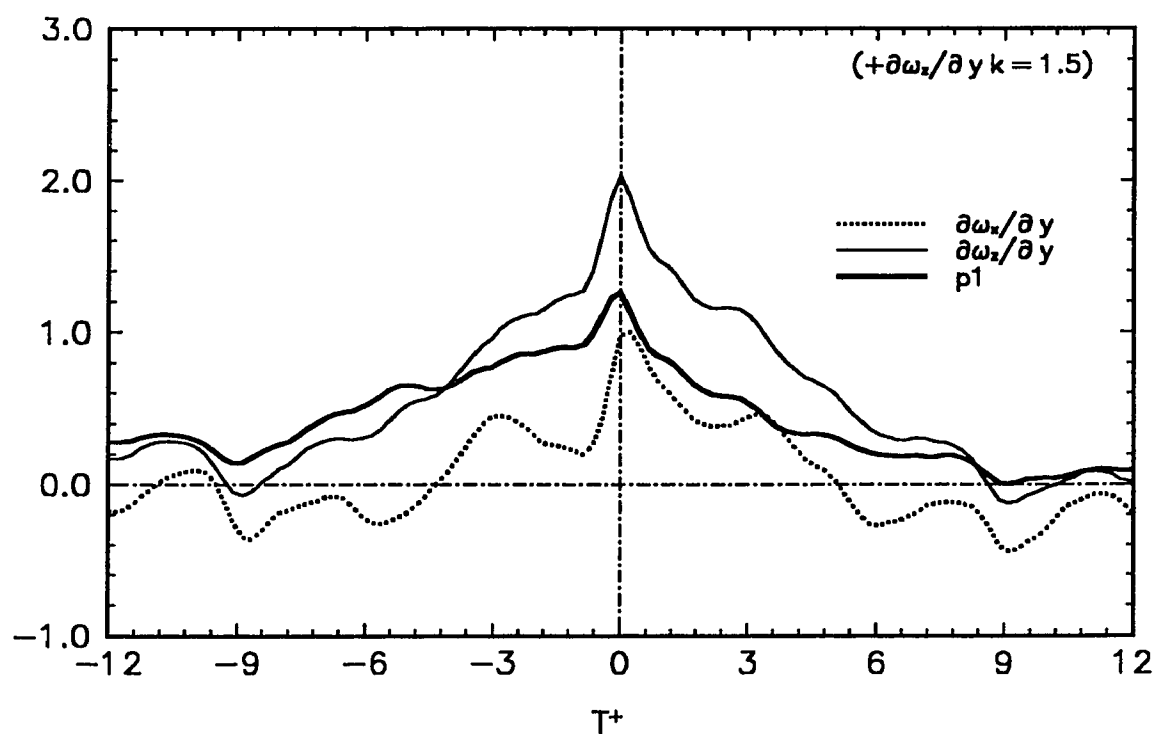


Figure 6.3.90. Relative amplitudes of the events associated with vorticity flux/pressure conditioned on positive $\partial\omega_z/\partial y$, threshold $k=1.5$.

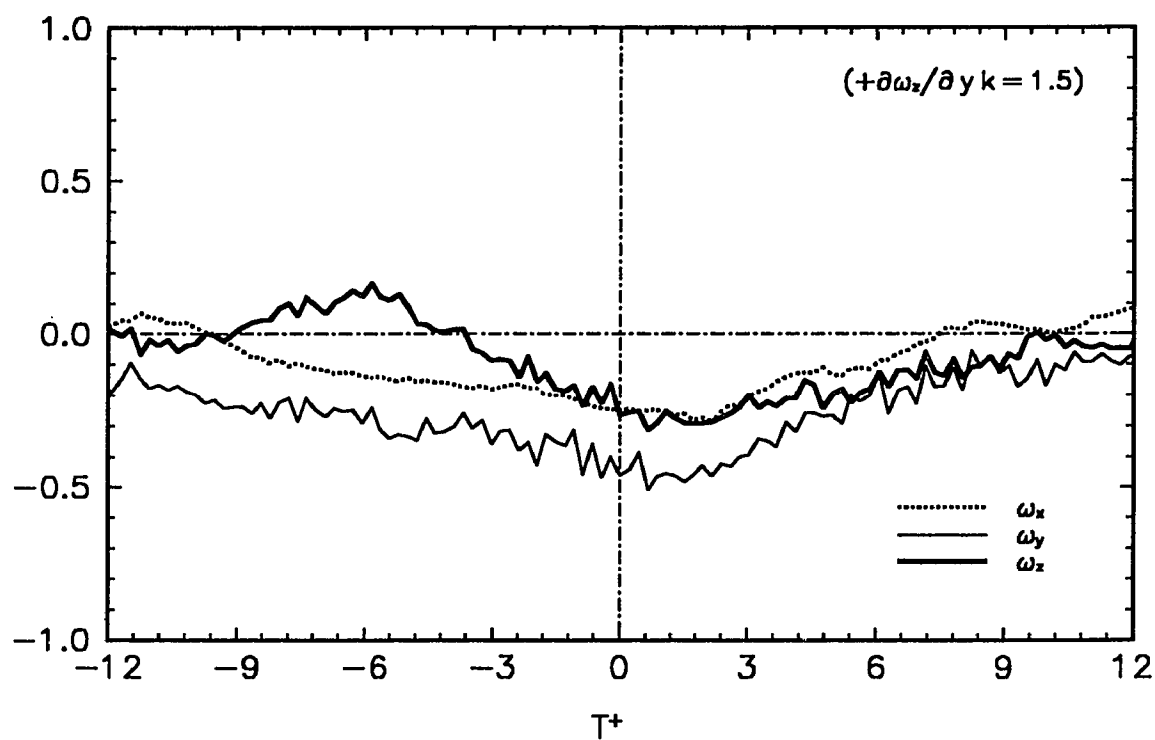


Figure 6.3.91. Relative amplitudes of the events associated with vorticity conditioned on positive $\partial\omega_z/\partial y$, threshold $k=1.5$.

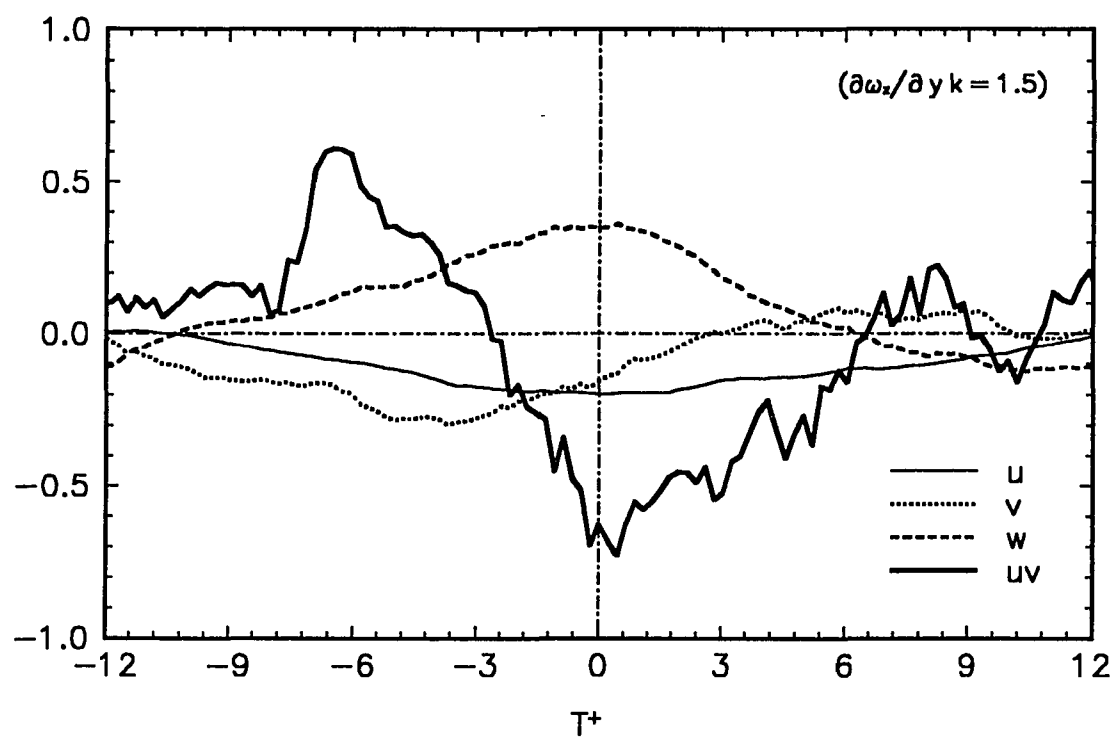


Figure 6.3.92. Relative amplitudes of the events associated with velocity conditioned on positive $\partial\omega_z/\partial y$, threshold $k=1.5$.

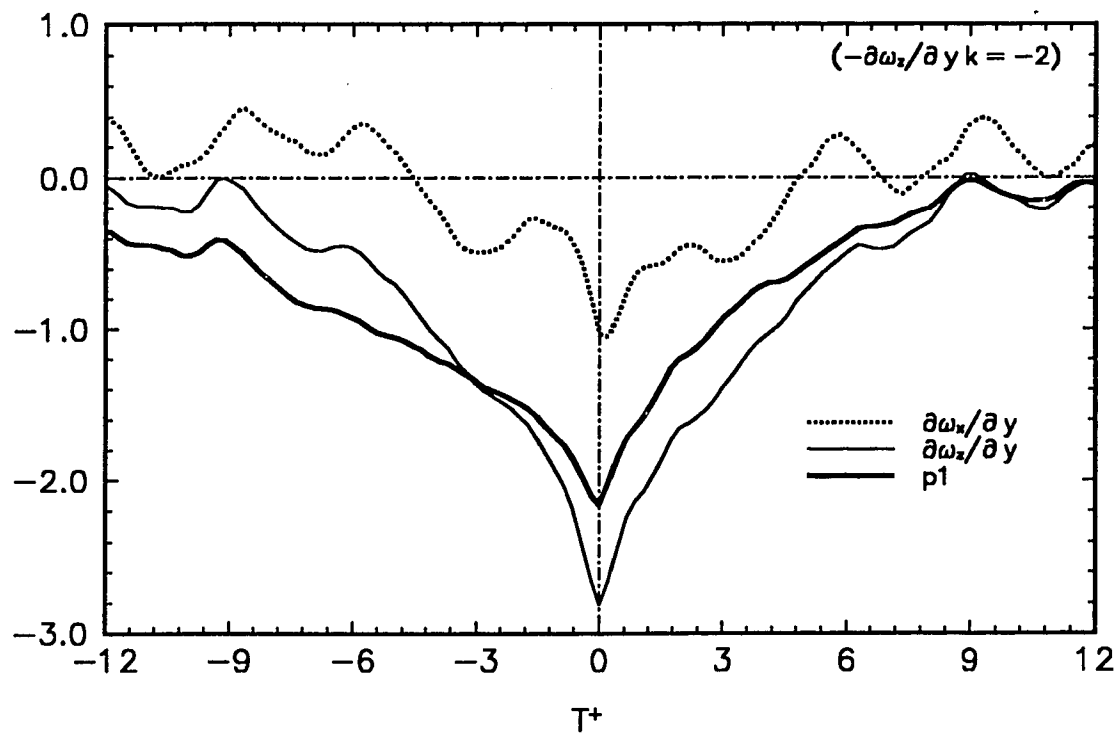


Figure 6.3.93. Relative amplitudes of the events associated with vorticity flux/pressure conditioned on negative $\partial\omega_z/\partial y$, threshold $k=-2$.

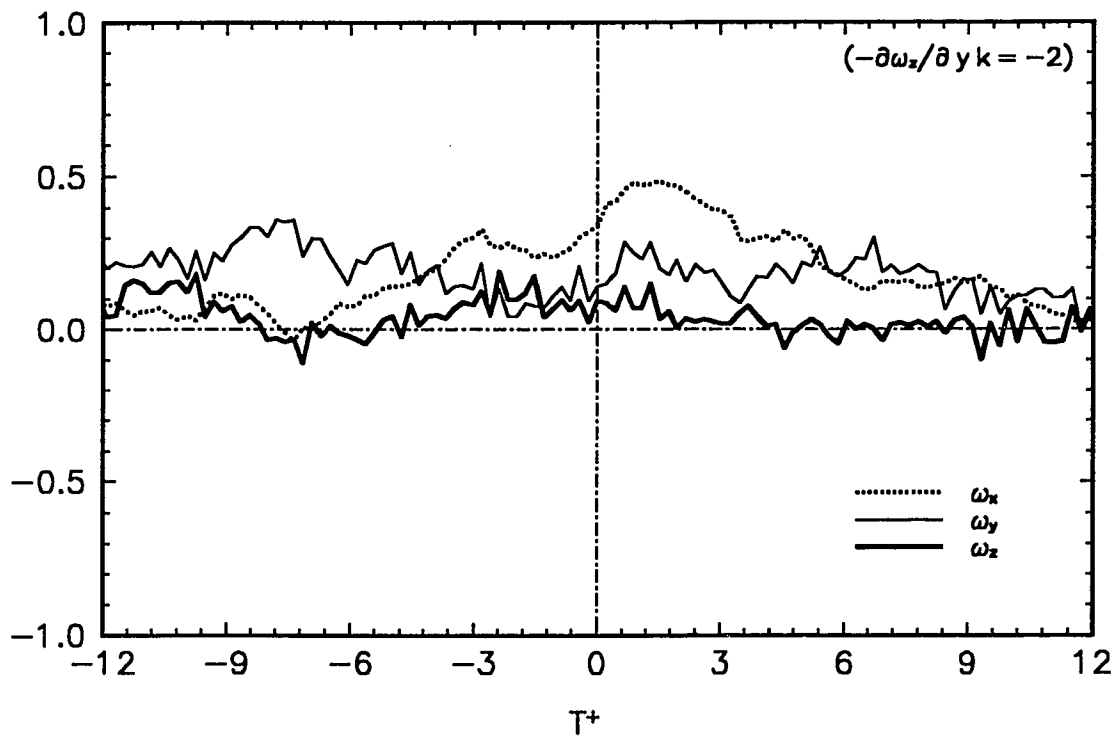


Figure 6.3.94. Relative amplitudes of the events associated with vorticity conditioned on negative $\partial\omega_z/\partial y$, threshold $k=-2$.

