



Measurements of supersonic boundary layer turbulence with a dynamic pitot probe
by Terrance Gerard Tritz

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Mechanical Engineering
Montana State University
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Abstract:

The use of a dynamic pitot probe to measure fluctuating pitot pressure of supersonic flow was investigated. Data were taken at three wind tunnel positions and 20 $Re\theta$ values. Mean flow measurements were taken to characterize the flow. The mean flow data were found to be consistent with previous data taken in the wind tunnel. An $Re\theta$ effect was also found. The flow appeared to have been in the transition region based on the mean flow measurements and a law of the wall analysis. Wideband RMS velocity measurements were obtained from the fluctuating pressure measurements with the dynamic pitot probe. An $Re\theta$ effect was also found for the wideband RMS data. The wideband measurements also supported the conclusion of transitional flow drawn from the mean flow data. Intermittency measurements of the boundary layer showed that the boundary layer thickness could differ depending on whether a time-average method or an intermittency method is used to define the edge of the boundary layer. Spectral measurements were made at the highest $Re\theta$ value of 2073. The dissipation spectra, in general, agreed with Pao's theory with much less scatter than previously experienced. The dissipation function was able to be measured precisely compared to previous methods which were unacceptable due to scatter. The velocity spectra approached the universal spectrum in a way dependent on the distance from the tunnel wall. Accurate measurement of signals at frequencies greater than 1 Megahertz in the boundary layer were obtained.

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TURBULENCE WITH A DYNAMIC PITOT PROBE**

by

Terrance Gerard Tritz

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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TABLE OF CONTENTS

	<u>Page</u>
LIST OF TABLES	vii
LIST OF FIGURES	viii
NOMENCLATURE	xii
ABSTRACT	xiv
1. INTRODUCTION	1
2. EXPERIMENTAL SETUP	5
Facilities	5
Wind Tunnel	5
Flow Conditions	6
Mean Flow Setup	6
Pitot Tube	6
Data Acquisition System	8
Dynamic Pitot Probe Setups	8
Dynamic Pitot Probe	8
Data Acquisition Systems	11
3. EXPERIMENTAL RESULTS	17
Mean Flow Measurements	17
Introduction	17
Mean Flow Data Reduction	17
Mean Flow Results	19
Law of the Wall Analysis	21
Coefficient of Friction	22
Wideband RMS Measurements	24
Data Reduction	24
Wideband RMS Results	24
Intermittency Measurements	26
Introduction	26
Results	28

TABLE OF CONTENTS—Continued

	<u>Page</u>
3. EXPERIMENTAL RESULTS (continued)	
Power Spectrum Measurements	31
Introduction	31
Fast Fourier Transform Data Reduction	31
Universal Spectrum Data Reduction	36
Universal Spectrum Results	45
4. CONCLUSIONS	62
Mean Flow	62
Wideband Measurements	62
Spectral Analysis	63
REFERENCES CITED	64
APPENDICES	67
Appendix A – Boundary Layer Data Conversion Program	68
Appendix B – Law of the Wall Program	77
Appendix C – Spectral Analysis Program	80
Appendix D – Noise Removal and Integrand Calculation Program	85
Appendix E – Spectral Non-Dimensionalization Program	87

LIST OF TABLES

Table	<u>Page</u>
1. Comparison of FFT Measurements with RMS Meter	35

LIST OF FIGURES

Figure	Page
1. Test Section of MSU Supersonic Wind Tunnel	7
2. Major Features of the DPP	9
3. Electronic Circuit used with DPP	11
4. Oscilloscope Amplication	13
5. Setup of DPP Data Acquisition System	16
6. Boundary Layer Velocity Profiles	20
7. Velocity at the Midpoint of the Boundary Layer	20
8. Law of the Wall Profiles	23
9. Comparison of C_f with Turbulent Datum and Theory	23
10. Velocity RMS Fluctuation Levels	25
11. Velocity RMS Fluctuation Levels at $y/\delta = .5$	25
12. Typical Output from the Intermittency Meter	27
13. Comparison of Two Methods for Boundary Layer Thickness Measurement	29
14. Intermittency Level Dependence on y/δ	30
15. Comparison of Noise Measurements	34
16. RMS Voltage Spectrum at $y/\delta = .091$	39
17. Integrant of Dissipation Function at $y/\delta = .091$	39
18. RMS Voltage Spectrum at $y/\delta = .496$ (# 1)	40

LIST OF FIGURES—Continued

Figure	Page
19. Integrand of Dissipation Function at $y/\delta = .496$ (# 1)	40
20. RMS Voltage Spectrum at $y/\delta = .496$ (# 2)	41
21. Integrand of Dissipation Function at $y/\delta = .496$ (# 2)	41
22. RMS Voltage Spectrum at $y/\delta = .738$	42
23. Integrand of Dissipation Function at $y/\delta = .738$	42
24. RMS Voltage Spectrum at $y/\delta = .981$	43
25. Integrand of Dissipation Function at $y/\delta = .981$	43
26. RMS Voltage Spectrum in the Freestream	44
27. Integrand of Dissipation Function in the Freestream	44
28. Incompressible Spectra Compared to Universal Spectrum	48
29. Re_λ Comparison	48
30. Kolmogoroff Wave Number	49
31. Microscale Comparison	49
32. Dissipation Function Comparison	50
33. Wideband Velocity RMS Fluctuations	50
34. Non-Dimensional Spectrum at $y/\delta = .091$	51
35. Non-Dimensional Spectrum at $y/\delta = .131$	51
36. Non-Dimensional Spectrum at $y/\delta = .172$	52
37. Non-Dimensional Spectrum at $y/\delta = .212$	52

LIST OF FIGURES—Continued

Figure	Page
38. Non-Dimensional Spectrum at $y/\delta = .253$	53
39. Non-Dimensional Spectrum at $y/\delta = .293$	53
40. Non-Dimensional Spectrum at $y/\delta = .334$	54
41. Non-Dimensional Spectrum at $y/\delta = .374$	54
42. Non-Dimensional Spectrum at $y/\delta = .415$	55
43. Non-Dimensional Spectrum at $y/\delta = .445$	55
44. Non-Dimensional Spectrum at $y/\delta = .496$ (# 1)	56
45. Non-Dimensional Spectrum at $y/\delta = .496$ (# 2)	56
46. Non-Dimensional Spectrum at $y/\delta = .536$	57
47. Non-Dimensional Spectrum at $y/\delta = .576$	57
48. Non-Dimensional Spectrum at $y/\delta = .698$	58
49. Non-Dimensional Spectrum at $y/\delta = .738$	58
50. Non-Dimensional Spectrum at $y/\delta = .779$	59
51. Non-Dimensional Spectrum at $y/\delta = .860$	59
52. Non-Dimensional Spectrum at $y/\delta = .900$	60
53. Non-Dimensional Spectrum at $y/\delta = .981$	60
54. Comparison of Two Spectra taken at $y/\delta = .496$	61
55. Reynolds Number Dependence of the Velocity Spectrum at a Low Wavenumber	61
56. Boundary Layer Data Conversion Program	69

LIST OF FIGURES—Continued

Figure	<u>Page</u>
57. Law of the Wall Program	78
58. Spectral Analysis Program	81
59. Noise Removal and Integrand Calculation Program	86
60. Spectral Non-Dimensionalization Program	88

NOMENCLATURE

a	constant for law of the wall calculations
a.f.	amplification factor
b	constant for law of the wall calculations
C_f	coefficient of friction
d.c.	direct current
f	frequency
H	frequency dependent variable for Fourier transform
h	time dependent variable in Fourier transform
I_u	integral within the dissipation function
i	square root of -1
k	wavenumber
M	Mach number
m	variable used in Fourier Transform (value = 0 to $N - 1$)
N	number of points taken in each waveform
n	variable used for summation in Fourier Transforms
P	pressure
R	gas constant
Re	Reynolds number
RMS	root mean square
s	sensitivity coefficient
T	temperature

NOMENCLATURE—Continued

t	time
u	velocity
y	position from wall
δ	boundary layer thickness
δ_I	boundary layer thickness based on intermittency
ϵ	dissipation function
γ	specific heat ratio
λ	velocity microscale
ρ	density
θ	momentum thickness
ν	kinematic viscosity
ϕ	non-dimensional power spectrum
π	3.14159...
∞	infinity
$()_2$	condition after normal shock
$()_0$	isentropic stagnation property
$()_e$	boundary layer edge condition
$()_K$	Kolmogoroff property
$()_P$	stagnation property after normal shock
$()_w$	property at wall
$()^+$	law of the wall variable
$()'$	RMS quantity
$\overline{()}$	property transformed to the incompressible plane

ABSTRACT

The use of a dynamic pitot probe to measure fluctuating pitot pressure of supersonic flow was investigated. Data were taken at three wind tunnel positions and 20 Re_θ values. Mean flow measurements were taken to characterize the flow. The mean flow data were found to be consistent with previous data taken in the wind tunnel. An Re_θ effect was also found. The flow appeared to have been in the transition region based on the mean flow measurements and a law of the wall analysis. Wideband RMS velocity measurements were obtained from the fluctuating pressure measurements with the dynamic pitot probe. An Re_θ effect was also found for the wideband RMS data. The wideband measurements also supported the conclusion of transitional flow drawn from the mean flow data. Intermittency measurements of the boundary layer showed that the boundary layer thickness could differ depending on whether a time-average method or an intermittency method is used to define the edge of the boundary layer. Spectral measurements were made at the highest Re_θ value of 2073. The dissipation spectra, in general, agreed with Pao's theory with much less scatter than previously experienced. The dissipation function was able to be measured precisely compared to previous methods which were unacceptable due to scatter. The velocity spectra approached the universal spectrum in a way dependent on the distance from the tunnel wall. Accurate measurement of signals at frequencies greater than 1 Megahertz in the boundary layer were obtained.

CHAPTER 1

INTRODUCTION

Currently, more knowledge is needed to understand turbulent and transitional boundary layers in supersonic flows. Design of supersonic vehicles is one area that requires more information on the friction and heat transfer characteristics of turbulent and transitional flows.

Essential to the understanding of these flows are the wideband fluctuation levels which enter the equations of motion as unpredictable unknowns. Numerous studies have been made of low-speed wideband fluctuation levels in turbulent boundary layers but data are very scarce at high speeds. The effect of Mach number on fluctuation levels in the high-speed boundary layer was investigated by Laderman and Demetriades [1]. They studied data from several sources whose data covered the edge Mach number range 0 to 9.4 and was measured mainly with the use of hot-wire anemometers and found that there was a Mach number effect on the fluctuation levels.

Owen, et al [2] also studied the effect of unit Reynolds number ($\equiv u_e/\nu_e$) on fluctuation levels in transitional boundary layers at $M = 7$ using a film anemometer technique. They used the level of film voltage fluctuations to study qualitatively the transition "history" of the boundary layer.

Also important are the spectral characteristics of these boundary layers. Much work has been done on the velocity spectrum of low speed turbulent boundary layers, for example Pao [3] and Uberoi and Freymuth [4]. Demetriades and

Martindale [5], [6] have reported work on the supersonic and hypersonic turbulent boundary layer spectra with Mach numbers from 3 to 9.4, using hot-wire anemometers. They found that the non-dimensional power spectra followed low speed theory which included a Reynolds number dependence. Very little work has been done on the fluctuation spectra in supersonic transitional boundary layers.

The major difficulty of the wideband measurements is that none of the work has determined if there is any systematic Re_θ effect. The data in [1] did show a Mach number effect but does not investigate the effect of Re_θ . To generalize to any boundary layer a Re_θ dependence needs to be found.

Reference [2] presented the evolution of fluctuations in the transition zone. This work did not involve any investigation of an Re_θ effect. It also did not involve any quantitative measurement of velocity fluctuations or power spectra. Instead it used the film voltage fluctuations only to show where the transition region occurred. Therefore very little quantitative knowledge of the wideband fluctuations exists in the transition region.

The hot-wire anemometer, which is used for most velocity fluctuation measurements, has several difficulties. First, in all cases the hot-wire frequency response limitations require complicated mathematical corrections to the hot-wire signals. This affects both the wideband and frequency-dependent measurements through the introduction of errors.

Second, due to the frequency limitations mentioned and the noise of the system required to measure the hot-wire signals, the highest frequency signal capable of being accurately measured by a hot-wire anemometer is approximately 600 kilohertz according to [1]. This limit on frequency also affects the dissipation spectra. Due to noise problems, [1] reported severe difficulties in measuring the spectrum at high frequencies. In the same reference the dissipation spectrum, needed to

express the spectrum in universal form, was shown to be almost impossible to measure with the hot-wire anemometer at high speeds. In fact, in [5] and [6] there were several dissipation spectra which did not return to zero, as they should at high frequencies. In this case the dissipation function, which is the integral of the dissipation spectrum, could not be computed from the data without major assumptions.

The third problem in high-speed flows is that the hot-wire anemometer is extremely fragile. This can cause long delays in experiments and require that several hot-wire anemometers are calibrated in advance of any experiment.

A dynamic pitot probe was chosen here as the best probe to eliminate the disadvantages of the hot-wire anemometer. Not only was this dynamic pitot probe durable but its frequency range extended to at least 1.5 Megahertz. This frequency range enabled measurement at frequencies much higher than would have been possible with the hot-wire anemometer. Because this probe had such good frequency response, no complex mathematical corrections were needed to measure spectra at high frequencies.

With the dynamic pitot probe, the goal was to make fluctuation measurements and compare the measurements with past data where possible. Since a new probe was involved its readings must be consistent with previous turbulence data. Mean flow data taken at the same time in the transition zone should also be consistent with the mean flow measured previously in the fully turbulent boundary layer. With such measurements, characterization of the transitional supersonic boundary layer and its turbulence is possible including a Re_θ effect.

In addition to characterizing the supersonic boundary layer in general, the dynamic pitot probe had unique promise in measuring the high frequency turbulence components. This ability raised the possibility of obtaining dissipation spectra and

dissipation functions accurately for the first time ever in high-speed flows. With this possibility, the development of the transition zone non-dimensional spectra and their relation to the universal turbulent spectrum could be observed.

CHAPTER 2

EXPERIMENTAL SETUP

Facilities

Wind Tunnel

All of the experimental work was performed in the Montana State University Wind Tunnel (SWT). The SWT uses air as the working fluid and has a nominal Mach number of 3 in the test section. The unit Reynolds number ranges from 48,000 to 140,000 per inch. For a more detailed description of this facility refer to Drummond et al [7].

In order to achieve the goals mentioned in Chapter 1, the regions in the wind tunnel with transitional or turbulent boundary layers had to be found. References [7] and [8] showed that stagnation pressures between 300 and 400 torr would cause the onset of transition in the floor boundary layer of the wind tunnel test section. The further downstream the measurements were made, the lower the stagnation pressure needed for a transitional boundary layer.

Based on this information, the region chosen for measurement of the boundary layer was the farthest downstream position in the wind tunnel test section within the range of movement of the dynamic pitot probe.

In order to achieve as wide a range of Re_θ ($\equiv \frac{u_e \theta}{\nu_e}$) as possible, three positions in the test section were chosen for boundary layer measurements. Also

approximately seven stagnation pressures were chosen to help vary Re_θ . The total number of pressures at any position depended on the wind tunnel's ability to maintain supersonic flow. Since the combination of positions and total pressures would give 21 Re_θ 's only one total temperature was used.

Flow Conditions

The three positions of the SWT floor chosen for boundary layer measurements were $x = .4, 1.6$ and 2.9 inches as measured from the front of the extension block seen in Figure 1 reproduced from [7] which shows the test section of the SWT. The free stream total temperature was maintained at a nominal 100 degrees Fahrenheit and the free stream total pressure was varied from 600 to 430 torr in increments of 20 or 30 torr. The total temperature and pressure were recorded for later use in data reduction. The range of Re_θ was 1016 to 2073 for these conditions.

Mean Flow Setup

Pitot Tube

A .005 inch pitot tube was used to make the mean flow measurements in the boundary layer. The time-average streamwise velocity (u), local Mach number and local static temperature were the main characteristics measured. A Kulite XTH-1-190-5A pressure transducer was inside the pitot tube housing and converted the pitot pressure to a d.c. voltage. The smallest boundary layer thickness measured was .146 inches based on 99 percent of the edge velocity. This gave a minimum resolution, based on the ratio of the pitot tube diameter to the thinnest boundary layer, for the pitot tube of .034.

0

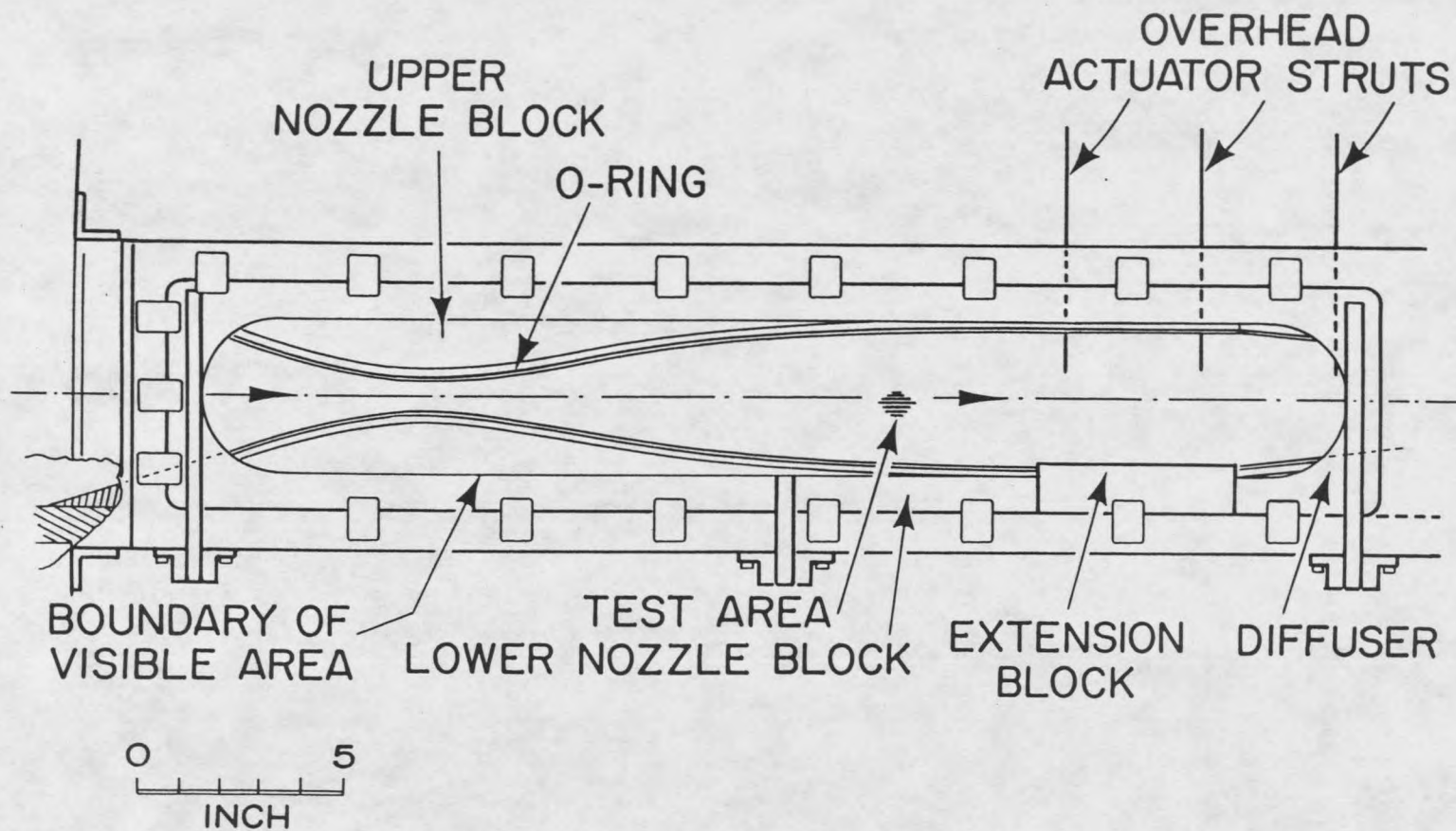


Figure 1. Test Section of MSU Supersonic Wind Tunnel.