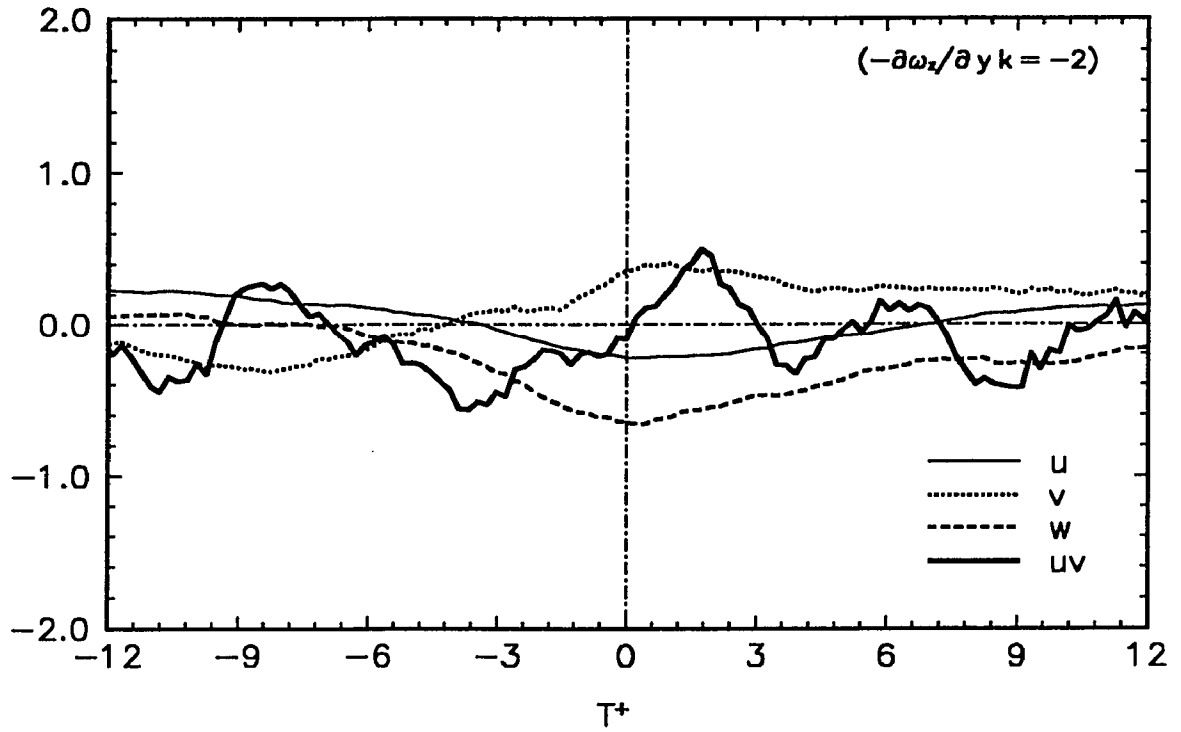


Figure 6.3.95. Relative amplitudes of the events associated with velocity conditioned on negative $\partial\omega_z/\partial y$, threshold $k=-2$.

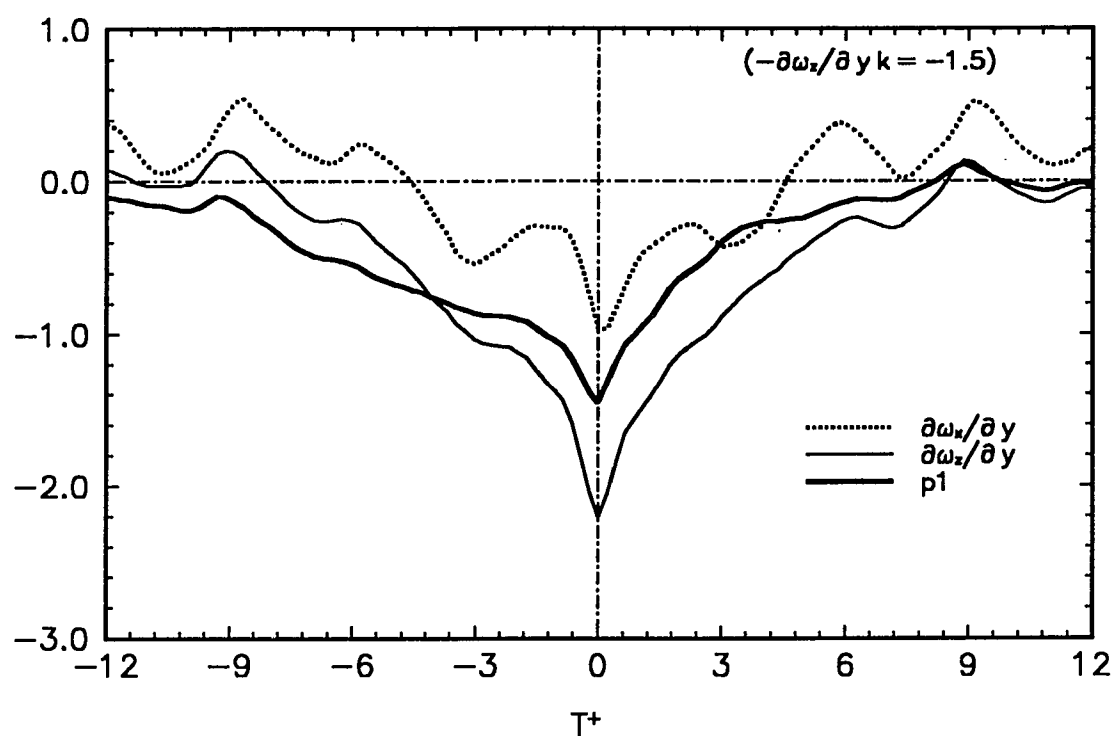


Figure 6.3.96. Relative amplitudes of the events associated with vorticity flux/pressure conditioned on negative $\partial\omega_z/\partial y$, threshold $k=-1.5$

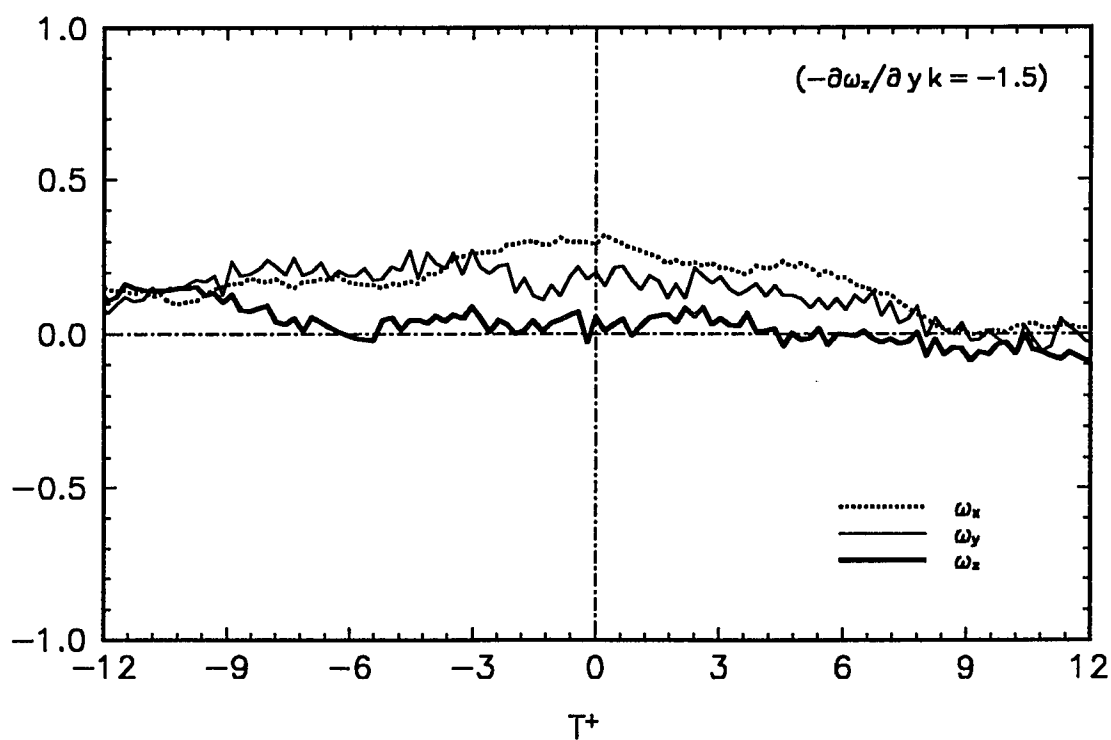


Figure 6.3.97. Relative amplitudes of the events associated with vorticity conditioned on negative $\partial\omega_z/\partial y$, threshold $k=-1.5$.

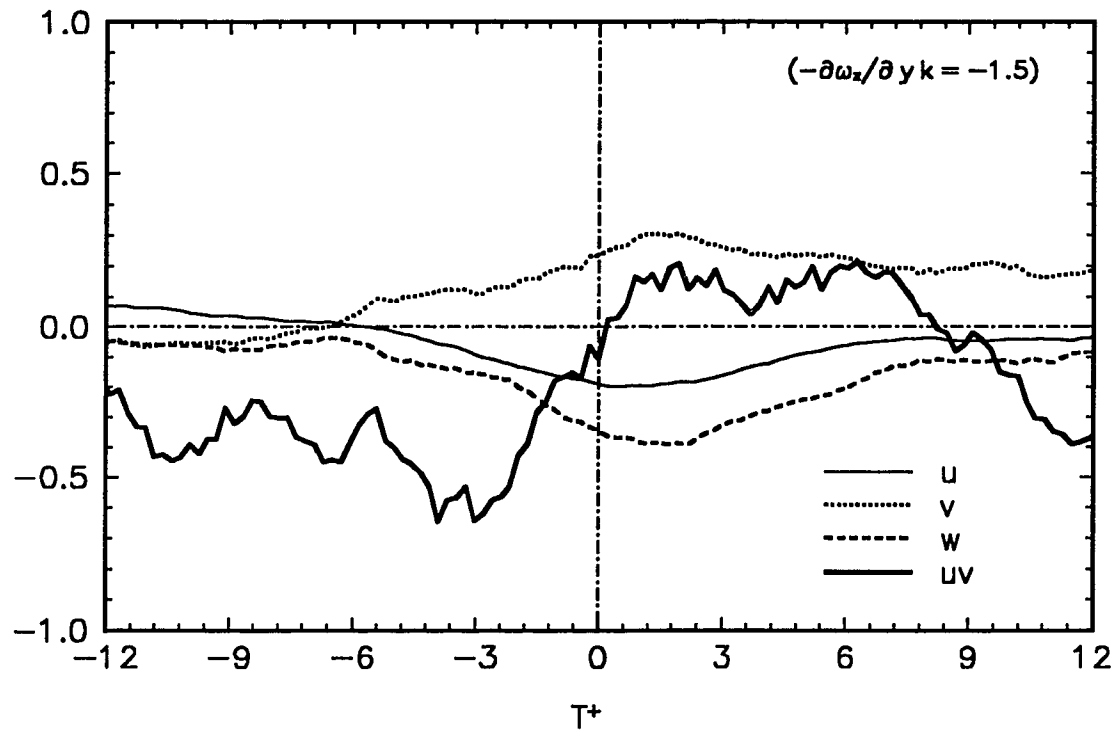


Figure 6.3.98. Relative amplitudes of the events associated with velocity conditioned on negative $\partial\omega_z/\partial y$, threshold $k=-1.5$.

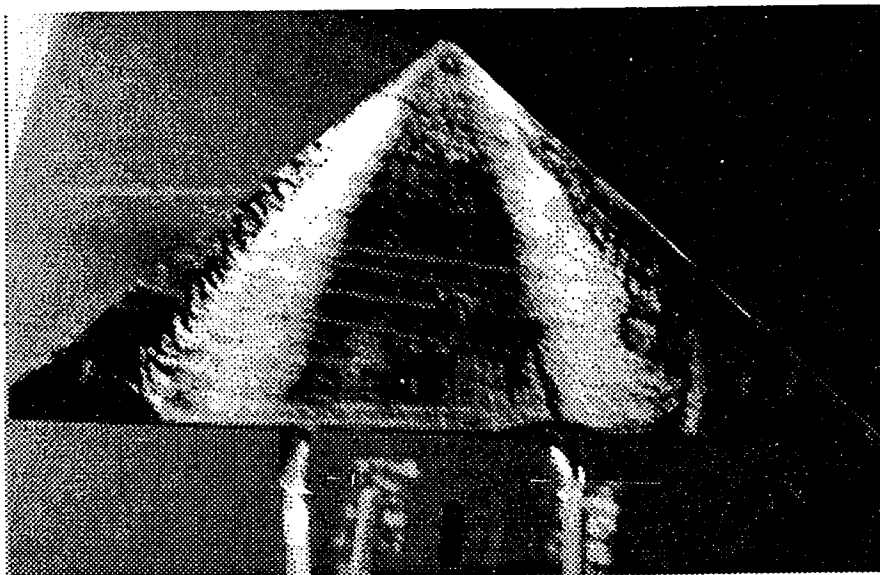


Figure 6.4.1. Imprint of delta wing surface flow at 20 degree angle of attack.

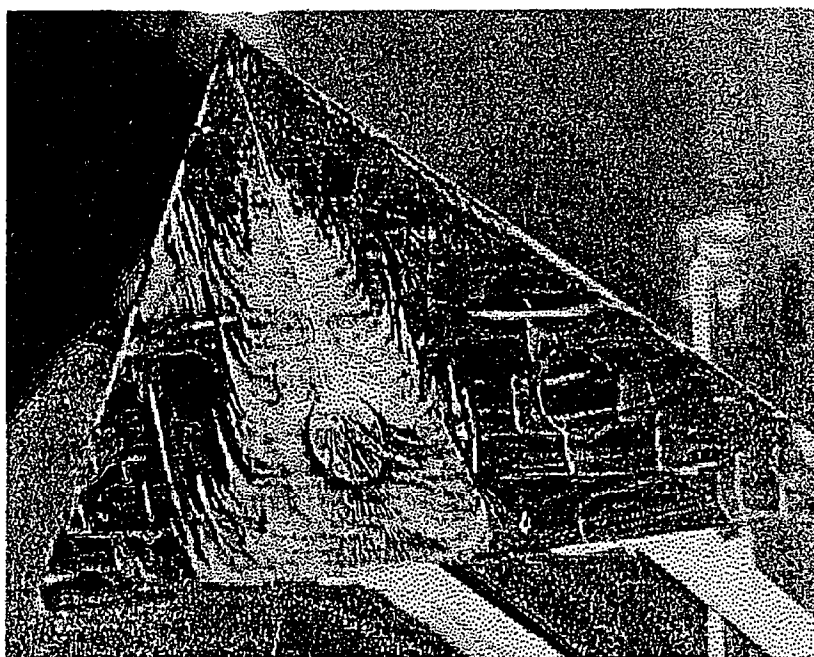


Figure 6.4.2. Imprint of delta wing surface flow at 45 degree angle of attack.

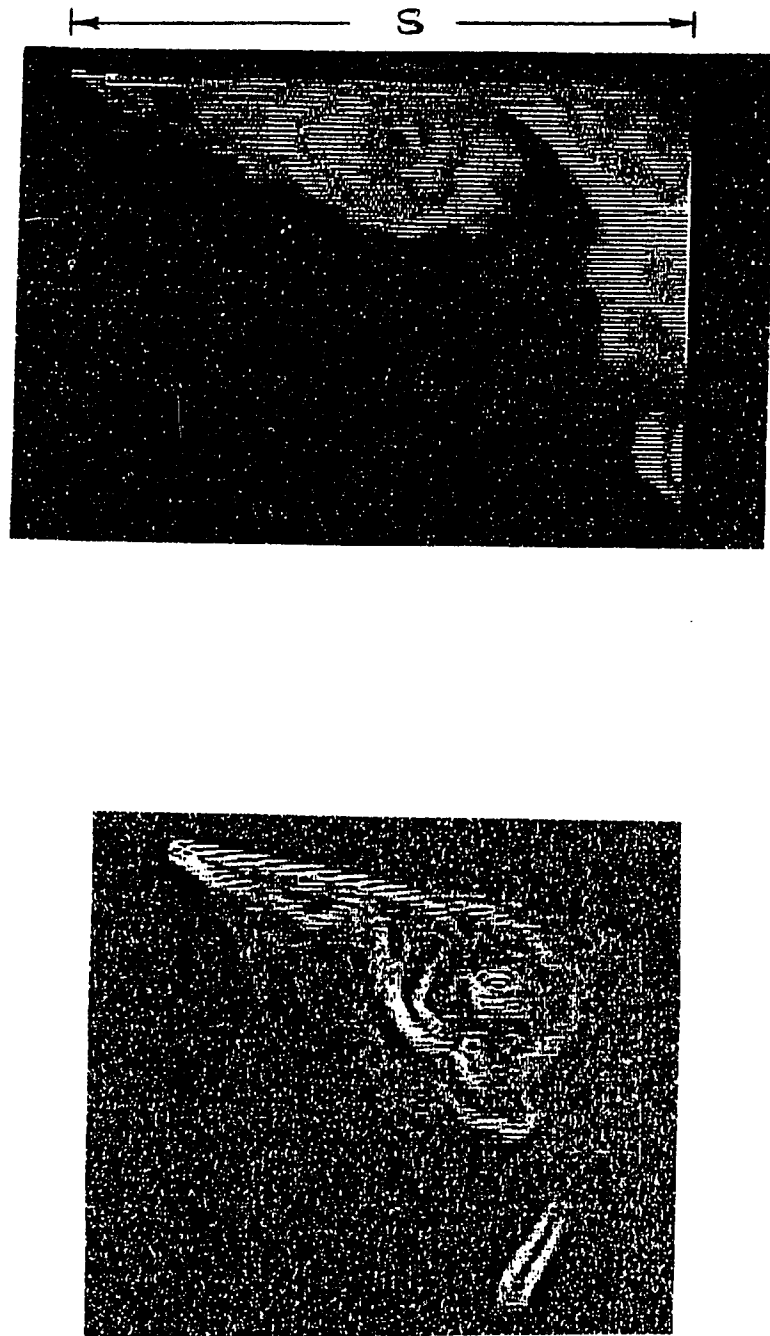


Figure 6.4.3. Filtered snap-shot of lateral laser sheet , $\alpha=10^\circ$ and $U_\infty=3$ m/s.

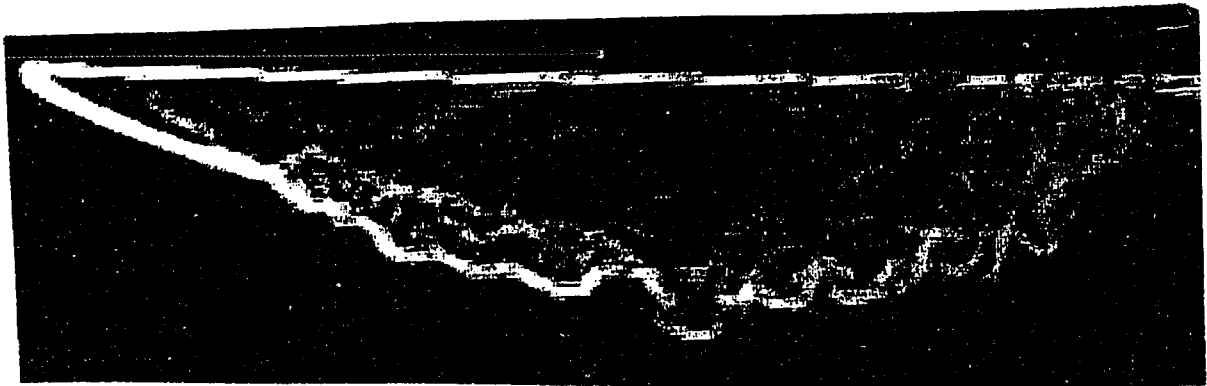


Figure 6.4.4. Filtered snap-shot of lateral laser sheet , $\alpha=15^\circ$ and $U_\infty=3$ m/s.

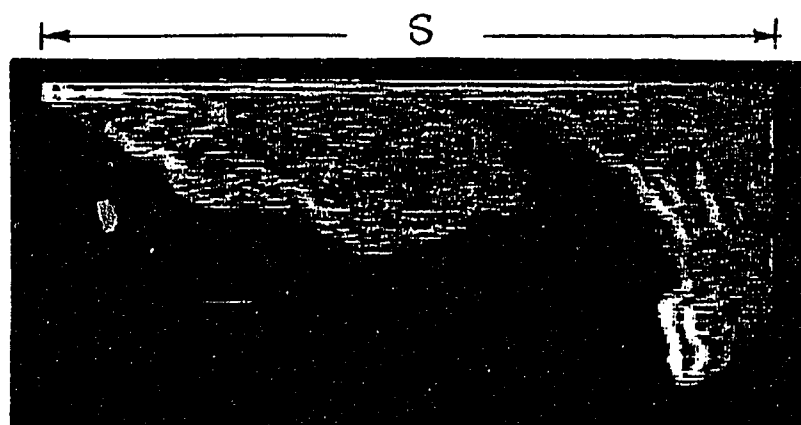


Figure 6.4.5. Filtered snap-shot of lateral laser sheet , $\alpha=5^\circ$ and $U_\infty=3$ m/s.



Figure 6.4.6. Filtered snap-shot of lateral laser sheet , $\alpha=15^\circ$ and $U_\infty=3$ m/s (reversed intensity).

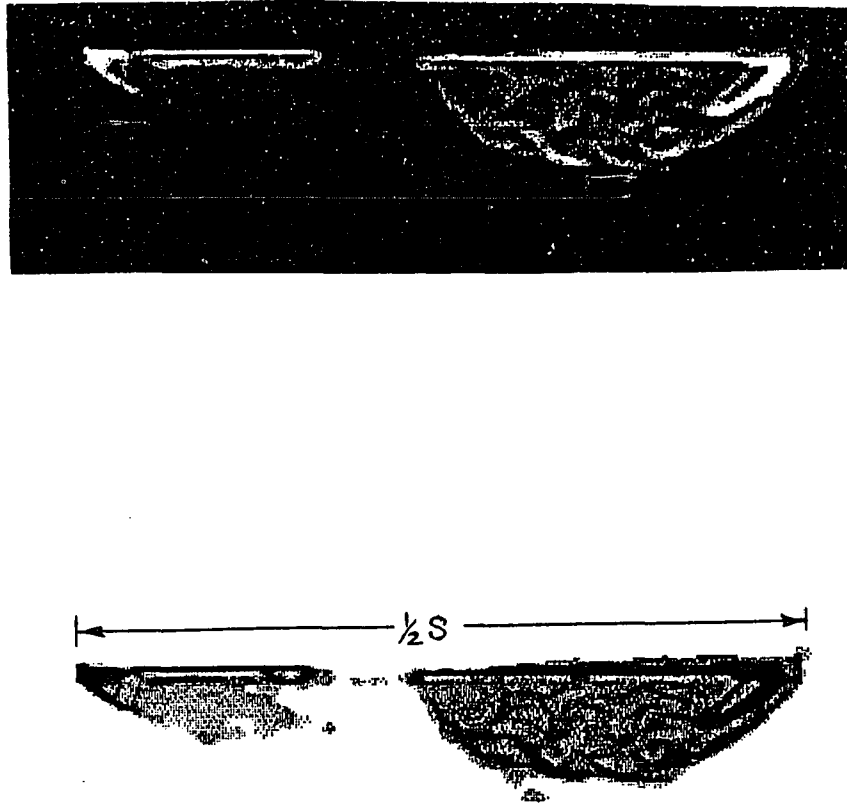


Figure 6.4.7. Filtered snap-shot of lateral laser sheet at a streamwise distance of half the chord, $\alpha=15^\circ$ and $U_\infty=3$ m/s.

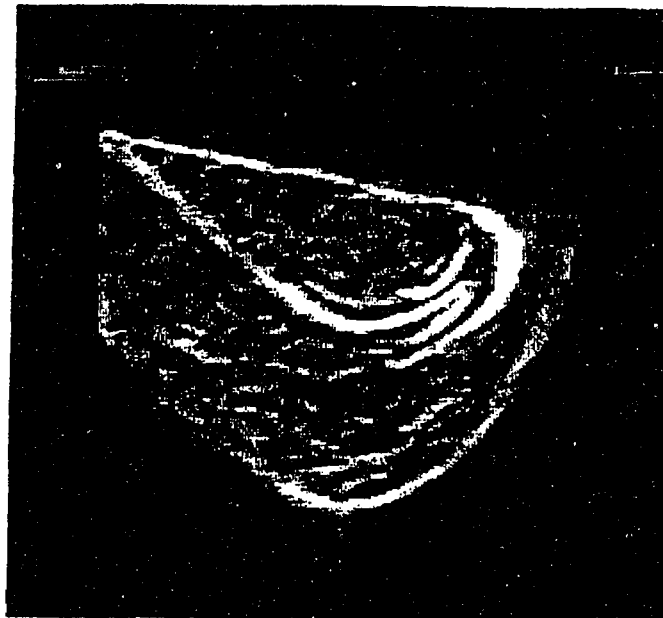


Figure 6.4.8. Filtered frame of snap-shot of lateral laser sheet , $\alpha=5^\circ$ and $U_\infty=3$ m/s.