Data Acquisition System

All mean flow data were taken using the SWT Automated Data Acquisition System. This system employed a Zenith Z-100 computer with an analog to digital card for conversion of the analog voltage from the pitot transducer to a digital reading. The first reading was taken at .0225 inches from the floor of the tunnel, since this distance was the closest that the probe used for fluctuation measurements could approach the floor. Subsequent readings were taken every .005 inches until the probe was .5 inches from the floor. All mean flow data were recorded directly on disk for storage and data reduction. For further information on the mean flow data acquisition system refer to Berger [9].

Dynamic Pitot Probe Setups

Dynamic Pitot Probe

A dynamic pitot probe (DPP) was used for all fluctuation flow measurements. The DPP, model CQ-030-100G, is a differential pressure transducer using a four arm Wheatstone bridge in a silicon diaphragm for sensing built by Kulite Semiconductor Products, Inc. The DPP has an outside diameter of .032 inches and an active area diameter of .010 inches, giving it a minimum resolution, based on the ratio of active area diameter to thinnest boundary layer thickness, of .068. The natural frequency of the DPP is 1.5 Megahertz. The DPP was used for fluctuating measurements only as it is incapable of mean flow measurements.

Since the DPP is a differential pressure transducer, it included a reference tube which could be connected to a pressure source. Since this pressure was unnecessary for fluctuating pressure measurements, the reference tube was left open to atmospheric pressure.

The sensitivity of the DPP is given by Kulite as .0982 millivolts/pounds per square inch/volts d.c. (from the power supply). From previous experimentation it was determined, using a mean flow calibration method, that the calculated sensitivities came within 17 percent of Kulite's stated sensitivity. It was then decided (Demetriades [10]) to accept Kulite's calibration since the DPP cannot measure mean flow conditions. Therefore the DPP cannot be accurately calibrated with the mean flow method employed.

The DPP was housed at the end of a fin attached to a sting. As can be seen in Figure 2, reproduced from [8], this arrangement allowed the DPP to take measurements near the floor of the tunnel as was needed for this experiment.

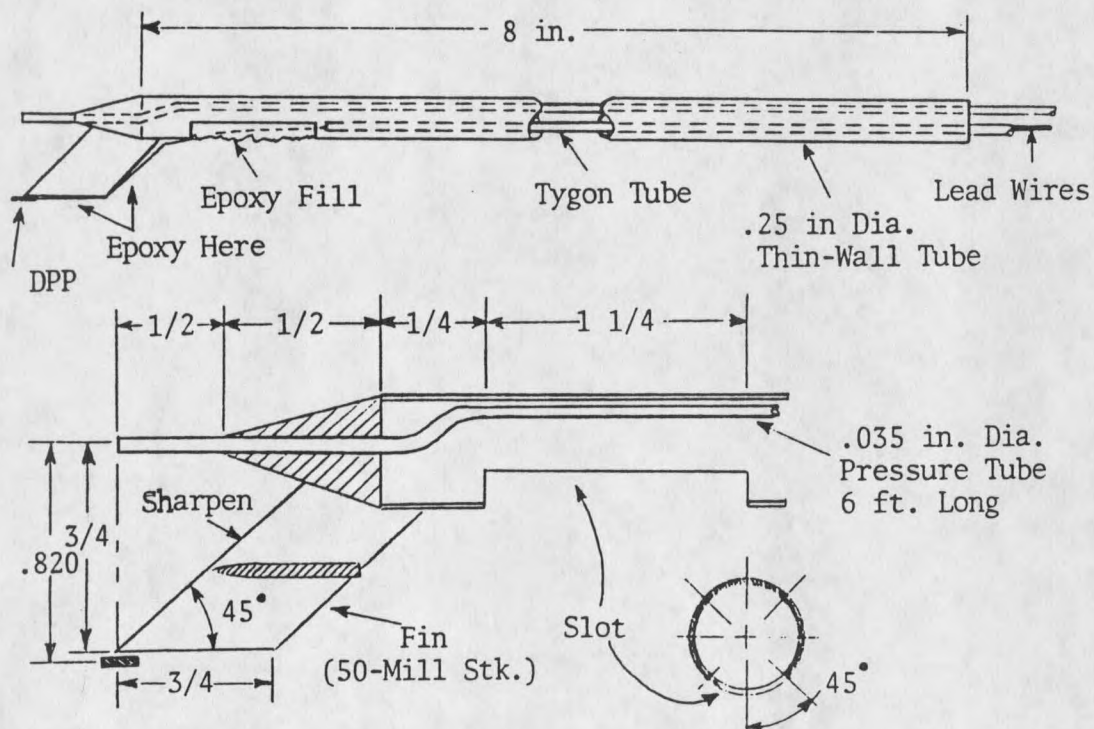


Figure 2. Major Features of the DPP.

The DPP measures pitot pressure fluctuations. What was required for this experiment was the velocity fluctuation. Therefore a relationship between pitot pressure fluctuation and velocity fluctuation is needed. Since the Mach number for this experiment was always greater than 1 the Rayleigh Supersonic Pitot Formula from [11] was used:

$$(1) \quad \frac{P}{P_P} = \left(\frac{2\gamma}{\gamma+1} M^2 - \frac{\gamma-1}{\gamma+1} \right)^{\frac{1}{\gamma-1}} / \left(\frac{\gamma+1}{2} M^2 \right)^{\frac{\gamma}{\gamma-1}} .$$

Differentiating (1) yields

$$(2) \quad \frac{dP_P}{P_P} = \frac{dP}{P} + 2\gamma \left(\frac{2M^2 - 1}{2\gamma M^2 - (\gamma - 1)} \right) \frac{dM}{M} .$$

Using the Mach number relation

$$(3) \quad \frac{dM}{M} = \frac{du}{u} - \frac{1}{2} \frac{dT}{T}$$

and the energy equation [11] with the assumption that $dT_0/T_0 = 0$,

$$(4) \quad \frac{dT}{T} = -(\gamma - 1)M^2 \frac{du}{u} ,$$

yields

$$(5) \quad \frac{dP_P}{P_P} = \frac{dP}{P} + \left[\gamma M^2 - \frac{(M^2 - 1)^2}{\left(M^2 - \frac{\gamma-1}{2\gamma} \right)} \right] \frac{du}{u} .$$

Defining the term in brackets as the sensitivity s gives

$$(6) \quad \frac{dP_P}{P_P} = \frac{dP}{P} + s \frac{du}{u} .$$

If the assumption that the pressure fluctuations inside of a boundary layer are much smaller than the velocity fluctuations is combined with the fact that the sensitivity is larger than 1 for $M > 1$, then the dP/P term can be eliminated giving

$$(7) \quad \frac{dP_P}{P_P} = s \frac{du}{u} .$$

With (7) the DPP can now be used to determine velocity fluctuations, provided that the local Mach number is known.

Data Acquisition Systems

Three different acquisition systems were employed for the fluctuating measurements. The first system involved taking only wide band (sum of all frequencies) root mean square (RMS) voltage measurements. The second system involved taking data for power spectrum (frequency dependent RMS levels) measurements. The third system was used for taking intermittency (defined later) measurements. The equipment common to all three systems will be described first with the equipment distinct to each system described separately.

The DPP was connected to an electronic circuit, seen in Figure 3, which was connected to a Hewlett Packard 6202B d.c. power supply. This circuit was installed to eliminate any possibility of voltage spikes from the power supply affecting the DPP. The circuit also took the voltage from the power supply and reduced it by approximately one-third. This voltage level powered the DPP. The power supply was set at approximately 12–15 volts. Therefore, the DPP was supplied with 4–5 volts.

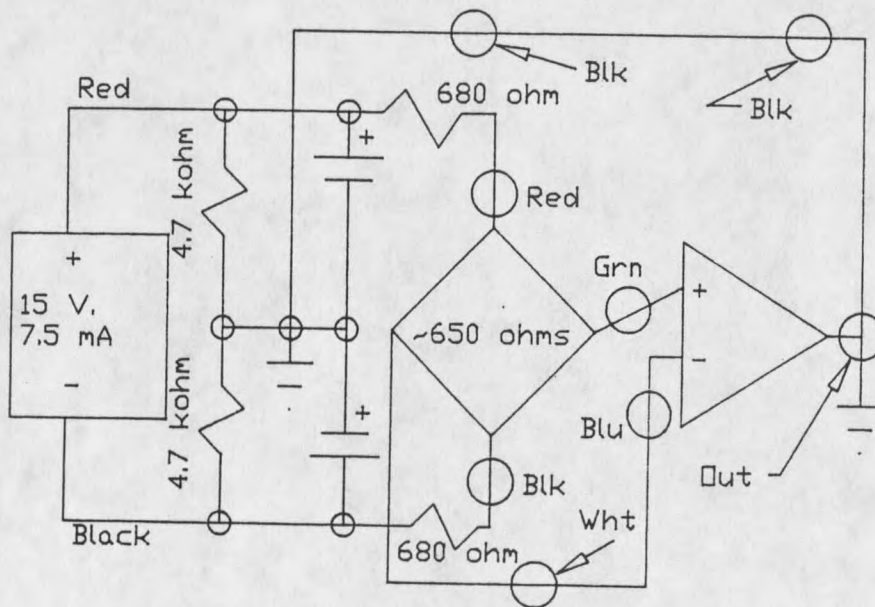


Figure 3. Electronic Circuit used with DPP.

A Fluke 8600A digital multimeter was connected to the input of the DPP. Whenever data were taken the excitation voltage supplied to the DPP was recorded.

The output signal from the DPP was connected to a Tektronix 549 oscilloscope which had a Tektronix 1A6 differential amplifier set to 1 millivolt per division on the screen. The oscilloscope had an output signal connection which was attached to a Hewlett Packard 3400A RMS meter. The output signal of the oscilloscope was normalized by the oscilloscope to provide 1 volt per division.

The amplification factor of the oscilloscope was measured to find its dependence on frequency. As can be seen in Figure 4, the amplification factor was constant to approximately 200,000 hertz (Hz) and then dropped off slowly. Since the majority of the signal from the DPP would be in the range from 0 to 200,000 Hz, the gain for the wide band measurements was taken as the average of the signals out to 200,000 Hz which was 1233. For the second set of measurements which were frequency dependent, the factor 1233 was used to 200,000 Hz and after that the data were curvefit to obtain the amplification factor equation

$$(8) \quad a.f. = 1302.87 - .000282932f \text{ (Hz)} \quad .$$

For the wide band RMS voltage measurements, the output signal of the RMS meter was attached to an X-Y plotter. Then as the DPP was traversed through the boundary layer the RMS voltage level was recorded. After the levels were recorded on graph paper, they were transferred to disk for storage and data reduction. At the end of each traverse, the noise level was noted for removal from the RMS voltage level recorded.

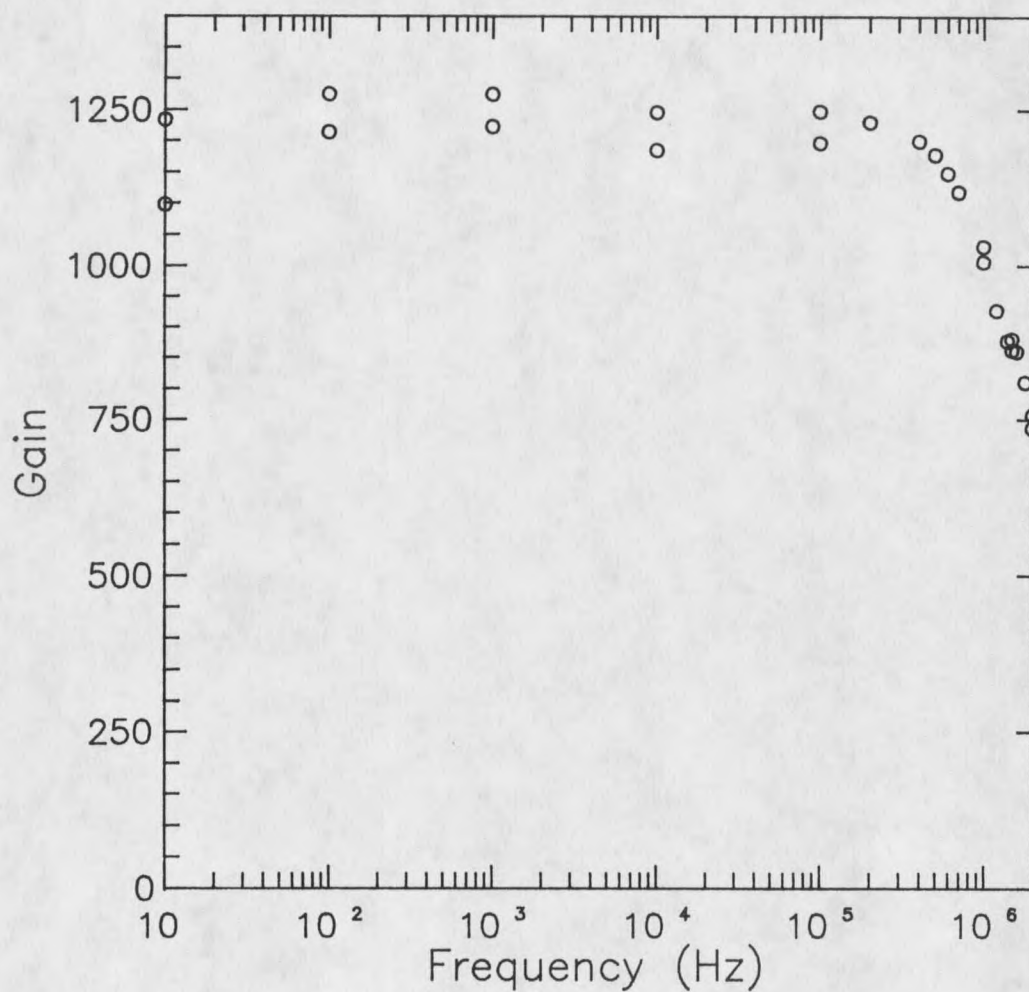


Figure 4. Oscilloscope Amplification.

Additional equipment was needed for the power spectrum and intermittency measurements. The signal from the oscilloscope was also connected to channel 1 of a Tektronix 2220 digital oscilloscope. This oscilloscope was then attached to a Zenith Z-159 computer via a serial port. The oscilloscope was set to either 10 or 20 microseconds per division. The RMS meter was left attached to determine if the RMS voltage level changed while taking the waveforms needed for each point.

The software used to transfer the waveforms from the 2220 oscilloscope to the Z-159 computer was Version 2.2 of the SPD Signal Processing & Display Programs, written by Tektronix, Inc. The specific program used was called SPDMENU which is a menu-driven program used to access all of the SPD functions. For details on how to use this program refer to [12].

Due to the fact that a serial port was used to transfer data, all data taking was manual. This meant the operator had to enter all file names and instruct the oscilloscope to send the waveform to the computer.

An alternative to a serial port would be to use a GPIB port. A GPIB (General Purpose Interface Bus) port is an Institute of Electrical and Electronics Engineers (IEEE) 488 standard. Tektronix designed the SPD software with this standard in mind. Therefore support for the GPIB standard in the SPD software is much more extensive than the serial port, including the ability for automation.

If a GPIB port were used all data collection could be automated, eliminating possible errors. The GPIB port also sends and receives information much faster than the serial port, enabling more data to be taken in any experiment.

In order to reduce scatter in the power spectrum data 100 waveforms were taken at every point in the boundary layer. It took approximately one hour to acquire and store these waveforms. Also every day that data were taken, 100 waveforms of the noise level were recorded to eliminate the noise from the power spectrum. Due to the amount of time involved to take this number of waveforms, data were only taken at the $x = 2.9$ inch position and at the highest pressure (600 torr). Therefore the spectral data were taken at the largest Re_θ which equalled 2073. Data were taken at nineteen y/δ positions in the boundary layer with one position repeated and one position in the freestream for a total of 21 sets of data. Due to the number of waveforms involved and the amount of storage room needed,

all data were stored in binary form. Each waveform took 16864 bytes of storage space, therefore the storage area needed for just the signal waveforms was greater than 35 Megabytes.

In addition, for intermittency data, the output signal from the Tektronix 549 oscilloscope was attached to a Hewlett Packard 465A amplifier. The amplifier then ran to the ADP-11-IM/IA intermittency meter. The intermittency level of the boundary layer was read off the meter and stored on disk.

If desired the intermittency meter could be attached to channel 2 of the Tektronix 2220 oscilloscope to compare the intermittency output to the waveform from which it was calculated. This setup can be seen in Figure 5.