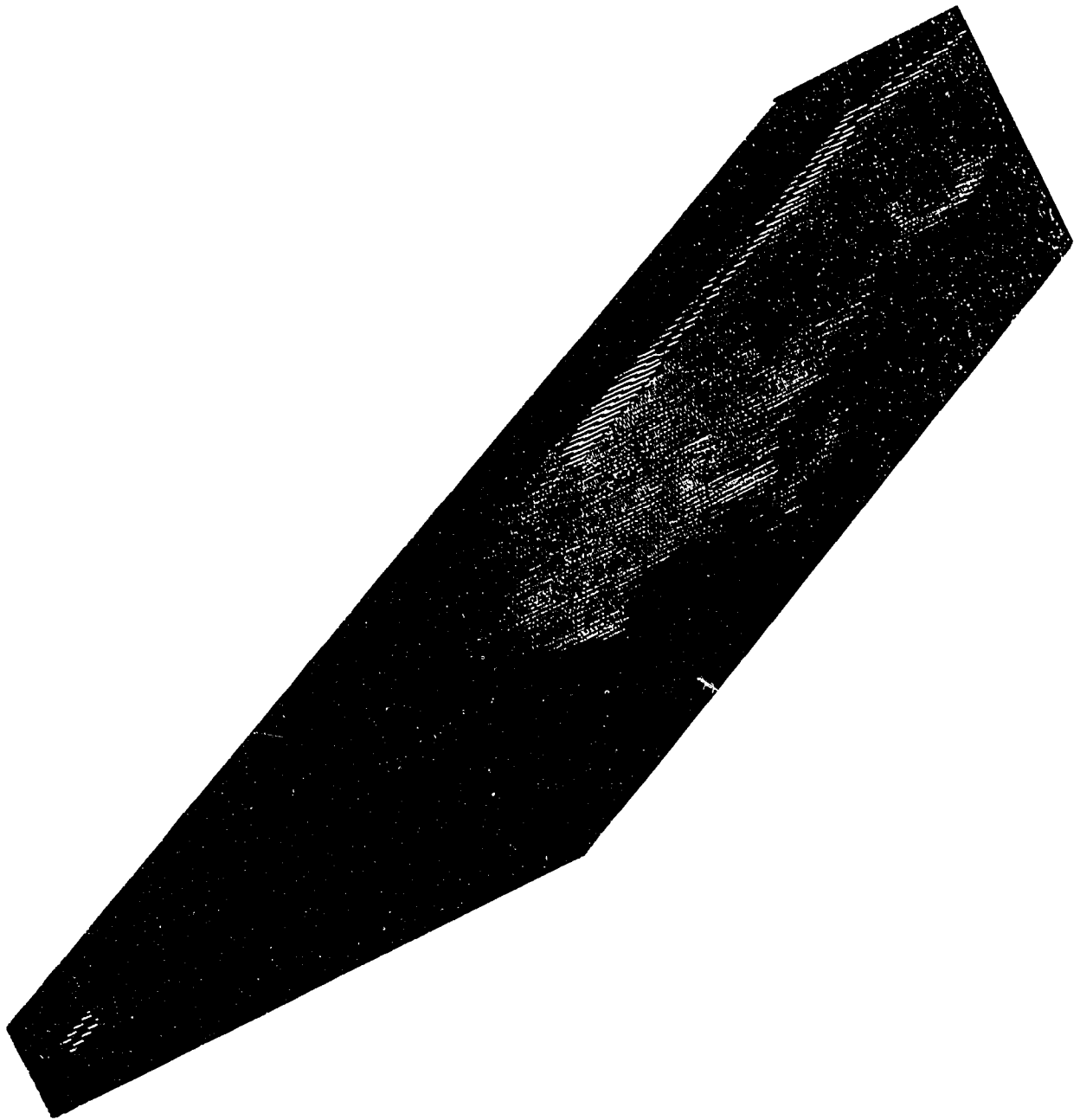


Figure 6.4.9. Filtered frame of longitudinal laser sheet , $\alpha=5^\circ$ and $U_\infty=3$ m/s.

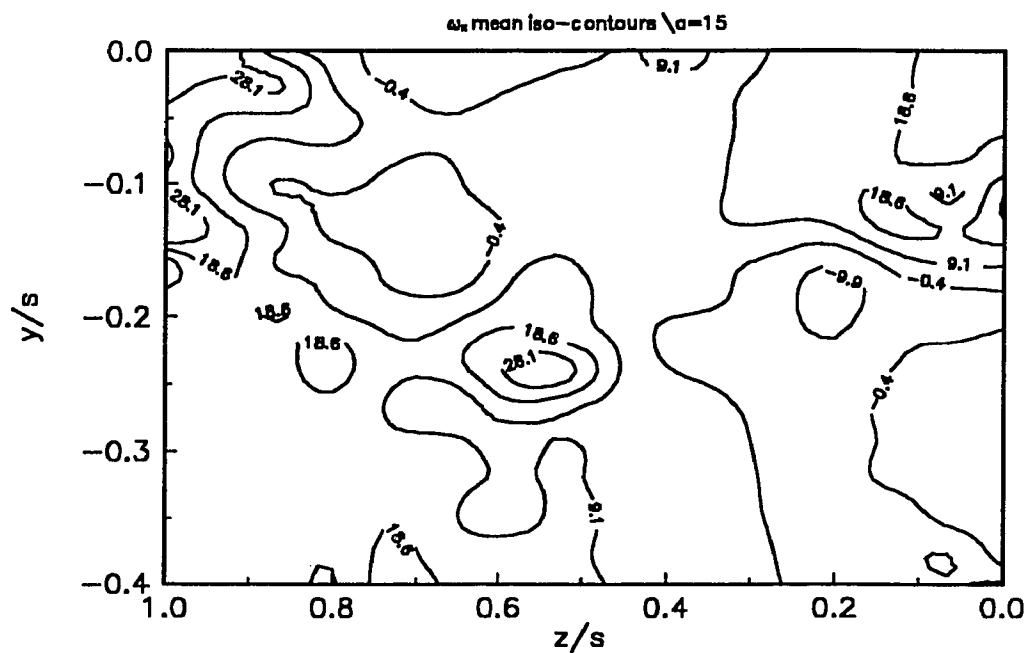


Figure 6.4.11. Contours of constant axial mean vorticity in a cross plane; $\alpha=15^\circ$.

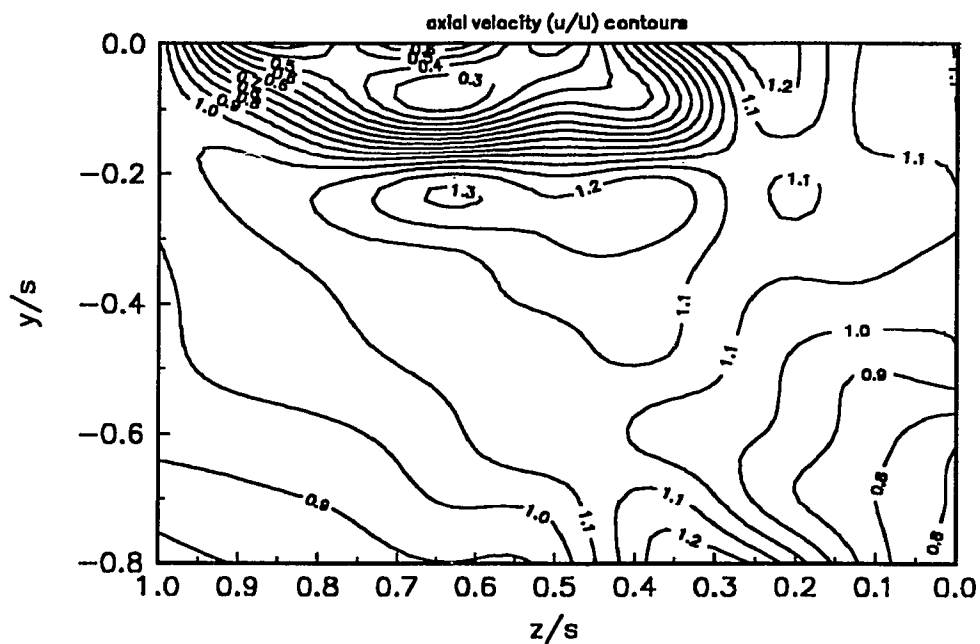


Figure 6.4.12. Iso-contours of mean axial velocity normalized by freestream velocity.

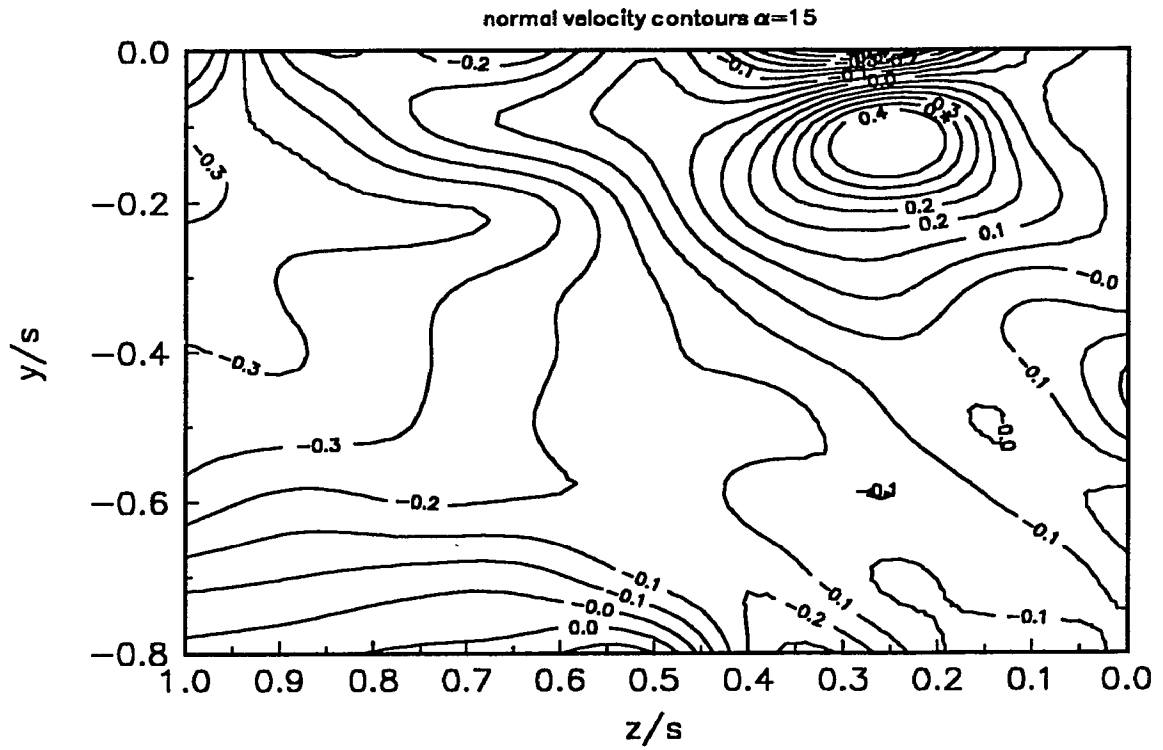


Figure 6.4.13. Iso-contours of normalized mean normal velocity in a cross plane; $\alpha=15^\circ$.

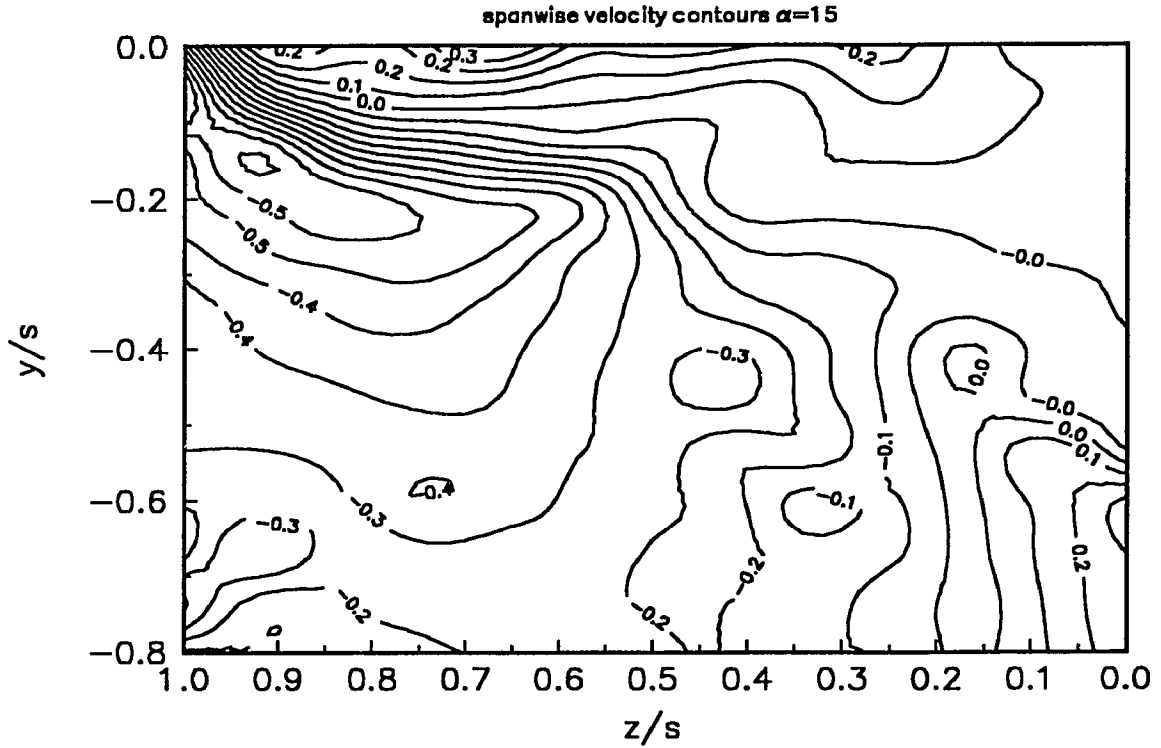


Figure 6.4.14. Iso-contours of normalized mean spanwise velocity.

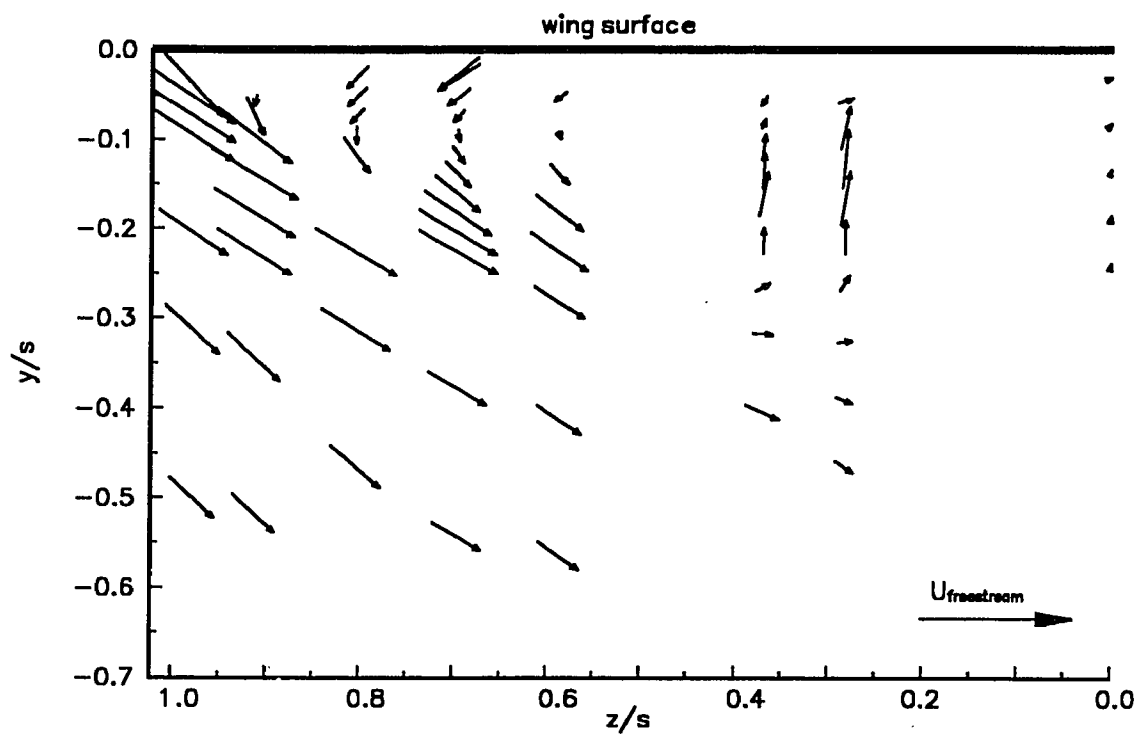


Figure 6.4.15. Velocity vector plot in crossflow plane; $\alpha = 15^\circ$.

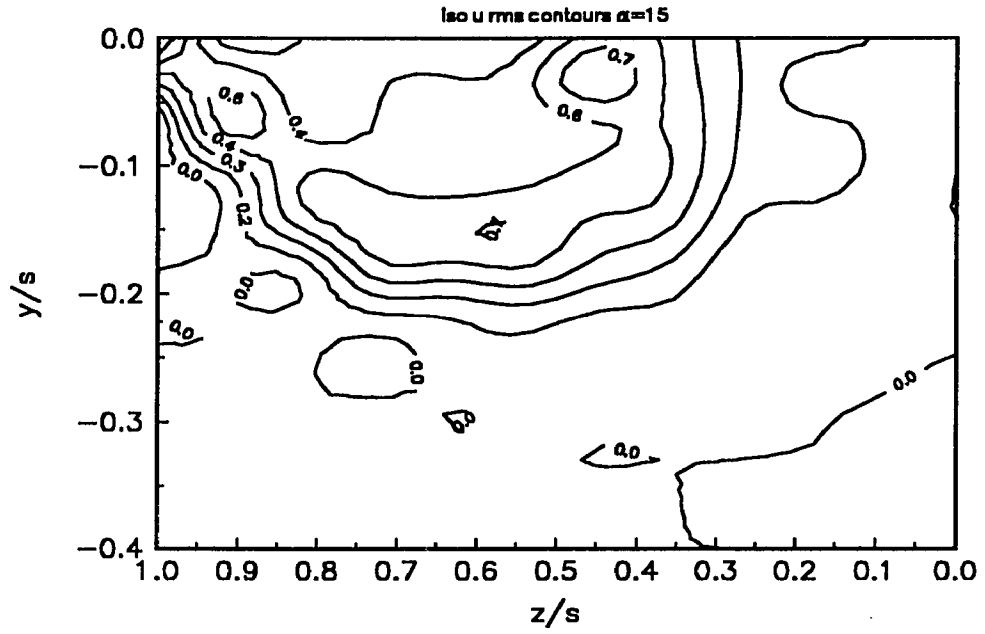


Figure 6.4.16. Iso-contours of fluctuating axial velocity u' in a cross plane; $\alpha=15^\circ$.

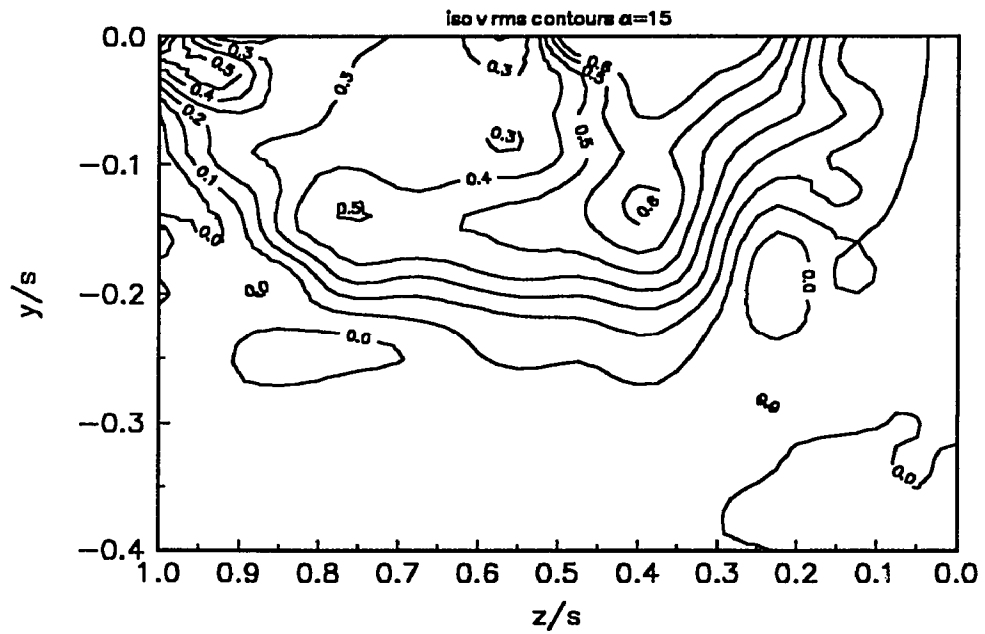


Figure 6.4.17. Iso-contours of fluctuating normal velocity v' ; angle of attack $\alpha=15$.

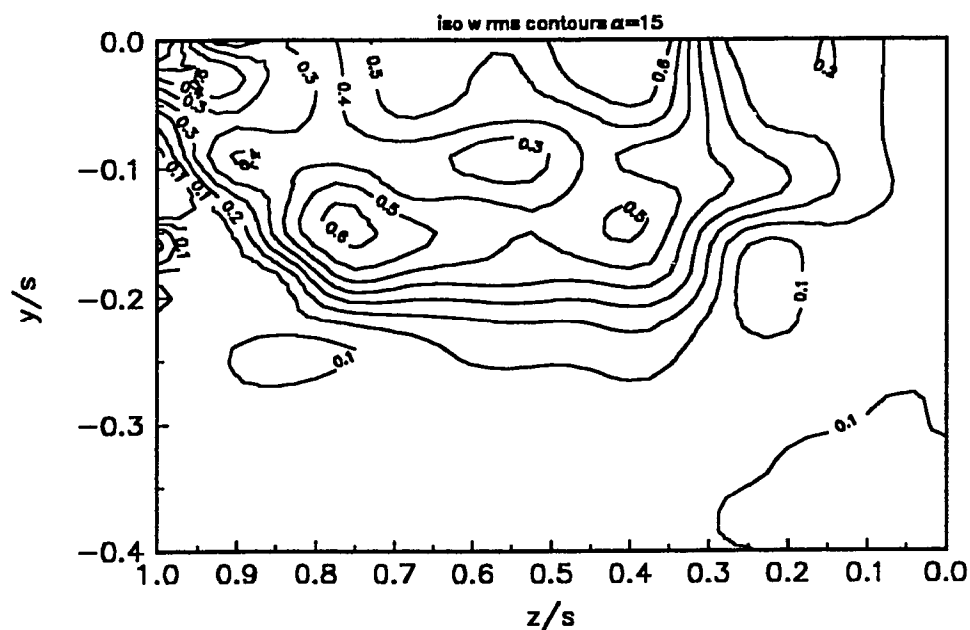


Figure 6.4.18. Iso-contours of fluctuating spanwise velocity w' in a cross plane; $\alpha=15^\circ$.

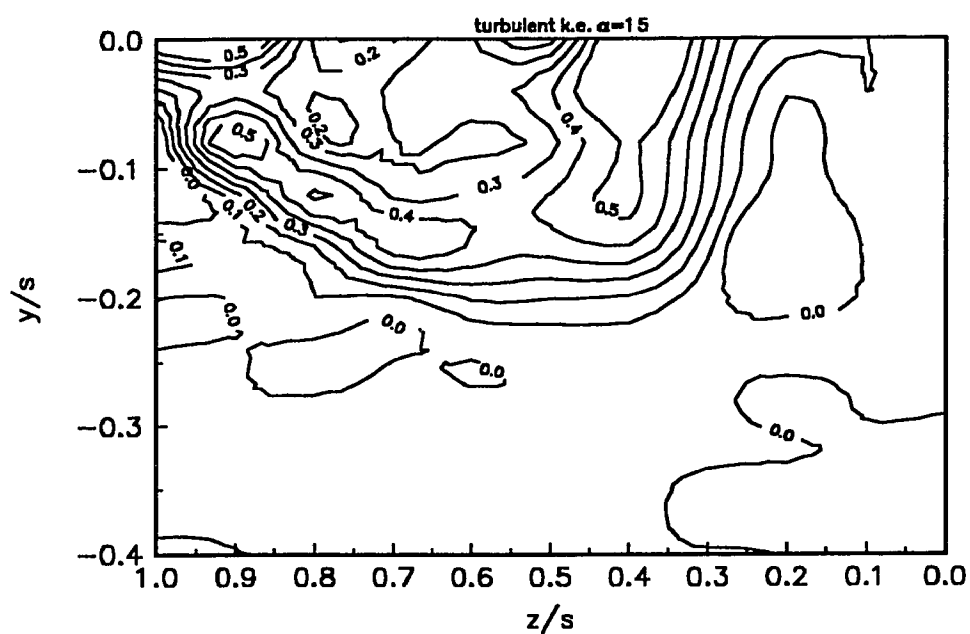


Figure 6.4.19. Iso-contours of turbulent kinetic energy.

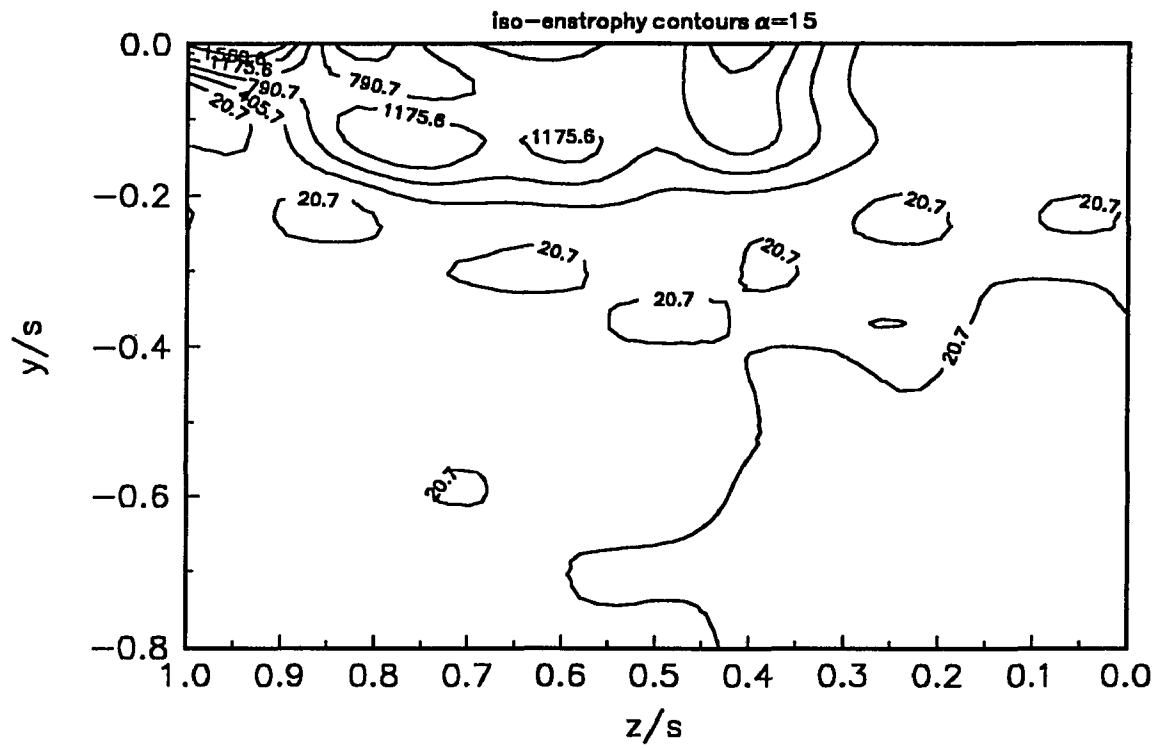


Figure 6.4.20. Iso-contours of normalized enstrophy in a cross plane; $\alpha=15^\circ$.