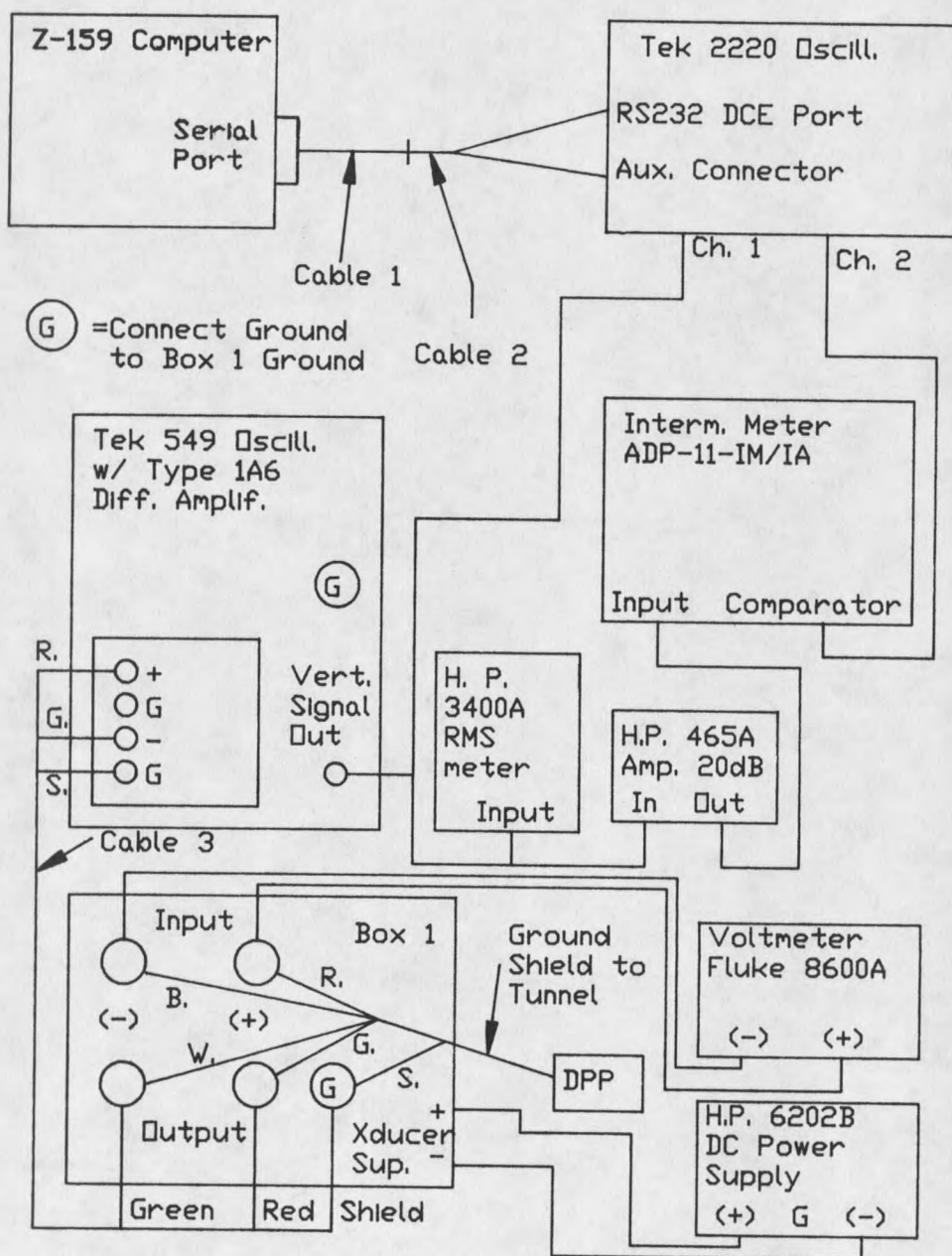


Figure 5. Setup of DPP Data Acquisition System.

CHAPTER 3

EXPERIMENTAL RESULTS

Mean Flow Measurements

Introduction

Mean flow data were taken for three reasons. First, without mean flow data, characterization of the boundary layers would have been impossible when the fluctuating data were taken. For comparison with other experiments, mean flow characteristics such as the momentum thickness and Reynolds numbers were needed. This data would determine if the boundary layer was transitional.

Second, the mean flow data were needed to reduce the fluctuating data. For example, the Mach number was needed for calculation of s in (6) which is needed to convert the pressure fluctuations to velocity fluctuations. The velocity was needed for finding the non-dimensional spectra and Reynolds numbers as will be seen in equations given later. Since viscosity is temperature dependent, the temperature was needed to find viscosity and the Reynolds number.

Third, since data were taken at several pressures and positions in the wind tunnel there were a wide range of Re_θ 's as mentioned previously. Therefore it was possible to determine if there was an Re_θ effect on the mean flow profiles.

Mean Flow Data Reduction

The pitot tube was calibrated using the SWT pressure station. Pressures were applied to the pitot tube and the voltage indicated by the pitot tube transducer

was recorded. The range used for calibration was approximately 10 to 200 mm Hg. The pressures were applied twice and in random order. Once the pressures and voltages were taken, the data were reduced by means of a linear least squares curvefit to find the relation between voltage and pressure.

At the time that the data were taken throughout the boundary layer, the total pressure and total temperature were also recorded since they were needed for data reduction. First the linear curvefit was used to convert the voltages obtained to total pressure behind the shock formed in front of the pitot tube. The last pressure taken outside of the boundary layer was used with the total pressure of the freestream to find the edge Mach number by the relation from [11]

$$(9) \quad \frac{P_0}{P_P} = \left(\frac{2\gamma}{\gamma+1} M^2 - \frac{\gamma-1}{\gamma+1} \right)^{\frac{1}{\gamma-1}} \left(\frac{1 + \frac{\gamma-1}{2} M^2}{\frac{\gamma+1}{2} M^2} \right)^{\frac{\gamma}{\gamma+1}}$$

The Mach number was used to find the static pressure for the x position of the wind tunnel by using the Rayleigh Supersonic Pitot Formula (1). The static pressure was assumed constant in the boundary layer for each x position.

The static pressure was used in conjunction with the total pressures found in the boundary layer with (1) to find the Mach number for each y position in the boundary layer where data were taken. The Mach number was then used to find the temperature and velocity.

To find velocity and temperature, an assumption needed to be made concerning the total temperature in the boundary layer. Based on previous work in the tunnel by Demetriades and McCullough [13], the wall temperature was assumed to be $.94T_{0e}$ and their curvefit of previous data was used for the total temperature profile in the boundary layer which was used to find the static temperature profile with the relation

$$(10) \quad \frac{T}{T_0} = 1 + \frac{\gamma-1}{2} M^2$$

With the static temperature calculated, the velocity was found by using the relation

$$(11) \quad M = \frac{u}{\sqrt{\gamma RT}}$$

The freestream properties were found by assuming that the maximum velocity within .5 inches of the wall was the freestream velocity (u_e) and then finding the position in the boundary layer that equaled $.99u_e$. The momentum thickness which is defined as

$$(12) \quad \theta = \int_0^\infty \frac{\rho u}{\rho_e u_e} \left(1 - \frac{u}{u_e}\right) dy$$

was found by integrating the appropriate properties by the trapezoidal method. A curvefit method given by Irvine and Liley [14] was used to determine viscosity and then Re_θ was computed. This data reduction process was programmed on a computer and all data were reduced on the computer due to the amount of data involved. The program, BLCONV1.BAS, is found in Appendix A.

Mean Flow Results

Figure 6 shows a comparison of the local streamwise mean velocity (u), measured in this experiment with the Blasius solution for compressible laminar flow using equations as developed in White [15]. As Re_θ increases the velocity profiles move away from the laminar solution. Even the lowest Re_θ is not close to the laminar solution. This indicated that the boundary layers were not laminar. Therefore the boundary layers were in the transition or turbulent region. Figure 7 shows the velocity of the flow at the midpoint of the boundary layer for the various Re_θ . It appears that at larger Re_θ 's the velocity had become constant, indicating that the higher Re_θ 's flows might have been turbulent, which will be checked in the next section.

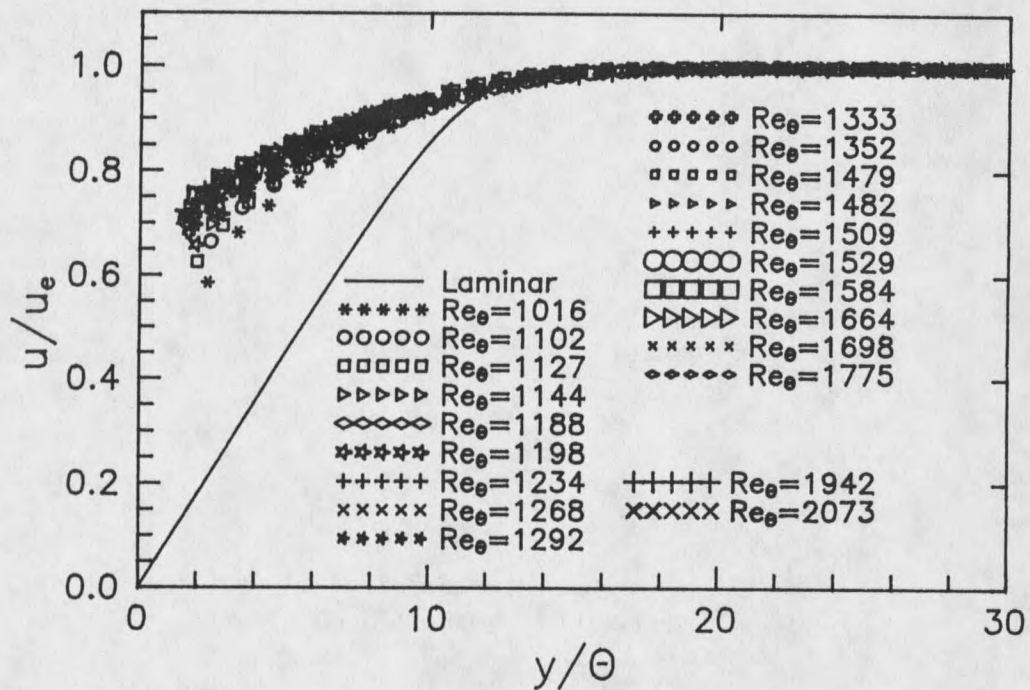


Figure 6. Boundary Layer Velocity Profiles.

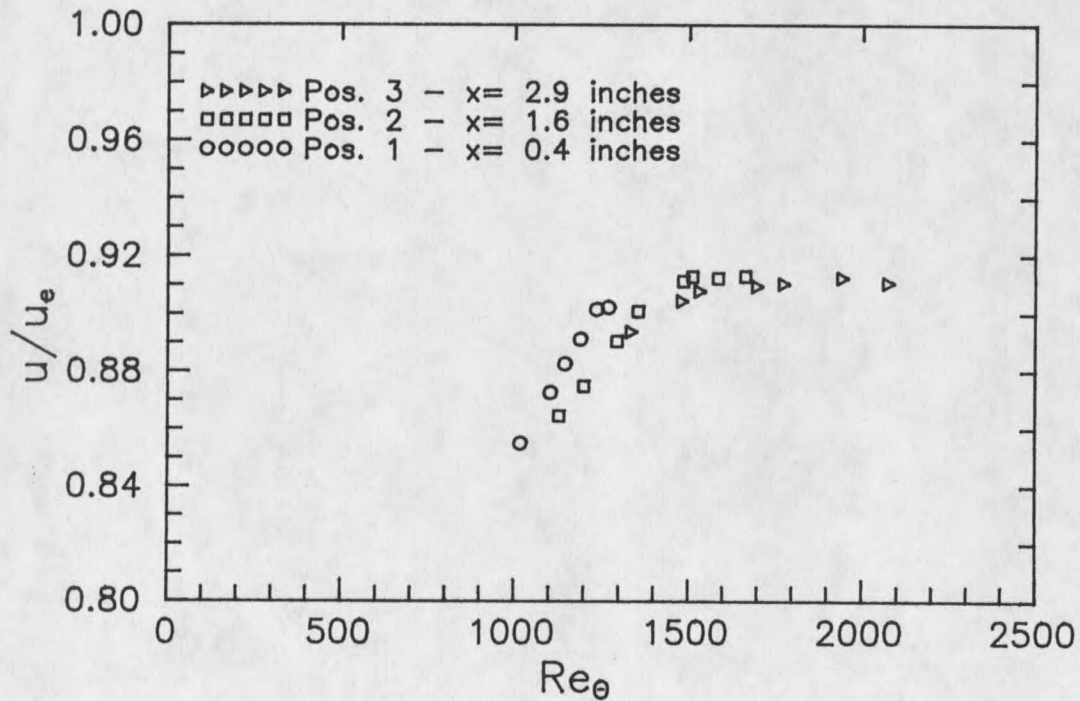


Figure 7. Velocity at the Midpoint of the Boundary Layer.

Law of the Wall Analysis

To determine whether the flow was in the transition region or fully turbulent, the velocity profiles needed to be converted to law of the wall form. In the law of the wall form, y is converted to y^+ and u is converted to u^+ , which are defined from [13] as

$$(13) \quad y^+ \equiv \frac{y \rho_e u_e^2 C_f}{2 \nu_w}$$

and

$$(14) \quad u^+ \equiv \frac{\left(\frac{.2 M_e^2}{T_w/T_e} \right)^{-1/2}}{\frac{1}{2} \rho_e u_e C_f} \left[\sin^{-1} \left(\frac{\frac{.4 M_e^2}{T_w/T_e} \frac{u}{u_e} - \frac{.2 M_e^2 + 1}{T_w/T_e} + 1}{\left(\left(\frac{.2 M_e^2 + 1}{T_w/T_e} - 1 \right)^2 + \frac{.8 M_e^2}{T_w/T_e} \right)^{1/2}} \right) \right. \\ \left. + \sin^{-1} \left(\frac{\frac{.2 M_e^2 + 1}{T_w/T_e} - 1}{\left(\left(\frac{.2 M_e^2 + 1}{T_w/T_e} - 1 \right)^2 + \frac{.8 M_e^2}{T_w/T_e} \right)^{1/2}} \right) \right]$$

In a turbulent flow

$$(15) \quad u^+ = a + b * \ln(y^+) \quad .$$

For this experiment the constants a and b were unknown and the coefficient of friction, needed for conversion to u^+ and y^+ , was also unknown. Using a procedure outlined by Demetriades and McCullough [13] for calculation of (15), the slope b is assumed to equal 2.43 from the universal law of the wall. The coefficient of friction can then be calculated. Using the mean flow data, u^+ and y^+ were calculated and compared to

$$(16) \quad u^+ = 5 + 2.43 \ln(y^+)$$

which is the universal law of the wall formula and had been verified in the SWT by Laderman and Demetriades [16] from previous experimentation. As before all

data reduction was performed on a computer. The program written to reduce the data is called LAWWALL.BAS and is found in Appendix B.

As can be seen in Figure 8, the present data approach but never reach (16) as Re_θ increases. This indicates that either the data are in the transition region or the law of the wall equation is dependent on Re_θ .

Coefficient of Friction

The coefficients of friction were computed from the data and compared to a turbulent coefficient of friction measured directly by Laderman [17] in this tunnel. Figure 9 shows this comparison. They were also compared with turbulent theory following the procedure of Hopkins and Inouye [18], which recommends using the Karman-Schoenherr [19] equation

$$(17) \quad \frac{1}{C_f} = 17.08 (\log_{10} \overline{Re_\theta})^2 + 25.11 \log_{10} (\overline{Re_\theta}) + 6.012$$

relating the coefficient of friction and Re_θ and the Van Driest II theory [20] for compressible transformation of these two variables. As can be seen in Figure 9, the turbulent point from Laderman [17] is in very good agreement with theory. However, the present data are well above the theoretical line whereas normally for the transition region the coefficient of friction appears below the theoretical line. There is no explanation for this behavior but there are two speculations. The coefficient of friction does show an "overshoot" similar to a Moody diagram, which could explain why the data were above the turbulent line. Also the coefficient of friction was backed out of the law of the wall results rather than measured directly, and since the flow is not fully turbulent the coefficient of friction could be inaccurate.

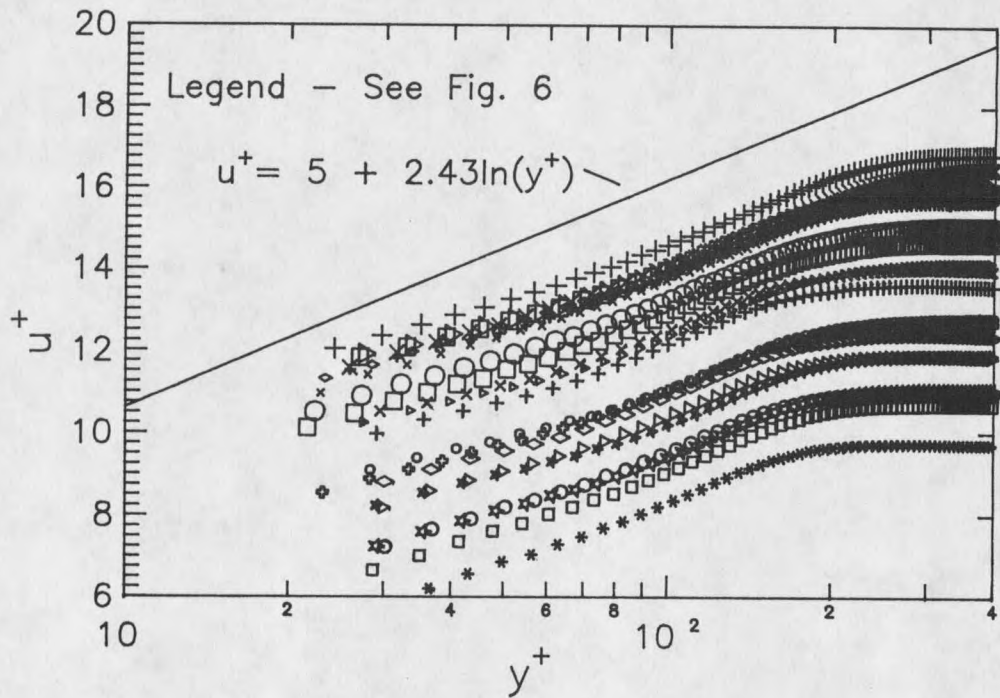
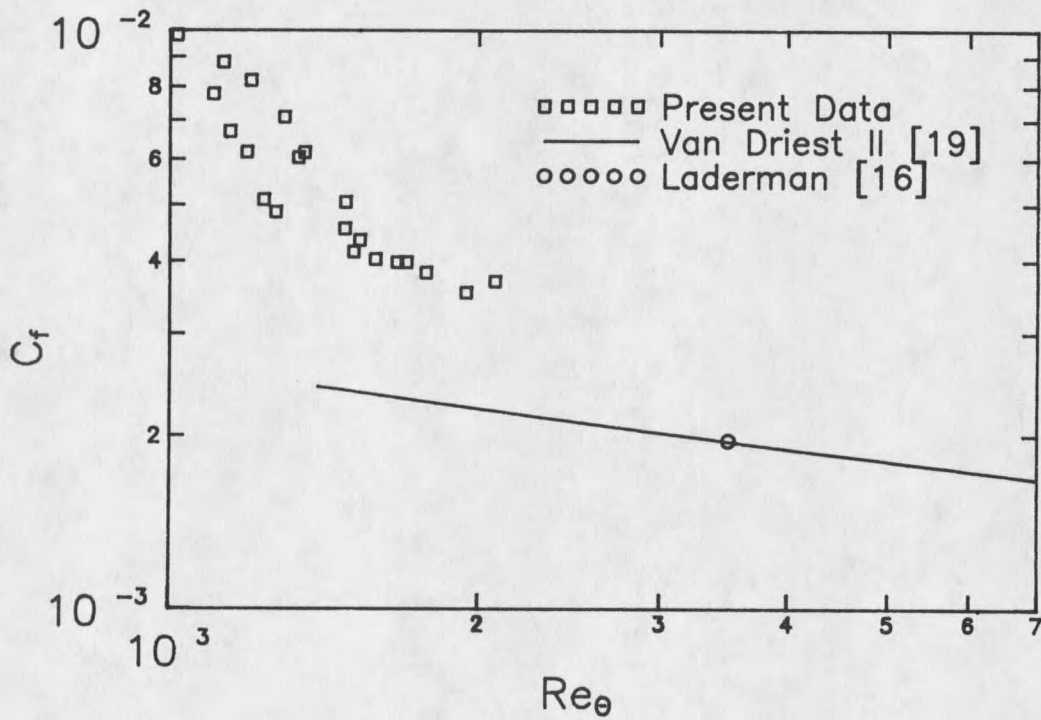


Figure 8. Law of the Wall Profiles.