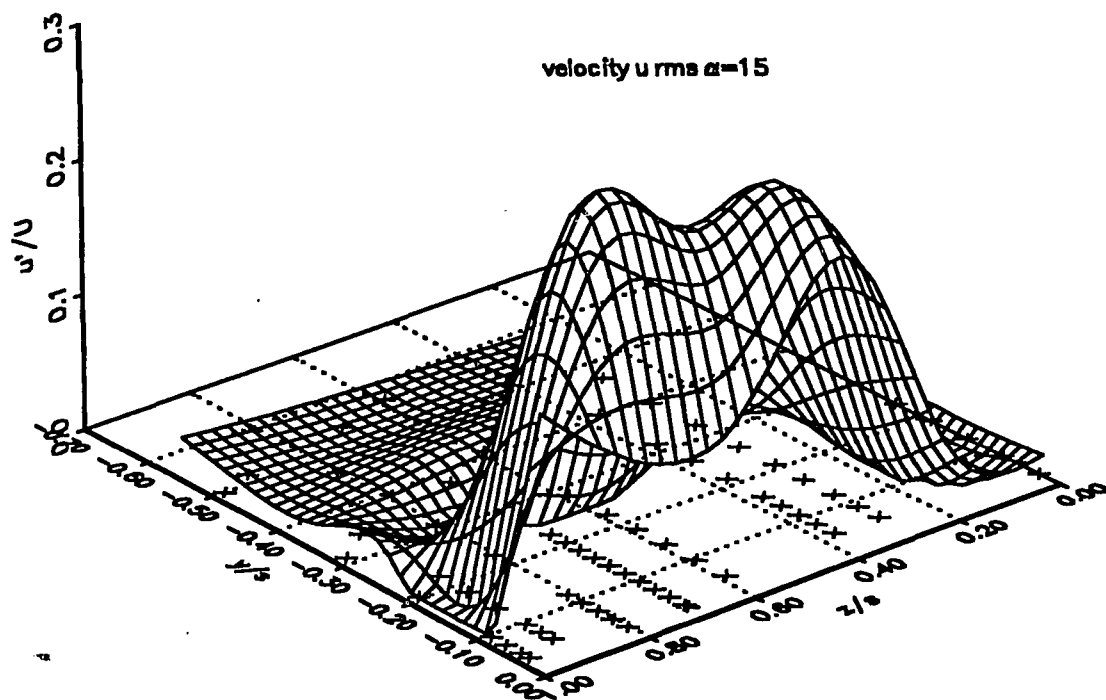


Figure 6.4.21. 3-d spline fitted surface plot of rms of axial velocity normalized by freestream velocity U ; angle of attack $\alpha = 15^\circ$.

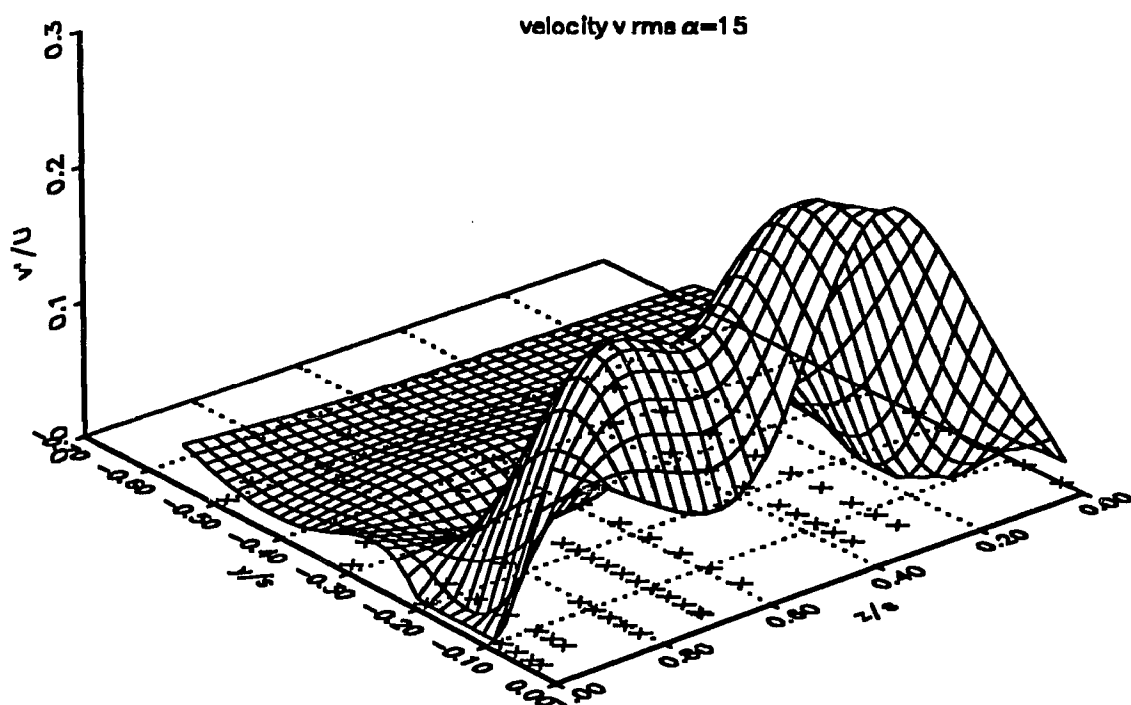


Figure 6.4.22. 3-d spline fitted surface plot of rms of normal velocity normalized by freestream velocity U ; angle of attack $\alpha=15^\circ$.

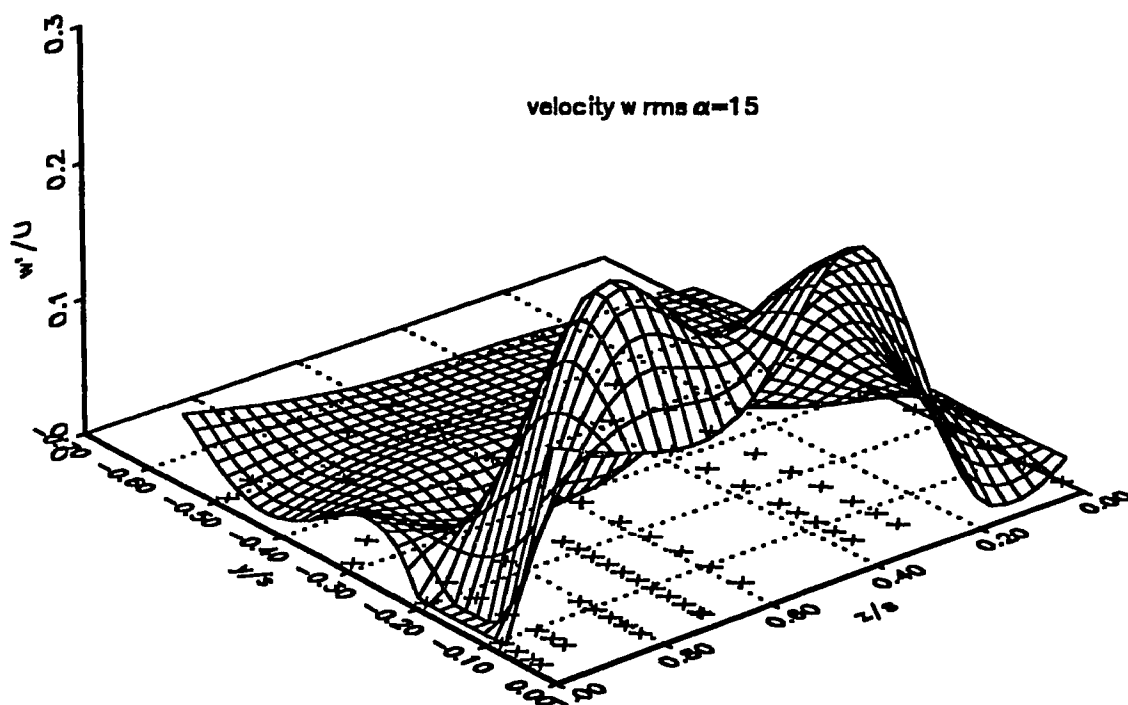


Figure 6.4.23. 3-d spline fitted surface of rms of spanwise velocity normalized by freestream velocity U ; angle of attack $\alpha=15^\circ$.

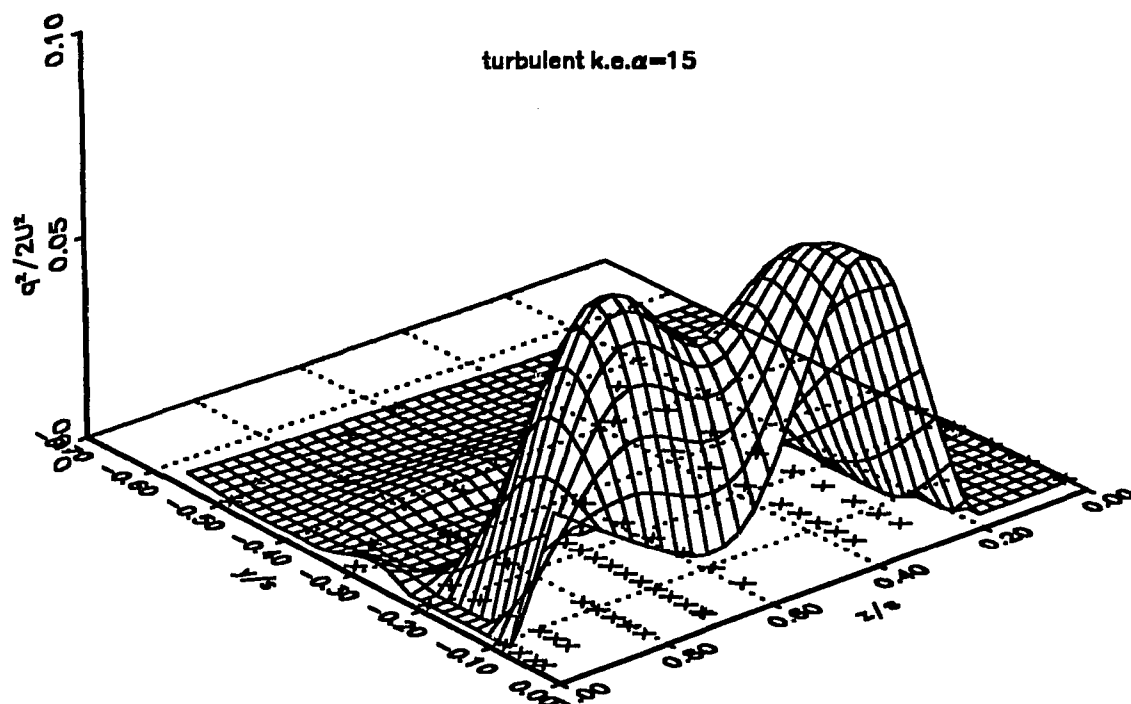


Figure 6.4.24. 3-d spline fitted surface plot of turbulent kinetic energy normalized by freestream velocity; angle of attack $\alpha=15^\circ$.

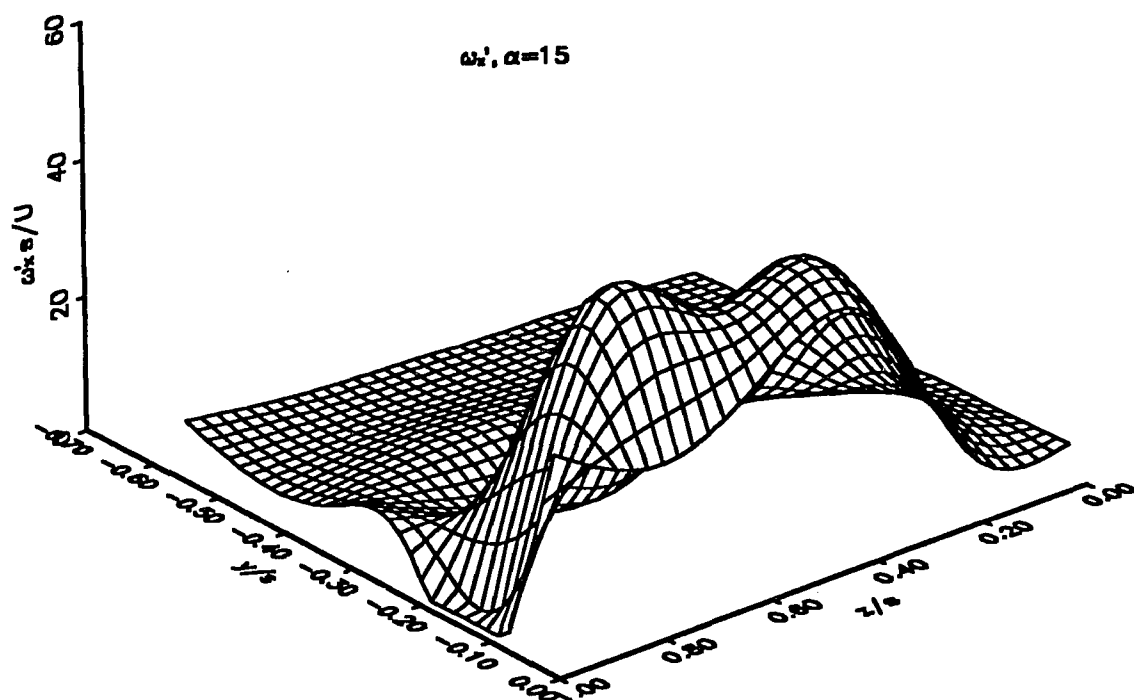


Figure 6.4.25. 3-d spline fitted surface plot of rms of axial vorticity normalized by semispan s and freestream velocity U .

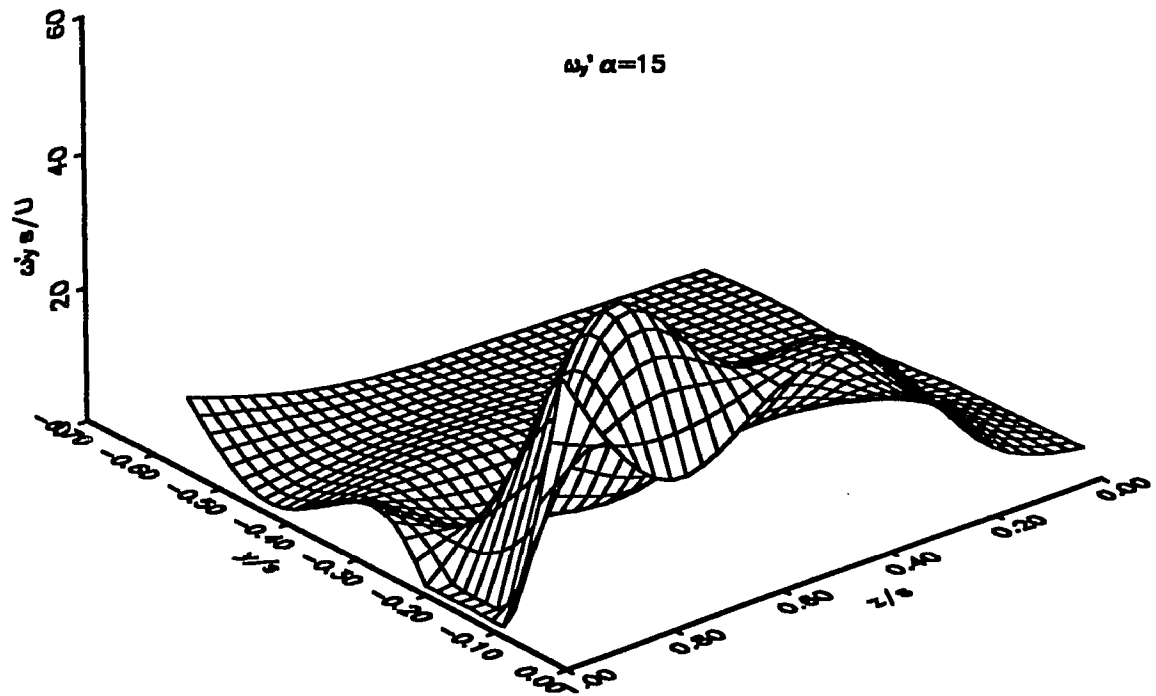


Figure 6.4.26. 3-d spline fitted surface plot of rms of normal vorticity scaled by semi-span s and freestream velocity U ; $\alpha=15^\circ$.

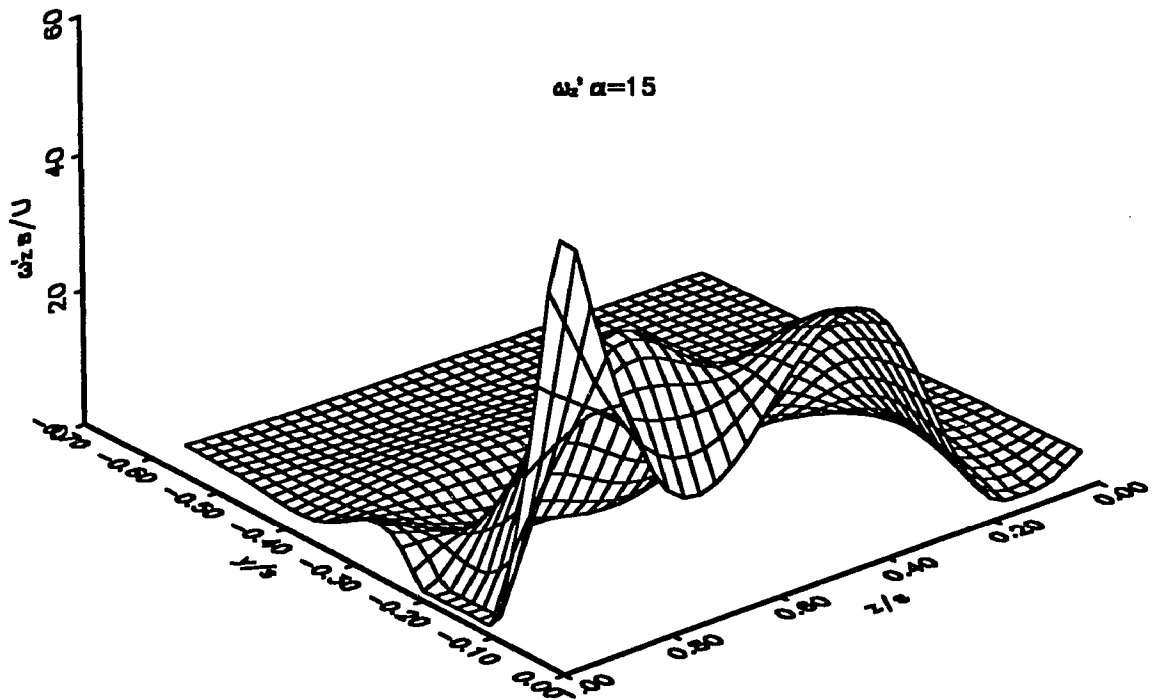


Figure 6.4.27. 3-d spline fitted surface plot of rms of spanwise vorticity normalized by semispan s and freestream velocity U ; angle of attack $\alpha=15^\circ$.

enstrophy $\alpha=15$

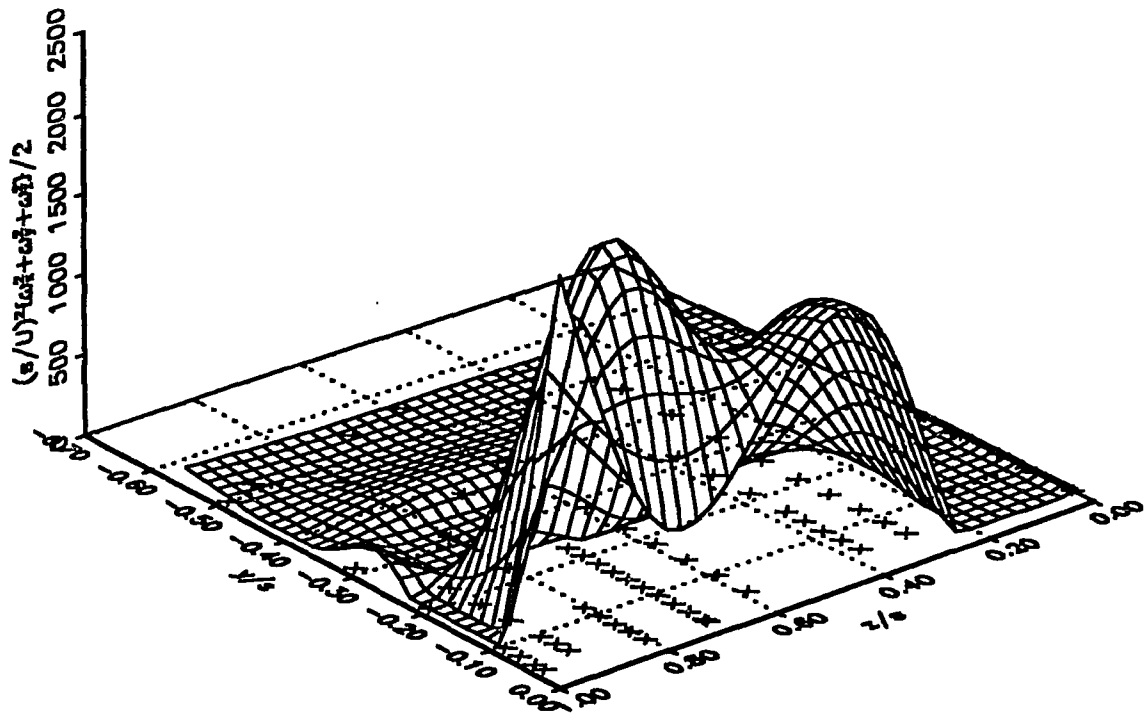


Figure 6.4.28. 3-d spline fitted surface plot of enstrophy normalized by semi-span s and freestream velocity U ; $\alpha=15^\circ$.

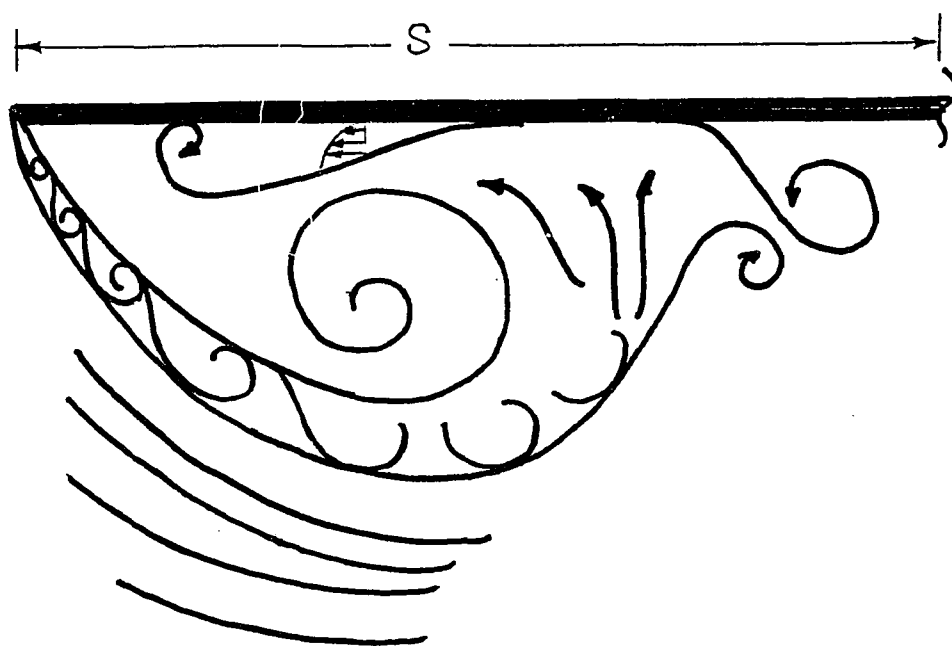


Figure 6.4.29. A sketch of the structure of vortex flow field deduced from the principal mean axial streamwise vorticity.

BIBLIOGRAPHY

- Alfredsson, P. H. and Johansson, A. V., 1984 "*On the Detection of Turbulence-generating Events*", J. Fluid Mech. **139**, p.325.
- Apostol, M., 1981 "*Calculus*", New York , McGraw Hill Inc.
- Andreopoulos, J., 1983 "*Improvements of the Performance of Triple Hot Wire Probes*", Rev. Sc. Instrum. **54**.
- Andreopoulos, J., 1981 "*Comparison Test of the Response to Pitch Angles of Some Digital Hot Wire Anemometry Techniques*", Rev. Sc. Instrum. **52**.
- Andreopoulos, J., Durst, F.; Zaric', Z., and Jovanovic, J., 1984 "*Influence of Reynolds number on Characteristics of Turbulent Wall Boundary Layers*", Exps. Fluids **2**, p. 7.
- Anderson, J. D. Jr., 1991 "*Fundamentals of Aerodynamics*", 2nd Edition, McGraw Hill, Inc., New York.
- Ashurst, W. T., Kerstein, A. R., Kerr, R. M. and Gibson, C. H., 1987 "*Alignment of Vorticity and Scalar Gradient with Strain Rate in Simulated Navier-Stokes Turbulence*", Phys. fluids, **30** (8).
- Ayoub, A., and McLachlan, B. G., 1987 "*Slender Delta Wing at High Angles of Attack-A Flow Visualization Study*", AIAA paper # 87-1230.
- Bakewell, H. P., Jr., and Lumley, J. L., 1967 "*Viscous Sublayer and Adjacent Wall Region in Turbulent Pipe Flow*", Phys. fluids, **10**.
- Balint, J., Wallace, J. M., Vukoslavcevic, P., 1991 "*The Velocity and Vorticity Vector Fields of a Turbulent Boundary Layer. Part 2 Statistical Properties.*", J. Fluid Mech., **228**, p. 53.
- Batchelor, G. K., 1951 "*Pressure Fluctuations in Isotropic Turbulence*", Proc. Camb. Phil. Soc. **47**, p. 359.
- Blackwelder, R. F. and Haritonidis, J. H., 1983 "*Scaling of the Bursting Frequency in Turbulent Boundary Layers*", J. Fluid Mech. **132**, p. 87.
- Blackwelder, R. F. and Kaplan, R. E., 1976 "*On the Wall Structure of the Turbulent Boundary Layer*", J. Fluid Mech. **76**, p. 89.

Blackwelder, R. F. and Eckelmann, H.; 1979 "*Streamwise Vortices Associated with the Bursting Phenomenon*", J. Fluid Mech, **94**, p. 577.

Bradshaw, P., 1971. "*Introduction to Turbulence and Its Measurements*", Pergamon Press.

Brodkey, R. S.; Wallace, J. M. and Lawalle, J., 1984 "*The Delta Conferences: A Discussion of Coherent Structures in Bounded Shear Flows*", Res. Found. Proj. 761061/711063, Rept. Ohio State University Research Foundation.

Brodkey, R. S.; Wallace, J. M., and Eckelmann, H., 1974 "*Some Properties of Truncated Signals in Bounded Shear Flows*", J. Fluid Mech. **63**. part 2. p. 209.

Brown G. L. and Thomas, A. S. W., 1977 "*Large Structure in a Turbulent Boundary Layer*", Phys. Fluids **20**, no. 10, p. 5243.

Chang P. H., Adrian, R. J. and Jones, B. G., 1983 "*Comparison Between Triple-Wire and x-wire Measurement Techniques in High Intensity Turbulent Shear Flows*", 8th Biennial Symposium on turbulence, University of Missouri-Rolla.

Chu, C. C., and Falco, R. E., 1986 "*A Vortex Ring/Viscous Wall Layer Interaction Model of the Turbulence Production Process Near Walls*", Proc. Tenth Symp. on Turbulence, University of Missouri-Rolla.

Coles, 1962.

Corino, E. R., and Brodkey, R. S., 1969 "*A Visual Investigation of the Wall Region in Turbulent Flow*", J. Fluid Mech., **37**, part I.

Corsin, S. and Kistler, A. L., 1954. NACA, TN-3133.

Eckelmann, H, Nychas, S. G., Brodkey, R. S. and Wallace, J. M., 1977 "*Vorticity and Turbulence Production in Pattern Recognized Turbulent Flow Structures*", Phys. Fluids Suppl. **20**, p. s225.

Elder, J. W., 1960 "*An Experimental Investigation of Turbulent Spots and Breakdown to Turbulence*", J. Fluid Mech. p. 235.

Er-El, J., and Yitzhak, Z., 1988 "*Experimental Examination of Leading Edge Suction Analogy*", J. Aircraft, **25**, No. 3.

Erickson, G. E., 1980 "*Vortex Flow Correlation*", Tech. Rept. AFWAL-TR-80-3143.