Figure 9. Comparison of C_f with Turbulent Datum and Theory.

Wideband RMS Measurements

Data Reduction

Using the calibration for the DPP, the RMS voltage levels recorded on the X-Y plotter and stored on disk were converted to RMS pressure levels. Using the stagnation pressures found from the mean flow data, P'/P was calculated. With P'/P and the Mach number found earlier, u'/u was calculated from (7). These calculations were also done in BLCONV1.BAS.

Wideband RMS Results

Figure 10 shows the wideband RMS velocity profiles for the boundary layer normalized with u . Although not readily apparent, as Re_θ increases the velocity fluctuation level decreases. Also, as would be expected, the RMS level decreases as the edge of the boundary layer is approached, indicating that the freestream turbulence level was much smaller than the boundary layer turbulence levels. Since the RMS levels are not closer to zero at the edge of the boundary layer, as would be expected at the edge, using $.99u_e$ may not have been the best method for designating the edge of the boundary layer. An alternative method will be discussed in the section on intermittency.

A better indication of what is happening is shown in Figure 11, comparing Re_θ and u'/u . There is a definite decrease in fluctuation level as Re_θ increases. The data point from Laderman and Demetriades [16] which is in the turbulent region also follows this trend.

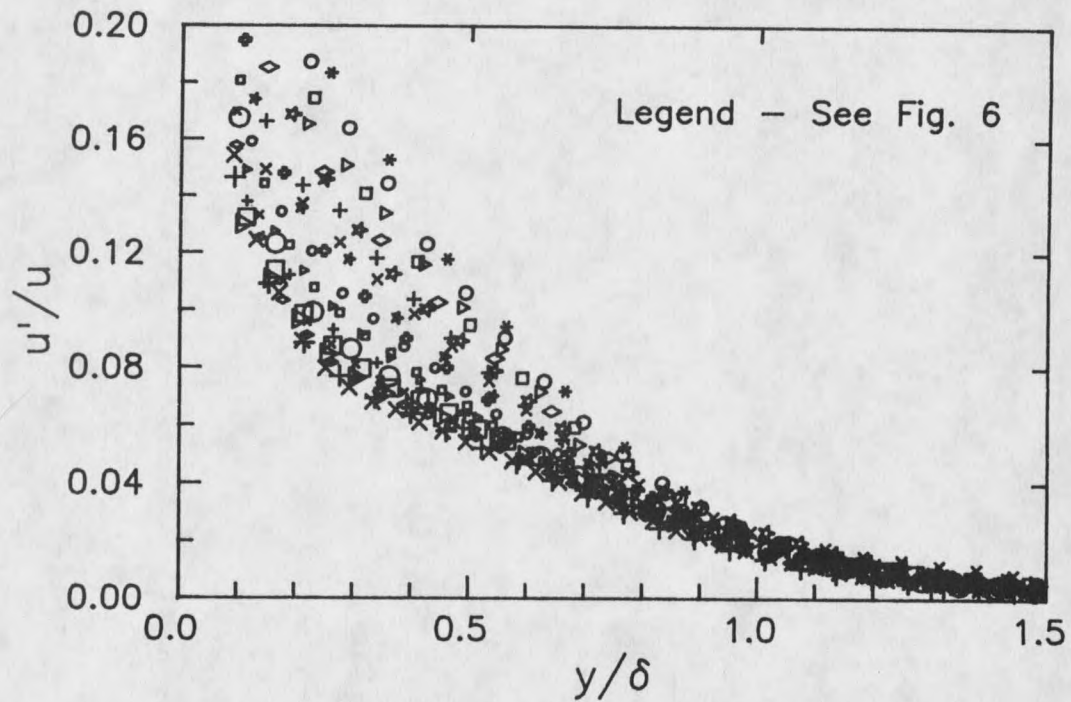


Figure 10. Velocity RMS Fluctuation Levels.

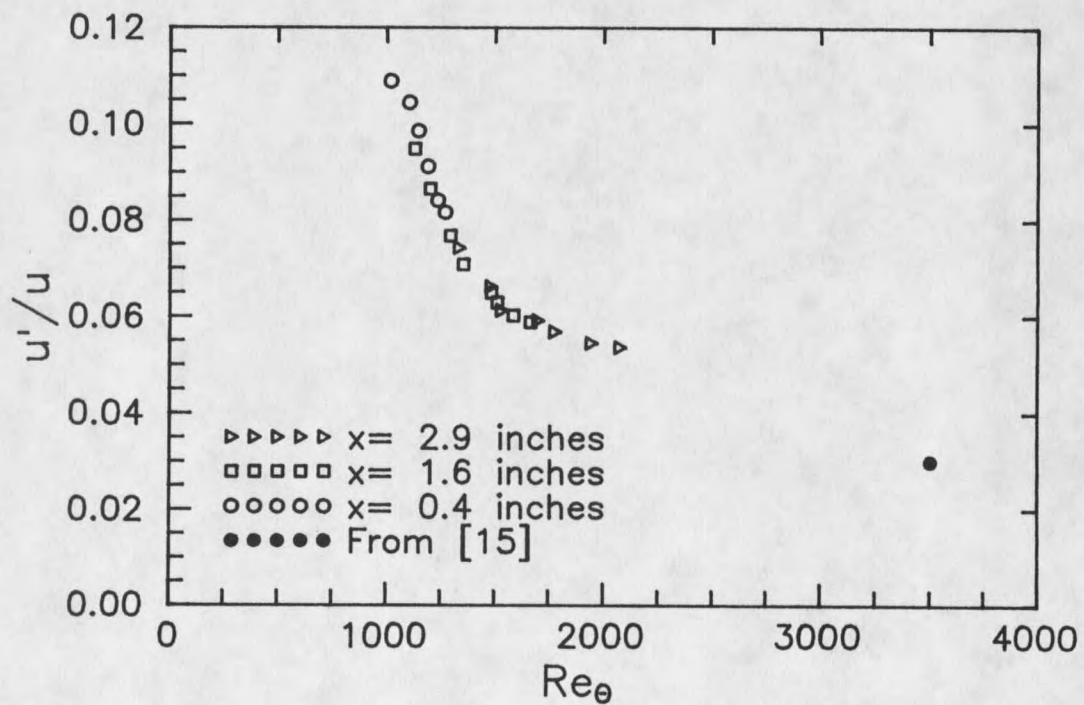


Figure 11. Velocity RMS Fluctuation Levels at $y/\delta = .5$.

According to Owen et al [2], if a boundary layer is initially laminar and the unit Reynolds number is increased, then during the transition process the fluctuations will rise, peak and drop and then level off in the turbulent region. Since the present data were taken at three different tunnel positions, Re_θ needs to be used in place of the unit Reynolds number which will not account for different position. It appears that the data are in the transition region beyond the peak and are dropping to the turbulent level.

This data helped verify the law of the wall calculations of the data. Both the mean and wideband RMS sets of data indicated that the boundary layer studied was definitely transitional at the lower Re_θ values used. The upper Re_θ values used seem to have been close to the end of the transition region.

Intermittency Measurements

Introduction

The edge of a boundary layer for turbulent or transitional flow is not smooth. In other words, near the edge of the boundary layer, any probe that is in the flow will be subjected to sections of laminar flow and sections of turbulent (or transitional) flow. Determining the "edge" of the boundary layer is extremely difficult with a sensor which only provides time averages. If a picture is taken of a turbulent boundary layer, there is a distinct boundary between laminar and turbulent zones but this edge is difficult to define with a time-averaging sensor. What is typically done in this case is to define the edge of the boundary layer as some percentage of the freestream velocity (i.e. 99 percent). Since the pitot tube and wideband RMS data were taken well before the intermittency data, this method was used to determine the edge of the boundary layer.

Intermittency measures the percentage of the time that the probe is in the laminar section of the flow. Figure 12 shows a typical output from an intermittency circuit compared to the signal that the DPP measures. When the probe is in a turbulent zone the intermittency signal is at a maximum, whereas when the probe is in a laminar zone the intermittency signal is at a minimum. The intermittency circuit continuously determines the percentage of laminar flow and displays the percentage on a meter.

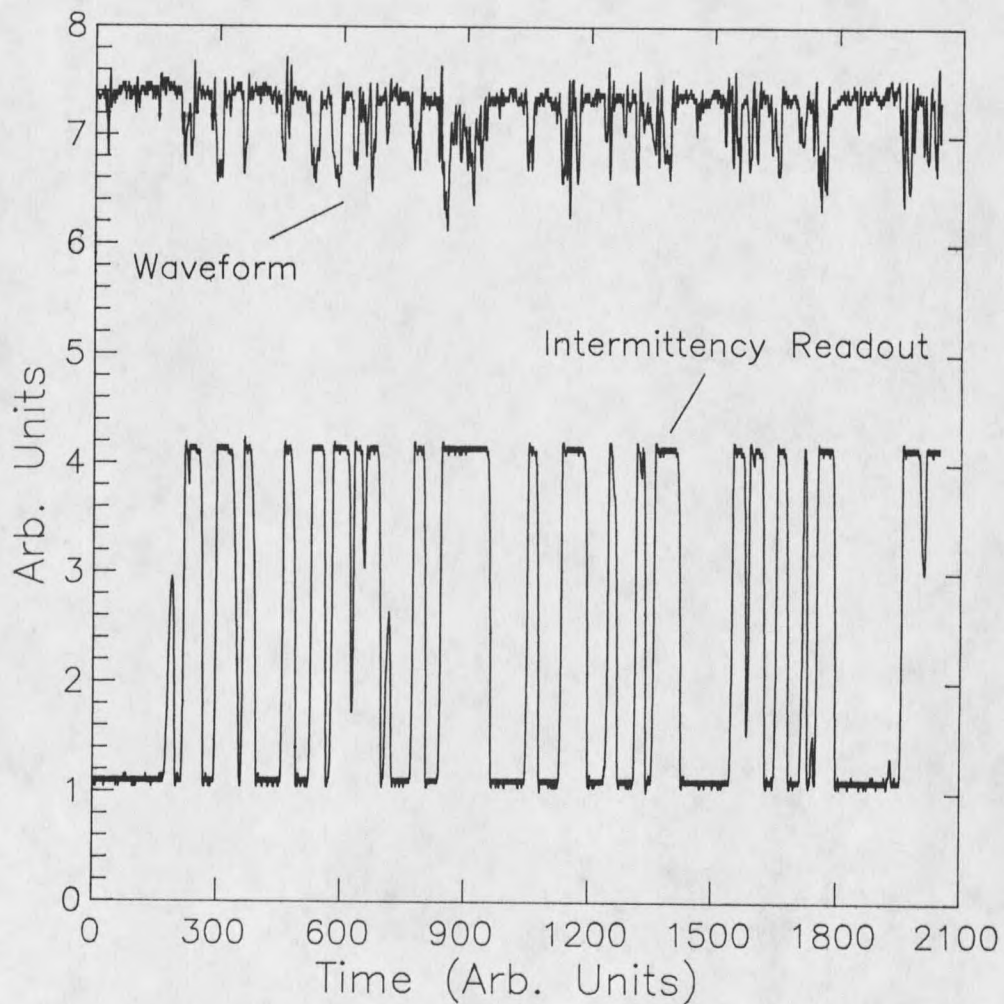


Figure 12. Typical Output from the Intermittency Meter.

A transitional boundary layer consists of laminar and turbulent regions traveling in the streamwise direction. Therefore the intermittency meter will not only detect when the probe is outside of a turbulent boundary layer but also any laminar regions inside the boundary layer. Therefore care is needed when using an intermittency meter for determination of the edge of the boundary layer.

When intermittency is used to determine the edge of the boundary layer, the edge can be arbitrarily based on an intermittency reading anywhere from 0 to 100 percent. Since this experiment was in transitional flow, the possibility existed that there would be no region where the intermittency was 100 percent due to the laminar regions, therefore the edge was chosen to be at 50 percent intermittency. The DPP was moved slowly from the tunnel floor while watching the meter. The y position at 50 percent intermittency was not recorded until after a peak in the intermittency level had been indicated to eliminate the possibility of finding a 50 percent intermittency in the laminar sub-layer.

Results

The boundary layer edge was found for all conditions and positions mentioned in the wideband results. All maximum intermittency levels were at least 80 percent, indicating that the transitional boundary layer was mainly turbulent regions.

Figure 13 compares the boundary layer thicknesses found by using the $.99u_e$ method and the intermittency method. At the lower Reynolds numbers the thicknesses were surprisingly close, indicating that either method could be used for flows that are "more laminar". However at the larger Reynolds numbers the intermittency method gave larger boundary layer thicknesses. Obviously, since the two methods produced differences, the method used must always be stated,

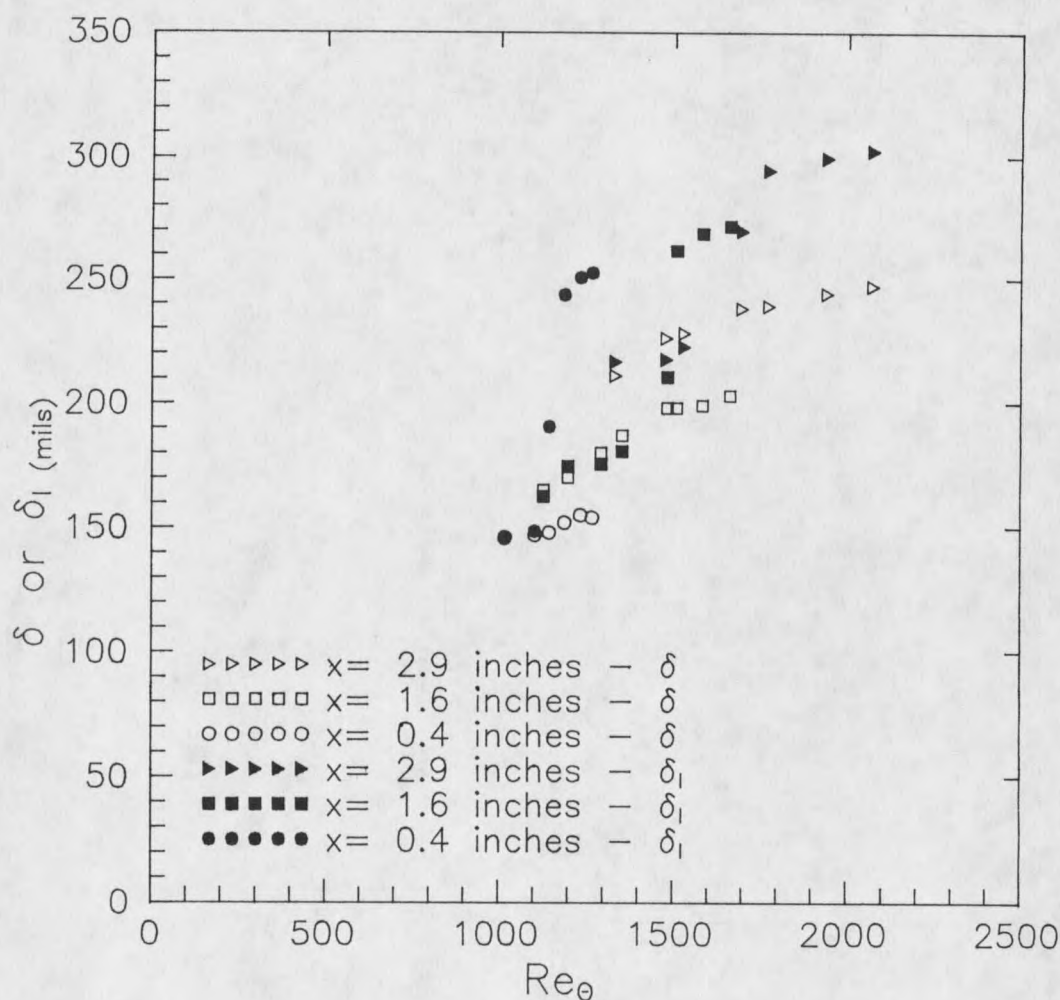


Figure 13. Comparison of Two Methods for Boundary Layer Thickness Measurement.

Figure 14 shows the intermittency level dependence on y/δ . These data were taken at the same conditions and position which gave the highest Re_θ which equalled 2073. The intermittency level starts at approximately .76, peaks at approximately .98 and drops to zero. The boundary layer at this Re_θ was almost completely turbulent, as indicated by the .98 level measured. This verifies previous mean flow conclusions.

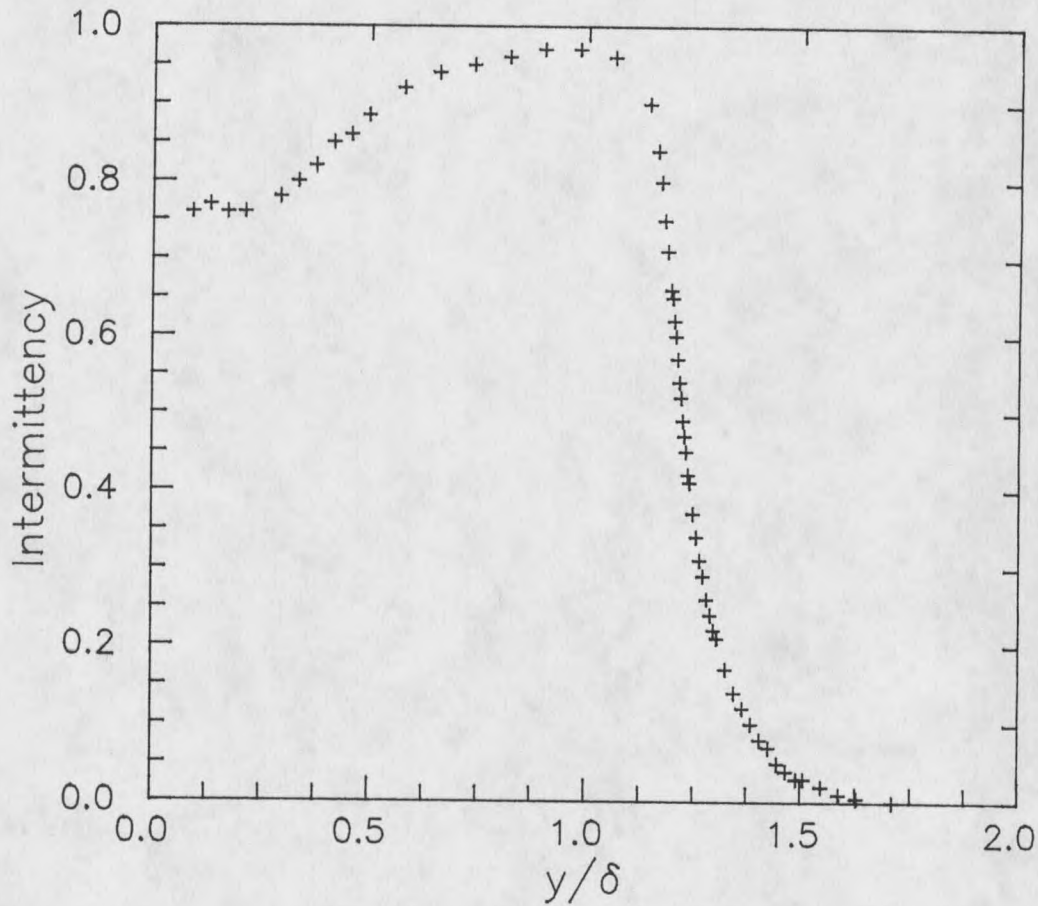


Figure 14. Intermittency Level Dependence on y/δ .

The drop from the peak is extremely abrupt. This indicates that the y position would not move a great deal if measurements of the .5 intermittency level were slightly inaccurate. In comparison, by looking back at Figure 6 which shows the velocity profiles, the region of $.99u_e$ has a very gradual change. Therefore, any inaccuracies could move the boundary layer thickness a significant amount. Based on this, for repeatability in the boundary layer thickness measurements, the intermittency method should be used if available.

Power Spectrum Measurements

Introduction

In order to determine the frequency dependent fluctuation levels, all time domain data had to be converted to frequency domain data. The Fourier transform, consisting of sinusoids at different frequencies, is a common method of transformation. The basic form of the Fourier transform integral from Brigham [21] is

$$(18) \quad H(f) = \int_{-\infty}^{\infty} h(t) e^{-i2\pi f t} dt$$

This form is used to determine the transform of a continuous signal. The fluctuations in the wind tunnel are continuous signals but discrete samples of these signals were taken. Therefore, the discrete Fourier transform was used which from Ramirez [22] is

$$(19) \quad H(m) = \frac{1}{N} \sum_{n=0}^{N-1} h(n) e^{-i2\pi m n / N}$$

In sinusoid form, (19) becomes

$$(20) \quad H(m) = \frac{1}{N} \sum_{n=0}^{N-1} h(n) \left(\cos \frac{2\pi m n}{N} - i \sin \frac{2\pi m n}{N} \right)$$

The real and imaginary Fourier coefficients can be calculated from (20). However, this form of the discrete Fourier transform is time consuming and is not in general use. The method used for transforming time domain data is called the Fast Fourier Transform (FFT).

Fast Fourier Transform Data Reduction

According to Ramirez [22], C. Runge in 1903 and Danielson and Lanczos in 1942 published papers that looked at minimizing the number of calculations

required for calculating the discrete Fourier transform; however Ramirez did not give any information on where either article was published. The FFT first became widely known when it was developed by Cooley and Tukey [23].

The discrete Fourier transform was looked at for any symmetries and periodicities that could be used to reduce the number of calculations. According to Bergland [24], for the discrete Fourier transform the approximate number of multiplications was N^2 whereas for the FFT it was $(N/2) * \log_2 N$ multiplications. Considering that the number of points taken in each waveform for this experiment was 4096, the number of multiplications for the discrete Fourier transform would be approximately $1.7 * 10^7$ and for the FFT $2.5 * 10^4$ giving a time savings of 680 to 1.

However, more time was saved by using an algorithm developed by Bergland [25], which reduced further redundancies in the Cooley-Tukey algorithm when real-valued time series are used. Not only was the number of calculations reduced by two but also the storage area for intermediate calculations was reduced by two. This algorithm is a radix-two algorithm (N is an integral power of two). For future work, Bergland [26] gives a radix-eight algorithm which would further reduce the calculations required.

The radix-two algorithm code was written into a program called REALFFT3.BAS. For speed, this program was converted to an executable file. This program took the data which were stored in binary and converted the data back to decimal form by use of the routines in the Tektronix SPD Signal Processing & Display Programs. Once the real and imaginary terms were found, they were converted to the amplitude of the Fourier coefficient by using

$$(21) \quad (\text{Real})^2 + (\text{Imaginary})^2 = (\text{Amplitude})^2$$

The program calculated these coefficients for all 100 waveforms stored and then averaged them. Then the program calculated the rms level of each coefficient by dividing by $\sqrt{2}$. The program ran for approximately 100 minutes on the Z-159 computer with a math co-processor. These values (still in voltage form) were then stored on disk.

The noise waveforms were handled by the program in the same manner since they were recorded in the same way as the signal waveforms. Figure 15 shows results of taking noise signals from the data acquisition system by four methods. The methods were with (a) the power supply off and the SWT off, (b) the power supply off and the SWT on, (c) the power supply on and the SWT on but the DPP hidden behind a wedge, and (d) the power supply on and the SWT off. As can be seen in the figure there are no substantial differences between any of the methods mentioned, even at individual frequencies. In fact looking at individual frequencies no particular method of measuring noise always had the largest amplitude. Since there were no differences in the way the noise spectrum was measured, the method usually employed was to have the power supply off and the SWT on. Occasionally the method with the power supply off and the SWT off was used due to problems with experiments next door giving off excessive amounts of particulate which entered the SWT.

As one check to determine if the program was correct, the wideband RMS voltage level was calculated from the spectrum and compared to the RMS meter reading which was noted at the same time that the waveforms were taken. They are listed for both the velocity fluctuation and noise measurements in Table 1 in no particular order. The table also lists the absolute percentage difference of the RMS levels as well as the absolute percentage difference of the mean square levels which is more correct for comparison. As can be seen in the table, the largest

error for the mean square comparison is only 23 percent which is quite good. In fact any error listed which is over 10 percent was taken on a noise sample, which could be expected since the magnitude of the noise was much smaller than the signal magnitude.

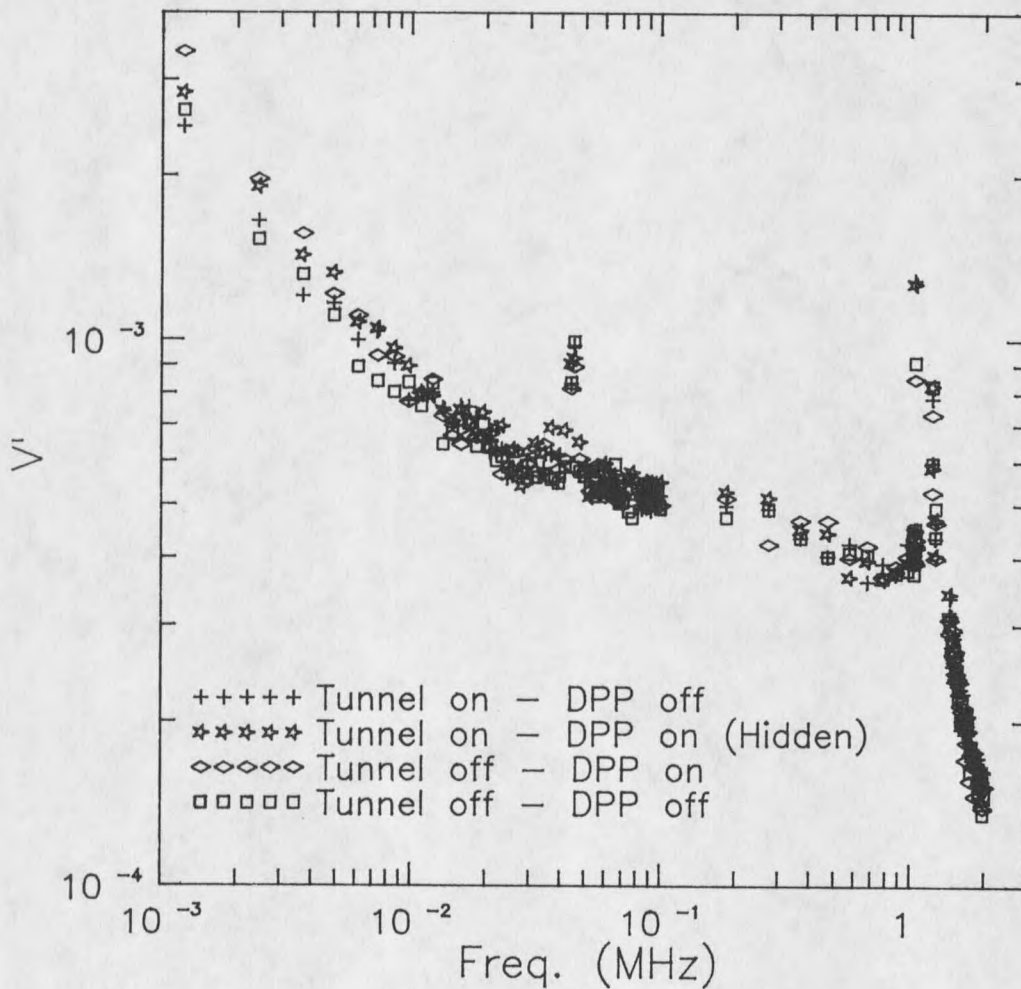


Figure 15. Comparison of Noise Measurements.

V'_{meter}	V'_{FFT}	% Difference (based on RMS)	% Difference (based on mean square)
.188	.1845	1.861702	3.830024
.0175	.01726	1.371428	2.800331
.19	.1832	3.578945	7.56135
.187	.1817	2.834225	5.918875
.212	.2057	2.971699	6.21923
.0172	.01582	8.023257	18.2072
.228	.2249	1.359646	2.775774
.22	.2133	3.045452	6.380892
.017	.017	0	0
.187	.1824	2.459895	5.107465
.0242	.0218	9.917354	23.23036
.018	.0179	.5555546	1.120438
.197	.1917	2.690356	5.605911
.215	.2117	1.534882	3.141914
.017	.0168	1.176479	2.395143
.172	.1709	.639537	1.29145
.201	.197	1.990054	4.102149
.0171	.0169	1.1696	2.380887
.205	.201	1.951216	4.019695
.0157	.0168	7.00637	12.66652
.166	.1632	1.68674	3.460793
.165	.1623	1.636364	3.354848
.167	.165	1.197598	2.438921
.0171	.017	.5847943	1.179929
.172	.1702	1.046512	2.126344
.179	.1758	1.787715	3.673645
.185	.1808	2.270268	4.699977
.0166	.0166	0	0
.203	.2006	1.182264	2.407131
.201	.1995	.7462739	1.509423
.0167	.01692	1.31737	2.583575

Table 1. Comparison of FFT Measurements with RMS Meter.

Universal Spectrum Data Reduction

The spectral data needed to be compared with non-dimensional theory. For a complete explanation see Pao [3]. For brevity, the highlights are included here.

The non-dimensional power spectrum of the velocity fluctuations is defined as

$$(22) \quad \phi(k) \equiv (u'(k))^2 u / 2\pi \nu u_K$$

where $(u'(k))^2$ is a function of frequency and is divided by the frequency bandwidth that it covers and $k = 2\pi f/u$. The Kolmogoroff wavenumber is defined as

$$(23) \quad k_K \equiv \left(\frac{\epsilon}{\nu^3} \right)^{1/4}$$

and the Kolmogoroff velocity is defined as

$$(24) \quad u_K \equiv (\nu \epsilon)^{1/4}$$

The dissipation function needed for calculating the universal spectrum is defined as

$$(25) \quad \epsilon \equiv \frac{60\nu\pi^2}{u^2} \int_0^\infty f^2 (u'(f))^2 df$$

where the integrand is the dissipation spectrum. As stated earlier, the main difficulty in finding the dissipation function in earlier research was due to the fact that the dissipation spectrum did not reach zero before the signal was indistinguishable from the noise. Therefore, the first quantity calculated for each spectrum was the integrand of the dissipation function. This was done in the program SPECINT.BAS which is found in Appendix D. The first quantity calculated was the signal with the noise removed at each frequency. This was calculated by taking the signal and noise RMS voltages saved on disk, squaring them, subtracting the

noise from the signal and then taking the square root giving the true mean square signal. This gave the true RMS signal as given by the DPP and was stored on disk.

The true mean square signal was also divided by the bandwidth of the signal and then multiplied by the square of its frequency. This gave the integrand of the dissipation function in terms of voltage. Voltage could be used to determine if the integrand approached zero since calculating the velocity RMS level is just the voltage times a constant.

Figure 16 shows the RMS voltage of the net signal for the position .0225 inches from the floor. As can be seen there is not much scatter in the data until the higher frequencies where the noise has more of an effect due to the low level of the signal. However, for this position the signal goes out to at least 600 kilohertz. What is more significant is seen in Figure 17 where the dissipation spectrum does approach zero as theoretically predicted by Pao [3]. This was much better than was possible with the hot-wire anemometer and gave a more accurate calculation of the dissipation function. Also seen in this figure is the large amount of scatter at the peak of the integrand. This is probably due to the fact that only 100 averages were taken and could be alleviated in the future by taking more averages.

Figures 18 through 25 indicate the same results as just discussed. But there are two other significant points to mention. First, the figures show that frequencies of up to and greater than 1 Megahertz are shown which the hot-wire anemometer is incapable of measuring accurately. For this position in the SWT the "boundary layer frequency" based on u_e/δ is approximately 100,000 Hz. The ratio of measured frequency to boundary layer frequency is then 10. Obviously, there are higher frequencies in the boundary layer than was previously thought possible.

Second, the data in Figures 18 through 21 were taken at the same y/δ position. The spectrum in Figure 18 extends to 1.3 Megahertz which is well past the .9 Megahertz seen in Figure 20. To try to explain this difference the sampling rate needs to be examined.

The data shown in Figures 18 and 19 were taken at twice the sampling rate of the data in Figures 20 and 21, giving that data twice the frequency bandwidth. Since the spectrum was measured at discrete frequencies, the energy indicated at a particular frequency is a sum of all the energy in the bandwidth around that frequency. Doubling the bandwidth increases the amount of energy measured at a particular frequency, therefore the signal and noise data measured for Figure 18 would have been approximately double in magnitude.

Since the variance of the estimate is the same whether the bandwidth is doubled (Oppenheim and Schafer [27] state that the variance of the estimate is proportional to the inverse of the number of waveforms averaged), the uncertainty in the signal and noise estimate do not depend on the bandwidth. Therefore, the signal could be resolved to much higher frequencies at the expense of frequency resolution and bias (Oppenheim and Schafer). The sampling rate used for data acquisition should be carefully investigated for future work.

Figures 26 and 27 show the data taken in the freestream of the SWT. Obviously there is much more scatter in the data and the integrand does not approach zero. This was due to the fact that the freestream signal was extremely small and became indistinguishable from the noise too soon. Therefore no further work was done with the freestream signal. The number of waveforms taken would have to be increased to obtain more information from the freestream.

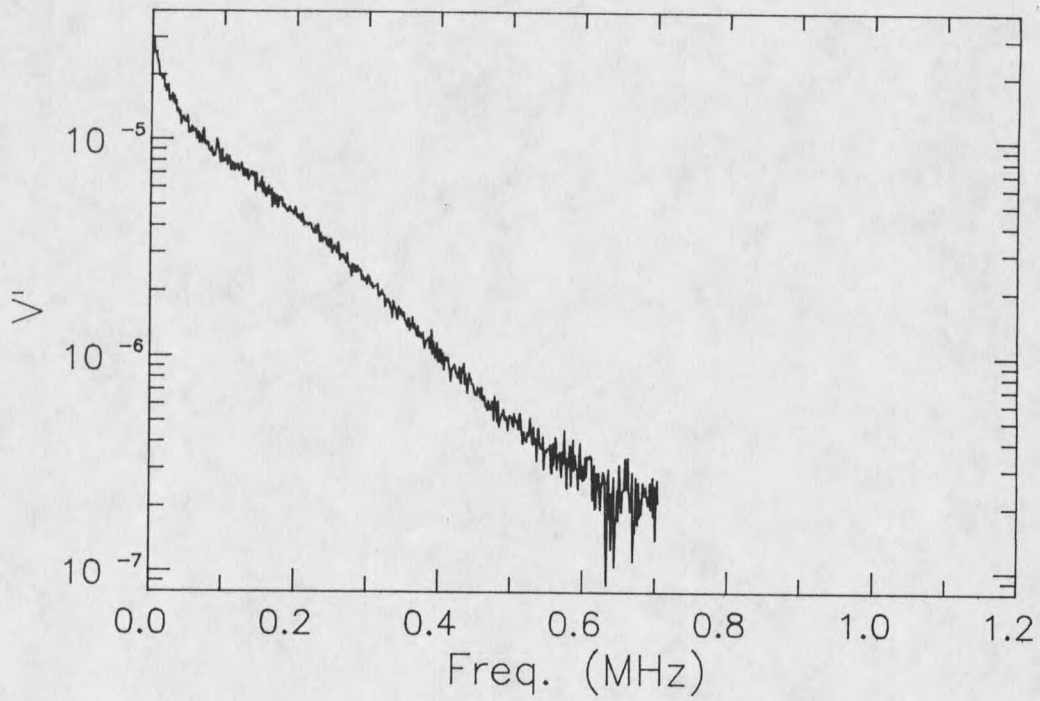


Figure 16. RMS Voltage Spectrum at $y/\delta = .091$.