Ewing, and George, W. K., 1993. (submitted to Exps. Fluids)

- Falco, R. E.; 1980 *"The Production of Turbulence Near a Wall"*, AIAA paper 80-1356.
- Fink, P. T., and Taylor, J., 1967 *"Some Low Speed Experiments with 20 Degree Delta Wings"*, Aeronautical Research Council Reports and Memoranda, No. 3489, Part II.
- Fiedler, H. E., 1986 *"Coherent Structures"*, Advances in Turbulence, Proceedings of the First European Turbulence Conference, Lyon, France. Editors G. Comte-Bellot and J. Mathieu.
- Foss, J. F., and Wallace, J. M., 1989 *"The Measurement of Vorticity in Transitional and Fully Developed Turbulent Flows"*, In Advances in Fluid Mechanics Measurements (ed. M. Gad-el-Hak), Lecture Notes in Engineering, 45.
- Gad-el-Hak, M. and Blackwelder, R. F., 1987 *"Control of the Discrete Vortices from a Delta Wing"*, AIAA Journal, 25, No. 8.
- George, W. K. and Hussain, H. J., 1991 *"Locally Axisymmetric Turbulence"*, J. Fluid. Mech., 233, p.1.
- George, W. K., 1993. Private communication.
- Grass, A. J., 1971 *"Structural Features of Turbulent Flow Over Smooth and Rough Boundaries"*, J.Fluid Mech., 150, part 2, p. 233.
- Haritonidis, J. H., Gresko, S. K. and Breuer, K. S., 1988 *"Wall Pressure Peaks and Waves"*.
- Head, M. R. and Bandyopadhyaya, P., 1981 *"New Aspects of Turbulent Boundary Layer Structure"*, J.Fluid Mech. 107, p. 297.
- Her, J-Y, 1986 *"The Relation between Wall Pressure and the Flow Field in the Wall Region of a Turbulent Boundary Layer"*, Ph.D. Thesis, Department of Ocean Engineering, Massachusetts Institute of Technology.
- Hinze, J. O., 1959 *"Turbulence, an Introduction to Its Mechanism and Theory"* New York, McGraw Hill Inc .
- Honkan, A. and Andreopoulos, J., 1993 *"The Wall as Source or Sink of Vorticity in Two-Dimensional Turbulent Boundary Layer Flows"*, Symposium on Near Wall Turbulent Flows, Elsevier Science Publishers, R.M.C. So, Speziale and B. E. Launder editors.
- Jimenez, J., Moin, P., Moser, R. D. and Keefe, L. R., 1987 *"Ejection Mechanisms in the Sub-layer of a Turbulent Channel"*, Proceedings of the Summer program 1987, P. 37, Center for Turbulence Research, NASA/Stanford.

- Jorgensen, F. E., 1971 "*Directional Sensitivity of Wire and Fibre-film Probes*", DISA Information 11, 31-7.
- Kasagi, N., Sumitani, Y., Suzuki, Y. and Iida, O., October, 1993 "*On the Kinematics of the Structure of the Quasi-coherent Vortical Structure in Near Wall Turbulence*", Exp. Heat Transfer, Fluid Dynamics and Thermodynamics.
- Kastrinakis, E. G. and Eckelmann, H., 1983 "*Measurement of Streamwise Vorticity Fluctuations in a Turbulent Channel Flow*", J. Fluid Mech., 137, p. 165.
- Kim, J., Moin, P., and Moser, R., 1987 "*Turbulence Statistics in Fully Developed Channel Flow at low Reynolds Number*", J. Fluid Mech., 177, p. 133.
- Kim, J. and Antonia, R., 1993 "*Isotropy of the Small Scales of Turbulence at Low Reynolds Number*", J. Fluid Mech., 251, p. 219.
- Klebanoff, P. S., 1954 "*Characteristics of Turbulence in a Boundary Layer with Zero Pressure Gradient*", NACA, TN-3178.
- Klewicki, J. C., 1989 "*On the Interactions Between the Inner and Outer Region Motions in Turbulent Boundary Layers*", Ph.D. dissertation, Michigan State University, East Lansing, Michigan.
- Klewicki, J. C. and Falco, R. E., 1990 "*On Accurately Measuring Statistics Associated with Small-Scale Structure in Turbulent Boundary Layers Using Hot-wire Probes*", J. of Fluid Mech., 219, p. 119.
- Kline, S. J., and Robinson, S. K., 1988 "*Quasi-Coherent Structures in the Turbulent Boundary Layer: Part I. Status Report on Community-wide Summary of the Data*", Zoran P. Zaric' Memorial Seminar on Near Wall Turbulence, Dubrovnik, Yugoslavia.
- Kline, S. J., and Runstadler, P. W., 1959 "*Some Preliminary Results of Visual Studies on the Flow Model of the Wall Layers of the Turbulent Boundary Layer*", J. Appl. Mech., Trans. ASME, Ser.D., 26.
- Kline, S. J., and Meyer, K., A., 1961 "*A Visual Study of the Flow Model in the Later Stages of Laminar-Turbulent Transition on a Flat Plate*", Rept. MD-7, Thermosciences Div., Dept. Mech. Eng. Stanford Univ.
- Kline, S. J., Reynolds, W. C., Schraub, F. A., and Runstadler, P. W., 1967 "*The Structure of Turbulent Boundary Layer*", J. Fluid Mech. 30, p. 741.
- Kolmogorov, A. A., 1941 "*The Local Structure of Turbulence in Incompressible Viscous Fluid for Very Large Reynolds Numbers*", C.R.Akad. Sci. SSSR 30, p. 301.

- Kovasznyai, L. S. G., Kibens, V., and Blackwelder, R. F., 1970 "*Large-scale Motion in the Intermittent Region of a Turbulent Boundary Layer*", J. Fluid Mech. **41**, part 2, p. 283.
- Kreplin, H. P. and Eckelmann, H., 1979 "*Instantaneous Direction of the Velocity Vector in a Fully Developed Turbulent Channel Flow*", Phys. Fluids **22**, p. 1210.
- Lam, K., and Banerjee, S., 1992 "*On the Condition of Streak Formation in a Bounded Turbulent Flow*", Phy. Fluids A, **4**.
- Landahl, M. T., 1984. Z. Flugwiss. Weltraumforsch, **8**, 4, 233.
- Lee, M. J., Kim, J., and Moin, P., 1987 "*Turbulence Structure at High Shear Rate*", Proceedings of the Sixth Symposium on Turbulent Shear Flows, Toulouse, France.
- Lee, M. and Ho, C. M. 1989 "*Vortex Dynamics of Delta Wings*", Lecture notes in Engg. Frontiers in Experimental fluid Mechanics, **46**.
- Lekakis, I. C., Adrian, R. J. and Jones B. G., 1989 "*Measurement of Velocity Vectors with Orthogonal and Non-orthogonal Triple Sensor Probes*", Exp. Fluids, **7**, p. 228.
- Lighthill, M. J., 1963 "*Boundary Layer Theory in Laminar Boundary Layers*", (ed. Rosenhead) Oxford University Press.
- Lowson, M. V., 1990 "*Visualization Measurements of Vortex Flows*", J. Aircraft **28**, No. 5.
- Lyman, F. A., 1990 "*Vorticity Production at a Solid Boundary*", Appl. Mech. Rev., **43**(8), p. 157.
- Lu, L. J., and Smith, C. R., 1988 "*Image Processing of Hydrogen Bubble Flow Visualization for Quantitative Evaluation of Hairpin-type Vortices as a Flow Structure of Turbulent Boundary Layers*", Tech. Report, FM-14, Lehigh University.
- Mansour, N. N., Kim, J. and Moin, P., 1988 "*Reynolds Stress Dissipation Rate Budgets in a Turbulent Channel Flow*", J. Fluid Mech., **194**, p. 15.
- Maskell, E. C., 1962 "*Some Recent Developments in the Study of Leading Edge Vortices*", Proceedings 3rd Congress ICAS, Spartan Books.
- Mehta, R. D., and Cantwell, E. R., Sept 7-9, 1987 "*Properties of Half Delta Wing Vortex*", Paper presented at the 6th Turbulent Shear Flows meeting, France.
- Morrison, J. F., Subramanian, C. S. and Bradshaw, P., 1992 "*Bursts and the Law of the Wall in Turbulent Boundary Layers*", J. Fluid Mech, **241**, p. 75.

- Panton, R. L., 1984. *"Incompressible Flow"*, New York., John Wiley and Sons.
- Payne, F. M., 1987 *"The Structure of Leading Edge Vortex Flows Including Vortex Breakdown"*, Ph.D. Dissertation, University of Notre Dame, Notre Dame, Indiana.
- Perry, A. E., Lim, T. T. and Teh, E. W., 1981 *"A Visual Study of Turbulent Spots"*, J.Fluid Mech, **104**, p. 387.
- Polhamus, E. C., 1966 *"A Concept of the Vortex Lift of Sharp-edge Delta Wings Based on the Leading-Edge Suction Analogy"*, NASA Tech Note No. TN-D-3767.
- Polhamus, E. C., 1971 *"Predictions of Vortex-Lift Characteristics by Leading Edge Suction Analogy"*, J. Aircraft, **8**, No.4.
- Rashidi, M., and Banerjee, S., 1990 *"The Effect of Boundary Conditions and Shear Rate on Streak Formation and Breakdown in Turbulent Channel Flows"*, Phys. Fluids A, **2**.
- Robinson, S. K., 1991 *"Coherent Motions in the Turbulent Boundary Layer"*, Ann. Rev. Fluid Mech.
- Robinson, S. K., Kline, S. J., and Spalart, P. R., 1988 *"Quasi-Coherent Structures in the Turbulent Boundary Layer:Part II. Verification and New Information from a Numerically Simulated Flat-Plate Layer"*, Zoran P. Zaric' Memorial Seminar on Near Wall Turbulence, Dubrovnik, Yugoslavia.
- Rizzi, A., and Purcell, C., 1987 *"On the Computation of Transonic Leading Edge Vortices using Euler Equations"*, J. Fluid Mech., **181**.
- Runstadler, P. W., Kline, S. J., and Reynolds, W. C., 1963 *"An Experimental Investigation of the Flow Structures of the Turbulent Boundary Layer"*, Rept. MD-8, Thermosciences Div., Dept. Mech. Eng. Stanford University.
- Schewe, G., 1983. *"On the Structure and Resolution of Wall-pressure Fluctuations Associated with Turbulent Boundary-layer Flow "*, J. Fluid Mech., **134**, p.311.
- Schraub, F. A., and Kline, S. J., 1965 *"A Study of the Turbulent Boundary Layer with and without Longitudinal Pressure Gradient"*, Rept. MD-12. Thermosciences Div., Dept. Mech. Eng. Stanford University.
- Shih, H. C., Lee, M. and Ho, C. M., 1987 *"Control of Separated Flow on a Symmetric Airfoil"*, Proc. of IUTAM conf., Bangalore, India.
- Skow, A. M. and Titiriga, A., 1978 *"A Survey of Analytical and Experimental Techniques to Predict Aircraft Dynamic Characteristics at High Angles of Attack"*, AGARD-Cp 235, No. 19.

Smith, C. R., and Metzler, S. P., 1983 "*The Characteristics of Low-Speed Streaks in the Near-Wall Region of a Turbulent Boundary Layer*", J. Fluid Mech., **129**.

Spalart, P. R., 1988 "*Direct Simulation of a Turbulent Boundary Layer up to $R_\theta = 1410$* ", J. Fluid Mech., **187**, p. 61.

Squire, L. C., 1961 "*An Experimental Investigation of the Characteristics of some Plane and Cambered 65° Delta wings at Mach Numbers from 0.7 to 2*", ARC Reports and Memoranda No. 3305.

Tennekes, H and Lumley, J. L., 1972. "*A First Course in Turbulence*", Boston, MA., MIT press .

Theodoresen, T., 1952 "*Mechanism of Turbulence*", Proc. 2nd Midwestern conference on Fluid Mechanics, Ohio State University, Columbus, Ohio.

Tiederman, W. G., Luchik, T. S., and Bogard, D. G., 1985 "*Wall-layer Structure and Drag Reduction*", J. Fluid Mech., **156**, p. 419.

Vrettos, N., "*Experimentelle Untersuchung der Ausbreitung von Külturmschwaden im Windkanal*", Studienarbeit, University of Karlsruhe.

Vukoslavcevic, P., Wallace, J. M. and Balint, J., 1991 "*The Velocity and Vorticity Vector Fields of a Turbulent Boundary Layer. Part 1 Simultaneous Measurement by Hot-wire Anemometry.*", J. Fluid Mech., **228**, p. 53.

Wallace, J. M., 1986 "*Methods of Measuring Vorticity in Turbulent flows*", Exps. fluids **4**.

Wallace, J. M, Balint, J. and Ong, L., 1992 "*An Experimental Study of Helicity Density in Turbulent Flows*", Phy. Fluids, A. **4** (9).

Wei, T and Willmarth, W. W., 1989 "*Reynolds Number Effects on the Structure of a Turbulent Channel Flow*", J. Fluid Mech., **204**, p. 57.

Willmarth, W. W., 1985 "*Geometric Interpretation of the Possible Velocity Vectors Obtained with Multiple Sensor Probes*", Phy. Fluids, **28** (2), p. 462.

Willmarth, W. W. and Bogar, J. J., 1977 "*Survey and New Measurements of the Turbulent Structure of Near the Wall*", Phy. Fluids, **20**, p. s9.

Willmarth, W. W., and Lu, S. S., 1972 "*Structure of the Reynolds Stress Near the Wall*", J. Fluid Mech., **55**, part I.

Wyngaard, J. C., 1969 "*Spatial Resolution of the Vorticity Meter and Other Hot-wire Arrays*", J.of Phys. E:Sci.Instrum. series 2, 2.

Zohar, Y., and Er-El, J., 1987 "*Influence of the Aspect Ratio on the Aerodynamics of the Delta Wing at High Angle of Attack*", J. Aircraft, 25, No. 3