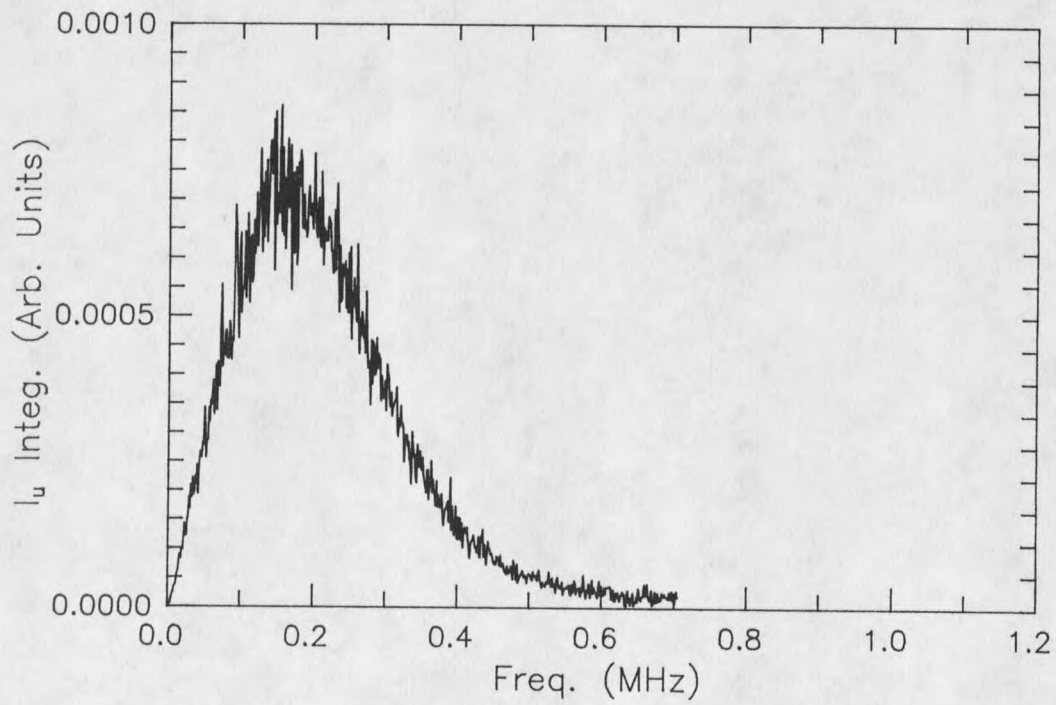


Figure 17. Integrand of Dissipation Function at $y/\delta = .091$.

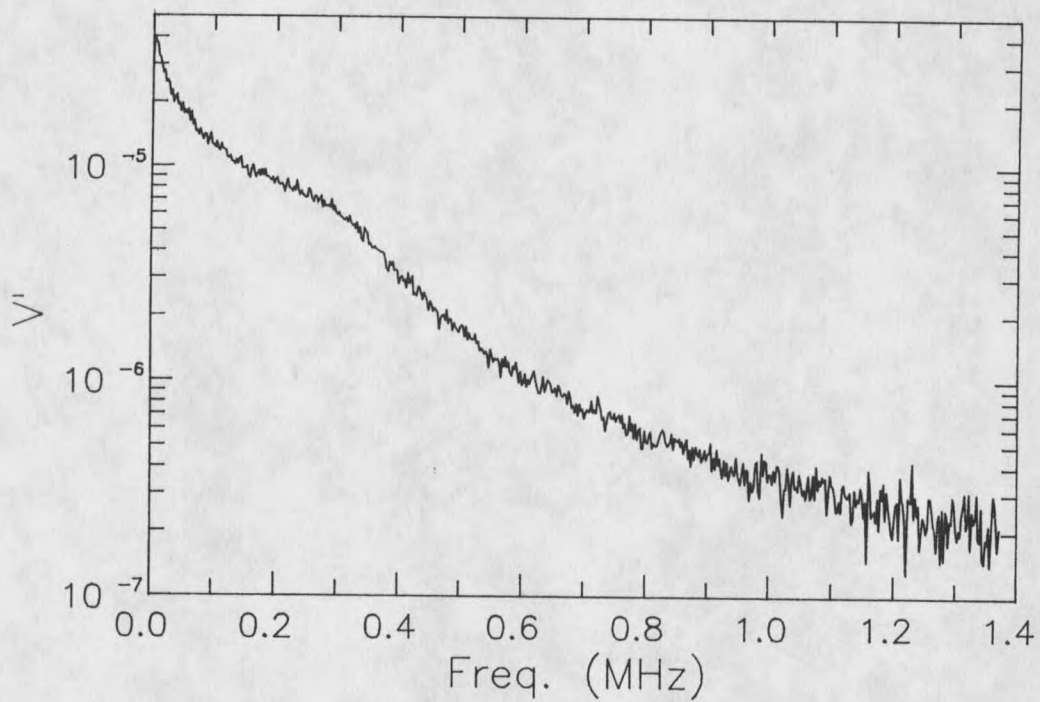


Figure 18. RMS Voltage Spectrum at $y/\delta = .496$ (# 1).

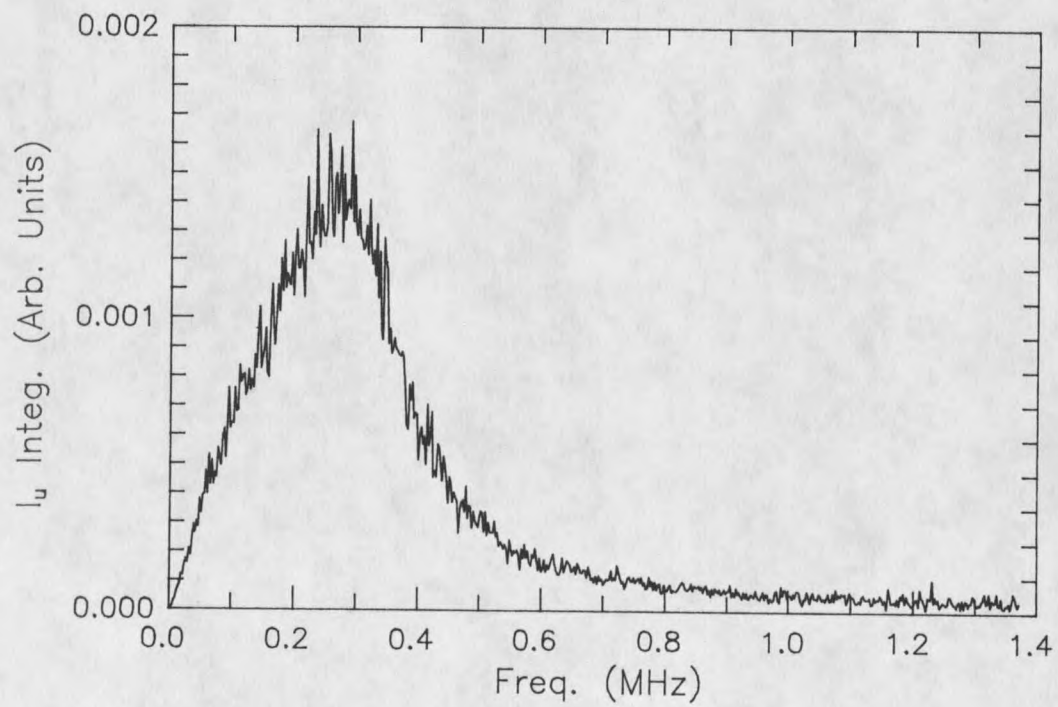


Figure 19. Integrand of Dissipation Function at $y/\delta = .496$ (# 1).

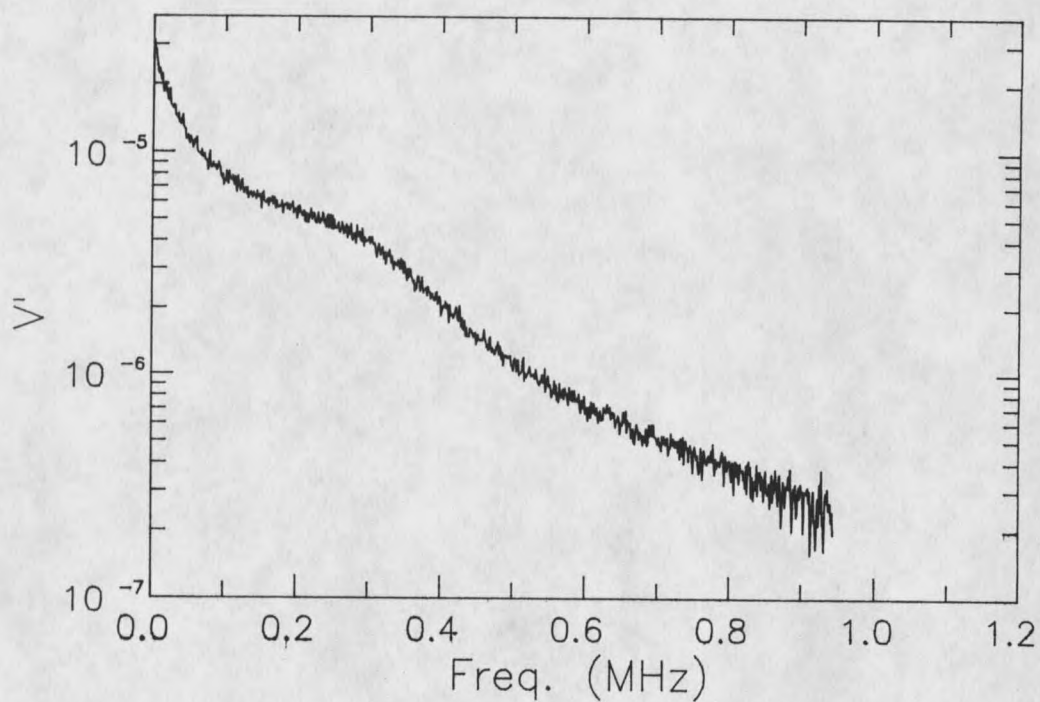


Figure 20. RMS Voltage Spectrum at $y/\delta = .496$ (# 2).

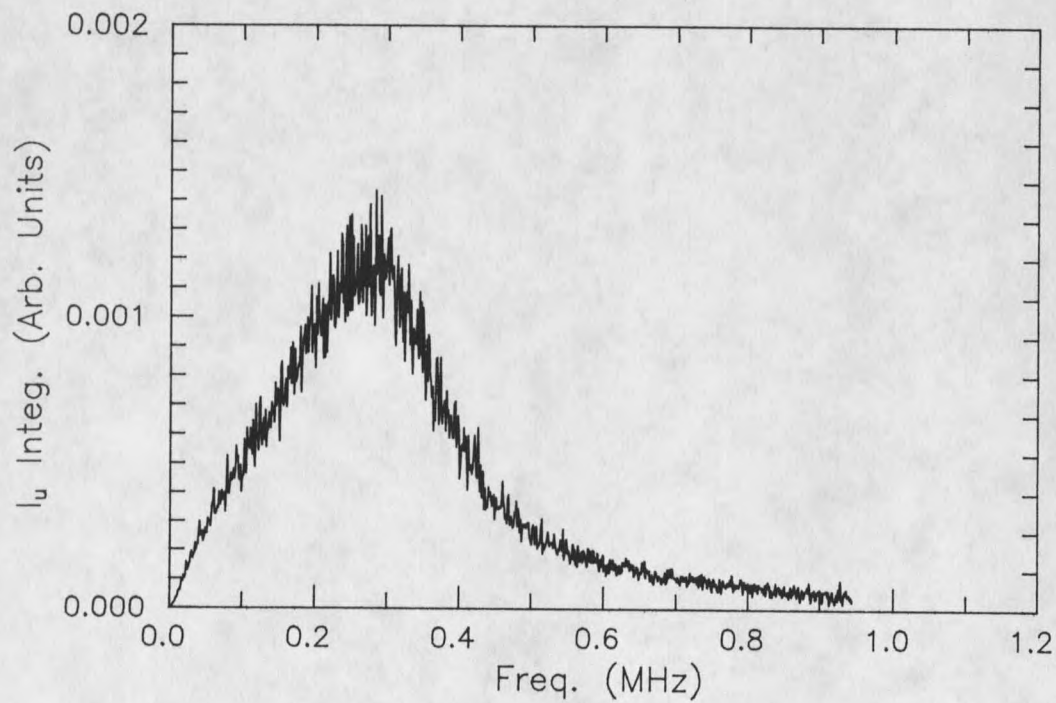


Figure 21. Integrand of Dissipation Function at $y/\delta = .496$ (# 2).

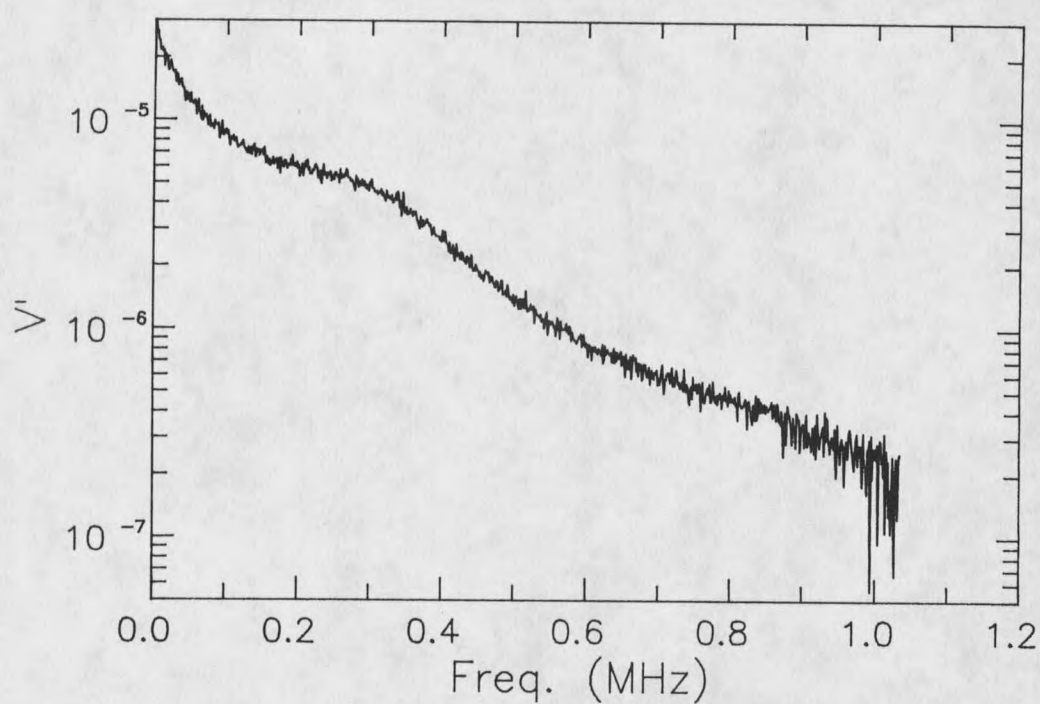


Figure 22. RMS Voltage Spectrum at $y/\delta = .738$.

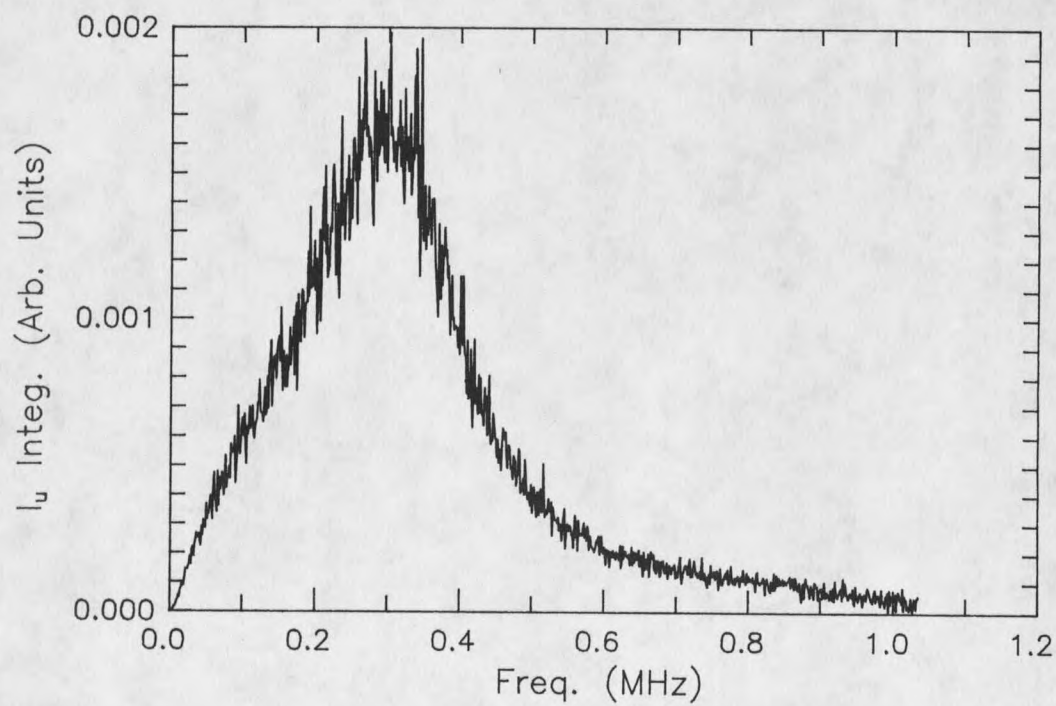


Figure 23. Integrand of Dissipation Function at $y/\delta = .738$.

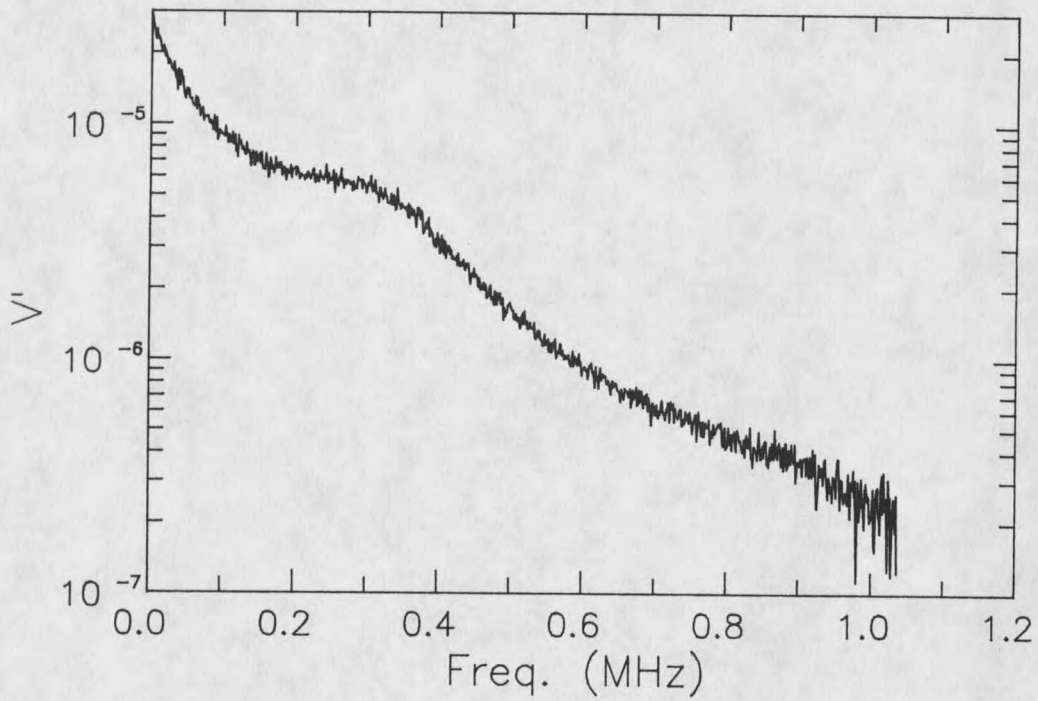


Figure 24. RMS Voltage Spectrum at $y/\delta = .981$.

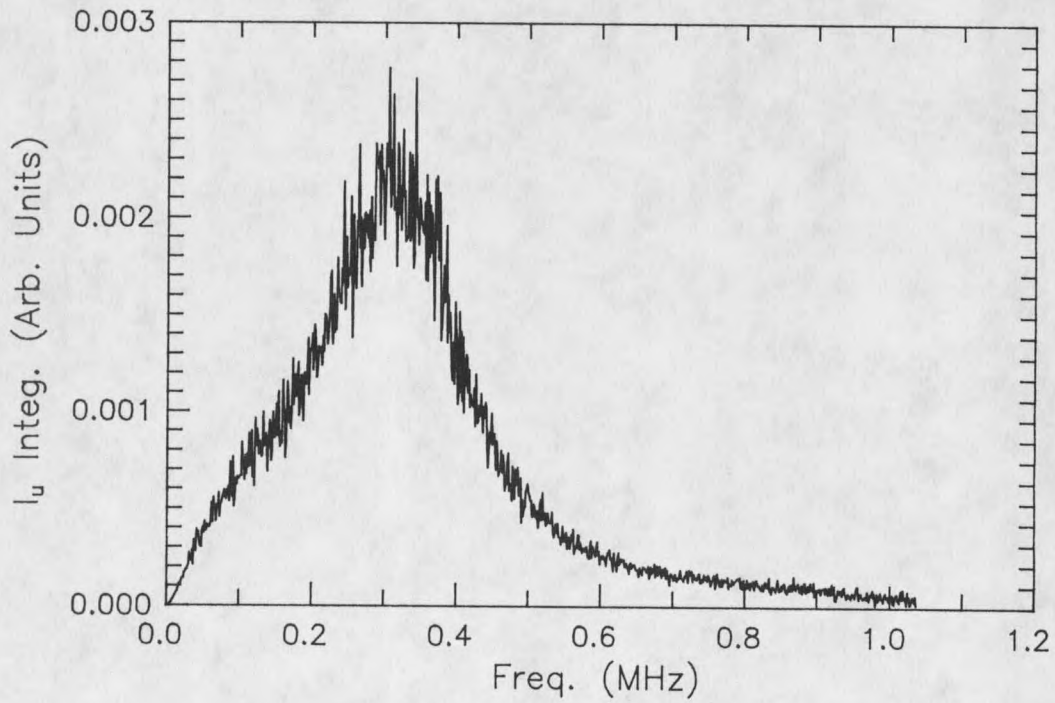


Figure 25. Integrand of Dissipation Function at $y/\delta = .981$.

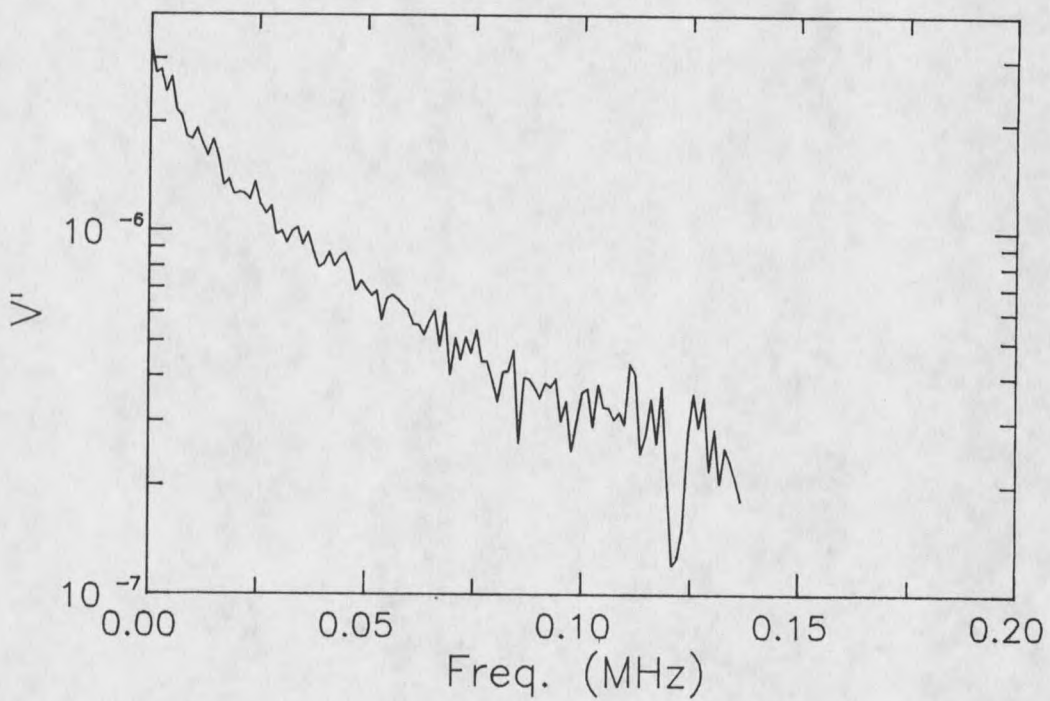


Figure 26. RMS Voltage Spectrum in the Freestream.

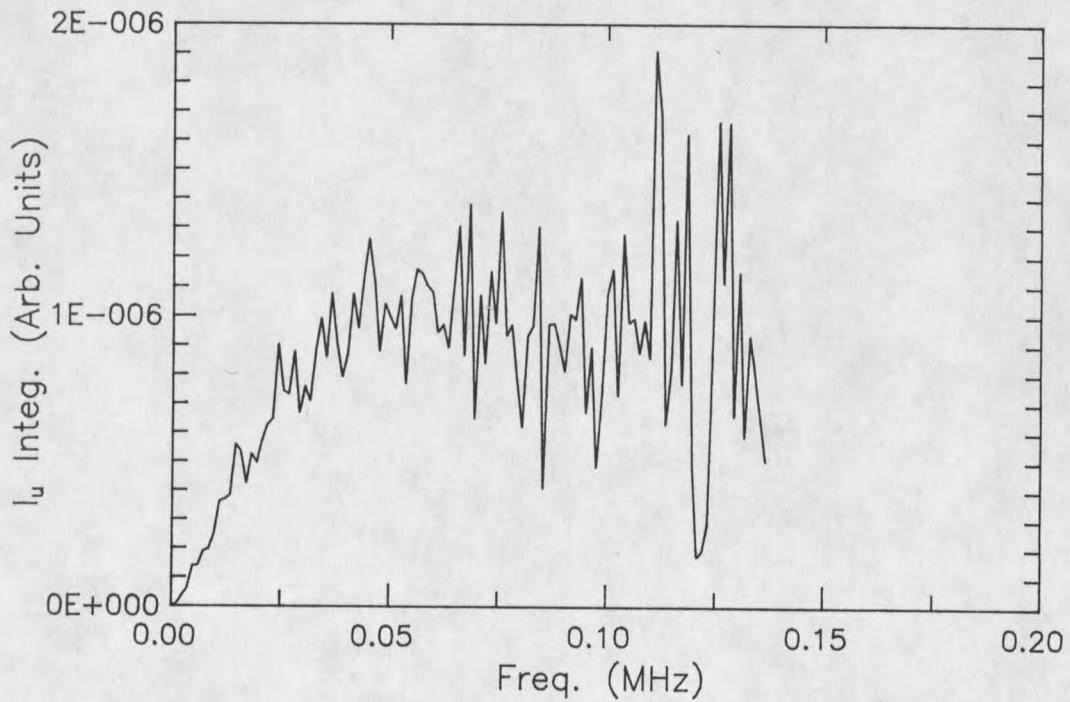


Figure 27. Integrand of Dissipation Function in the Freestream.

Since there was confirmation that the dissipation spectrum approached zero at high frequencies, the integration necessary to calculate the dissipation function was straightforward. The program DISSIP.BAS was written to do the last of the data reduction. The conversion of the voltage RMS levels to velocity RMS levels was similar to that done for the wideband data reviewed earlier. With the conversion and the integration done, the dissipation function was calculated. Once these calculations were done, the Kolmogoroff velocity (u_K), Kolmogoroff wavenumber (k_K) and dimensionless power spectra were calculated. Also of interest was the velocity microscale, which is defined as

$$(26) \quad \lambda \equiv \frac{u' u}{2\pi \sqrt{I_u}}$$

where I_u is

$$(27) \quad I_u \equiv \int_0^\infty f^2 (u'(f))^2 df$$

In order to compare the spectra calculated with the universal spectrum Re_λ was calculated. It is defined as

$$(28) \quad Re_\lambda = \frac{u' \lambda}{\nu}$$

Universal Spectrum Results

The non-dimensional spectra will be compared with Pao's [3] universal spectrum. This theory was developed under the assumption of incompressible, homogeneous and isotropic turbulence. The theory assumes a $Re_\lambda = \infty$. Figure 28 shows Pao's universal spectrum with incompressible non-dimensional spectra from Chapman [28]. This plot demonstrates the "leveling off" of the spectra due to the effect of Re_λ .

The Re_λ calculated for the present data are shown in Figure 29. The numbers shown compare very well with the Re_λ 's found by Demetriades and Martindale [6] also shown. The Re_λ values have not come closer to zero as was expected at the edge of the boundary layer. As was stated in the intermittency section, this result could be due to the definition of the boundary layer edge used.

Figure 30 shows the Kolmogoroff wave number. It appears to be approximately constant throughout the boundary layer. These data are somewhat lower than the wave numbers reported by Demetriades and Martindale [6]. However one possible explanation is that their data concerned fully turbulent flow whereas the present data was in the transition region,

Figure 31 shows the microscales found for the present data. Again it is compared to data from Demetriades and Martindale [6]. As seen in the figure, the microscales are above those found by Demetriades and Martindale but have much less scatter. Again this result could be due to the calculation of the dissipation function.

The dissipation function is usually compared in non-dimensional form shown in Figure 32. These data are compared with data from Demetriades and Martindale [6]. The present data are lower than their data but have much less scatter. Their data is in doubt due to the uncertainty and scatter in their dissipation spectra.

The wideband RMS velocity fluctuations are shown in Figure 33. They are lower than the velocity fluctuations found in the wideband section previously discussed. However the present wideband RMS levels were compared to those found by the RMS meter as mentioned earlier and were converted to velocity fluctuations by the same method as used in the wideband section. Therefore, two

speculations could be that the DPP calibration may have drifted somewhat or that the positions in the boundary layer were measured inaccurately. The calculations were double checked but there is no explanation for this discrepancy.

Figures 34 through 53 show the twenty non-dimensional spectra calculated in comparison to the universal spectrum which has an $Re_\theta = \infty$. They are shown in increasing order of y/δ . As has been mentioned earlier, there is not much scatter in the data until the high end of the spectra is reached where the noise had more influence on the signal.

The first few spectra are all below the universal spectrum. As the y/δ is increased, the spectra move closer to the universal spectrum and a "hump" forms which extends above the universal spectrum. Although not seen in the Mach 3 data, Demetriades and Martindale [6] presented spectra from other wind tunnels that exhibited this phenomenon to some extent. A possible explanation is that the data were in the transition region and not isotropic.

Figure 54 shows the two spectra taken at the same y/δ but different sampling rates. They were also taken at slightly different power supply voltages approximately twenty days apart. As can be seen in the figure the two spectra fall on top of one another indicating that the DPP is repeatable. The spectrum with the higher sampling rate does extend to higher wavenumbers as was explained earlier.

Figure 55 compares the velocity spectrum at $k/k_K = .002$ with data taken from Demetriades and Martindale [5]. The present data seems to be going against the trend demonstrated by their data but it is within the scatter of their data. Again this could be attributed to the fact that the flow was transitional.

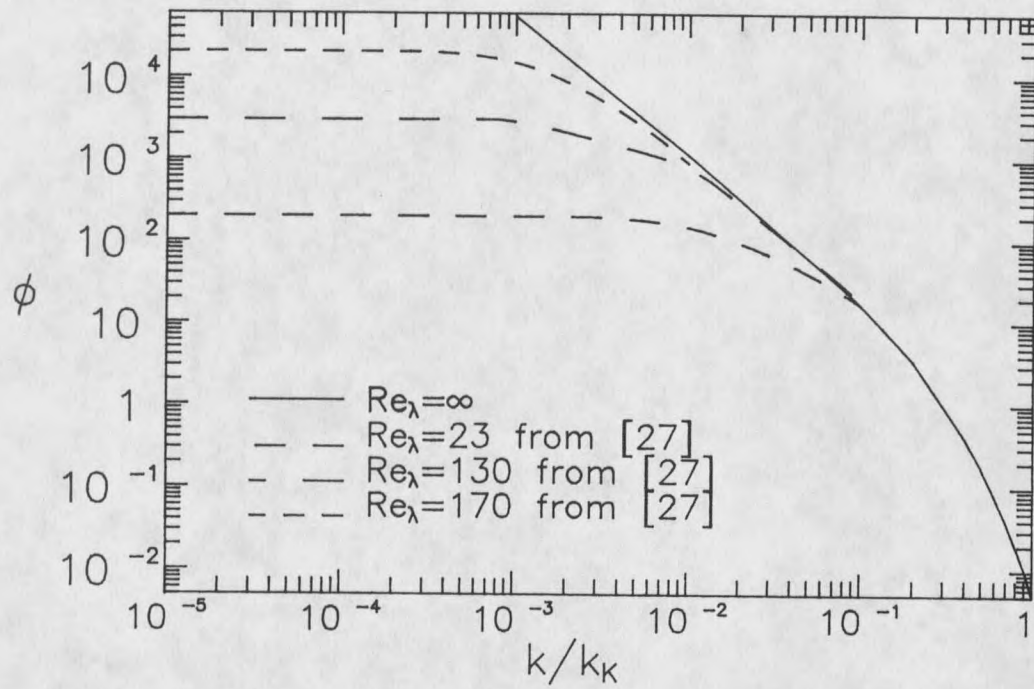


Figure 28. Incompressible Spectra Compared to Universal Spectrum.

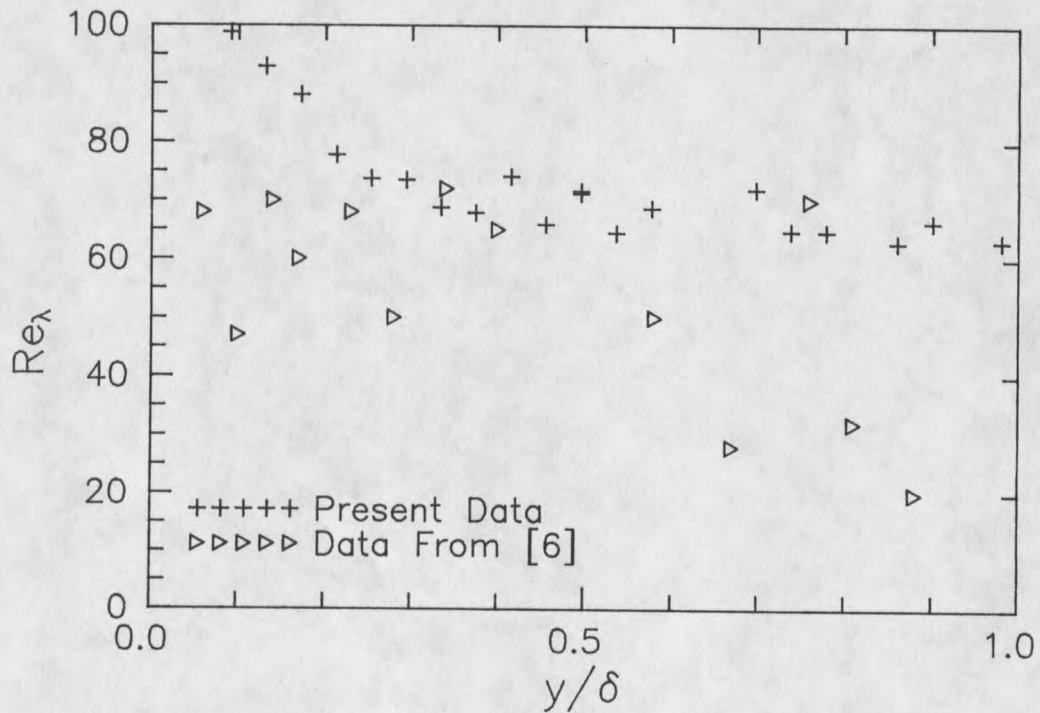


Figure 29. Re_λ Comparison.

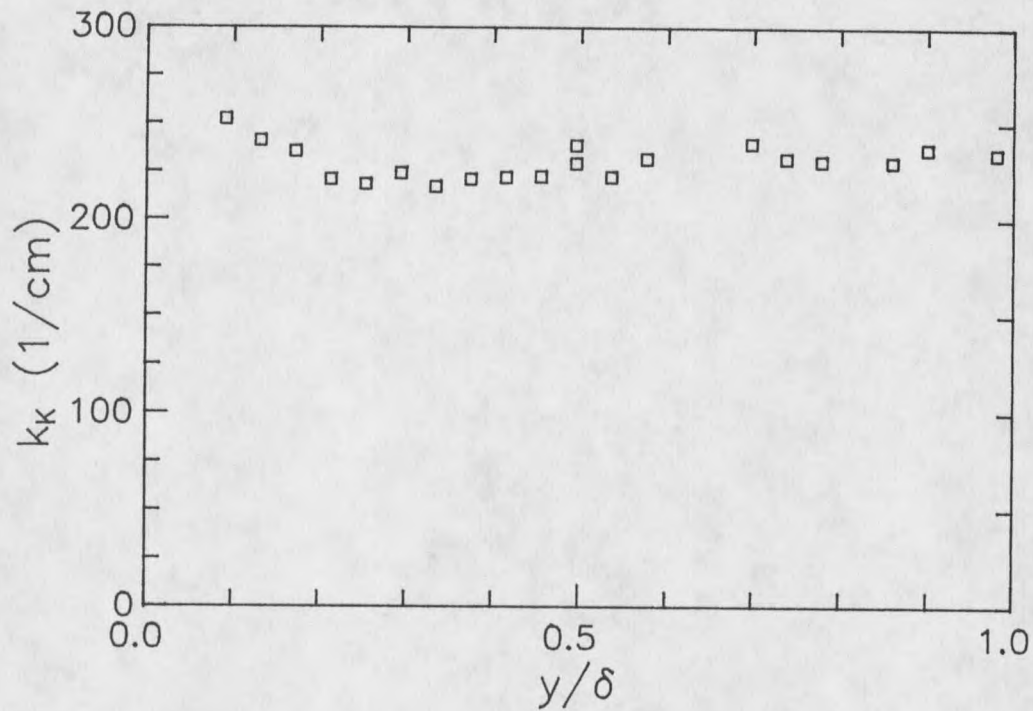


Figure 30. Kolmogoroff Wave Number.

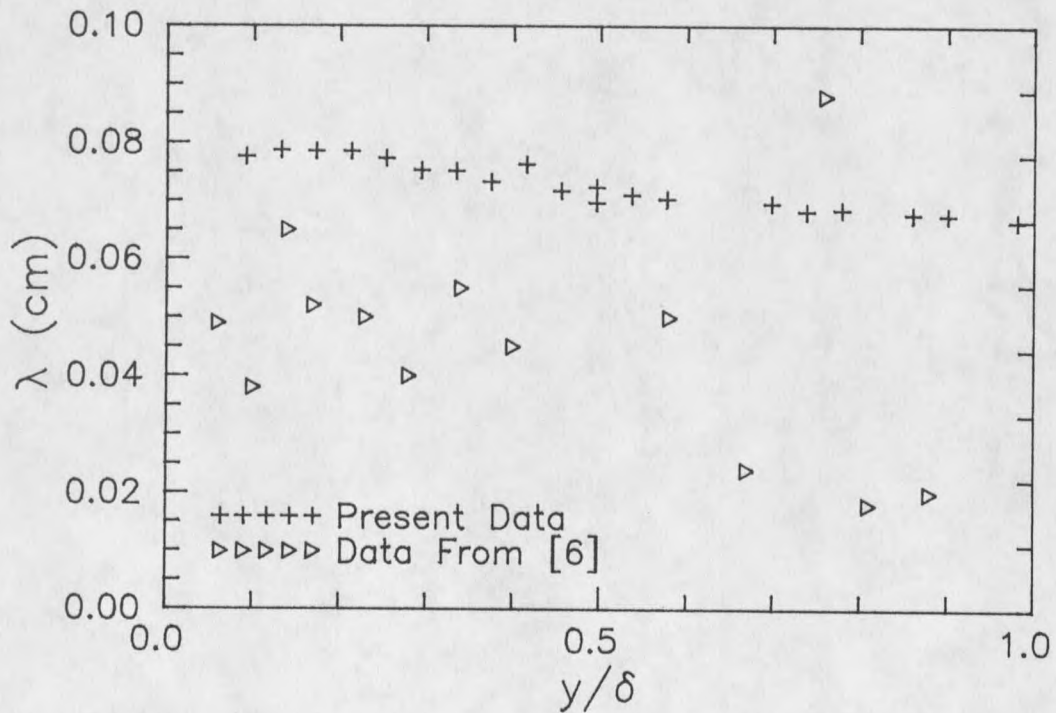


Figure 31. Microscale Comparison.

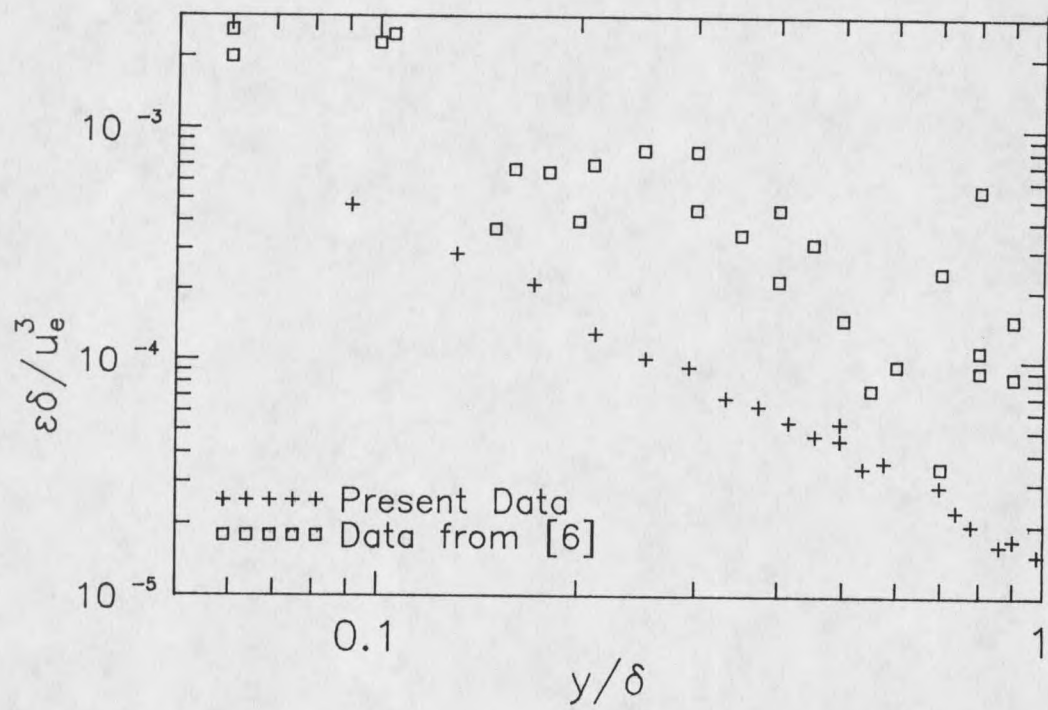


Figure 32. Dissipation Function Comparison.

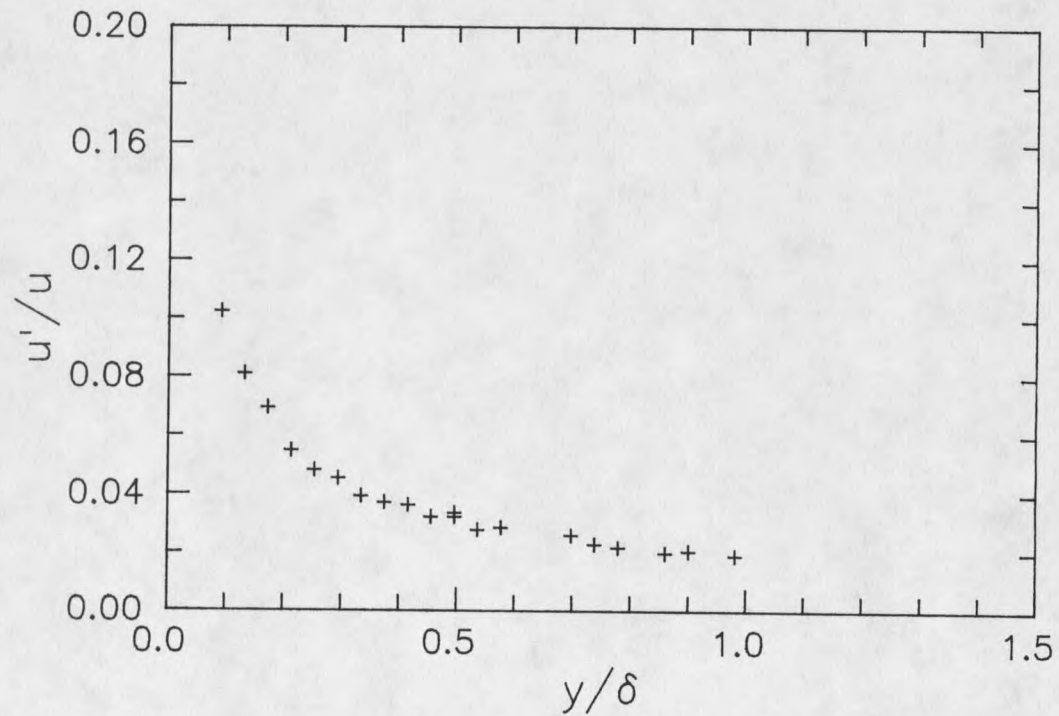


Figure 33. Wideband Velocity RMS Fluctuations.

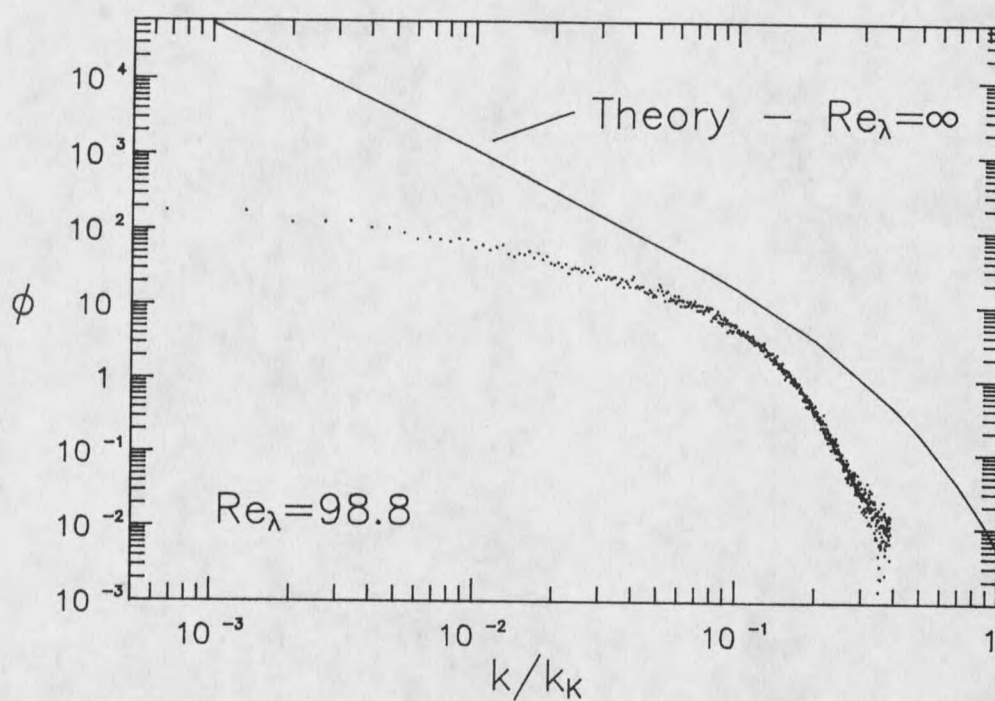


Figure 34. Non-Dimensional Spectrum at $y/\delta = .091$.

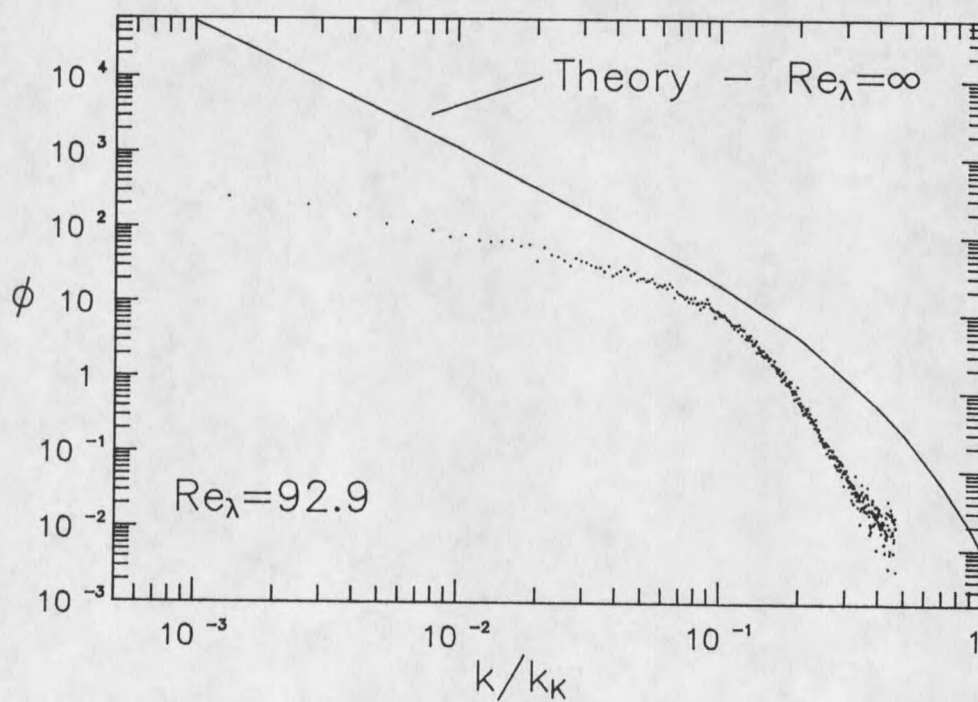


Figure 35. Non-Dimensional Spectrum at $y/\delta = .131$.

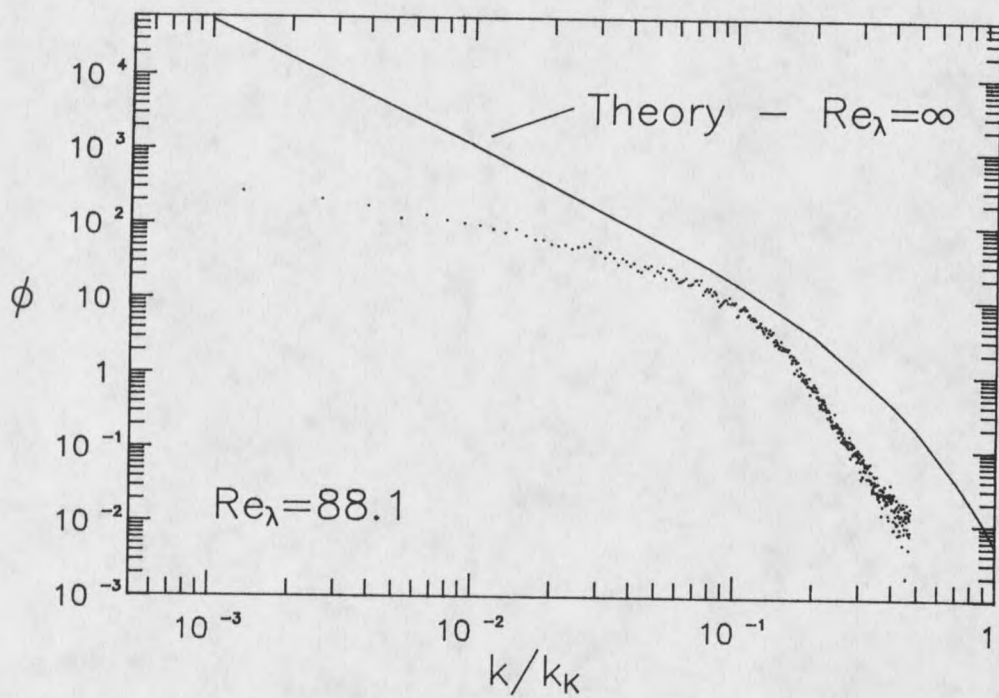


Figure 36. Non-Dimensional Spectrum at $y/\delta = .172$.

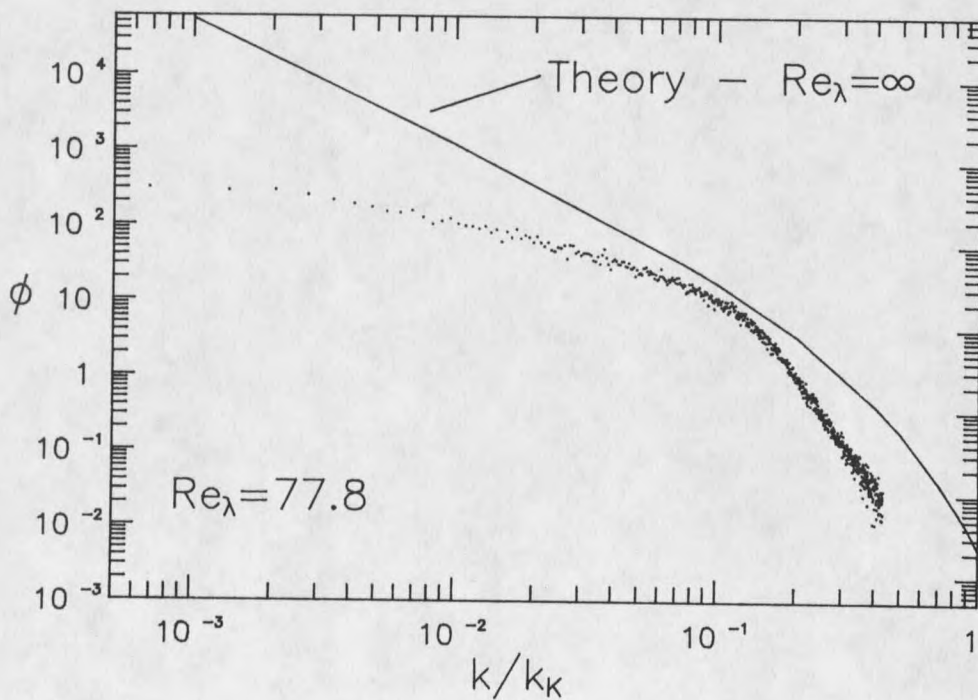


Figure 37. Non-Dimensional Spectrum at $y/\delta = .212$.

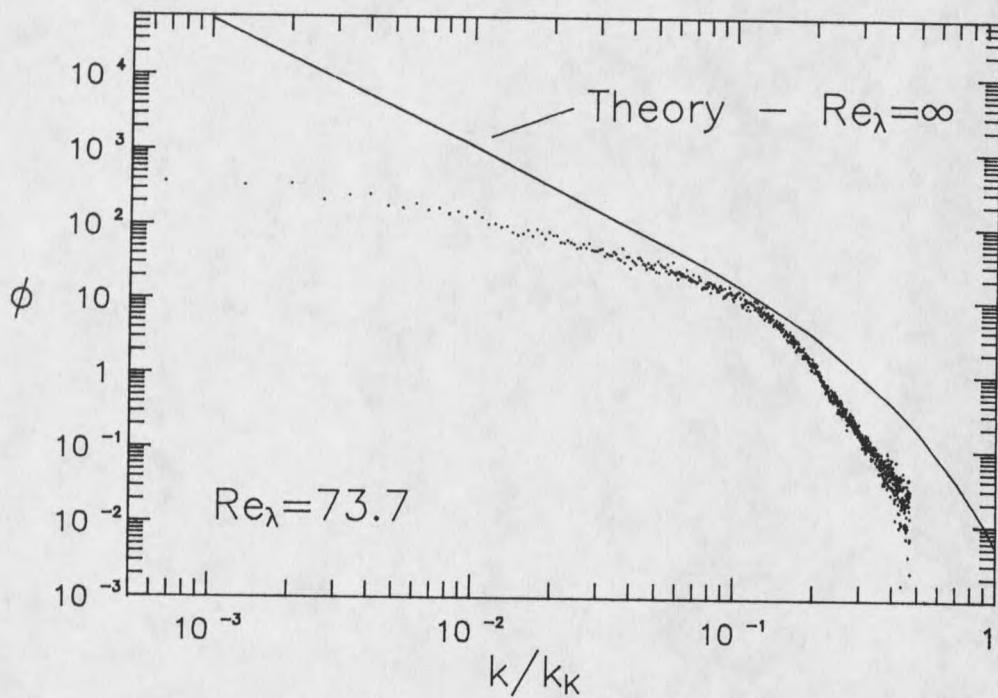


Figure 38. Non-Dimensional Spectrum at $y/\delta = .253$.

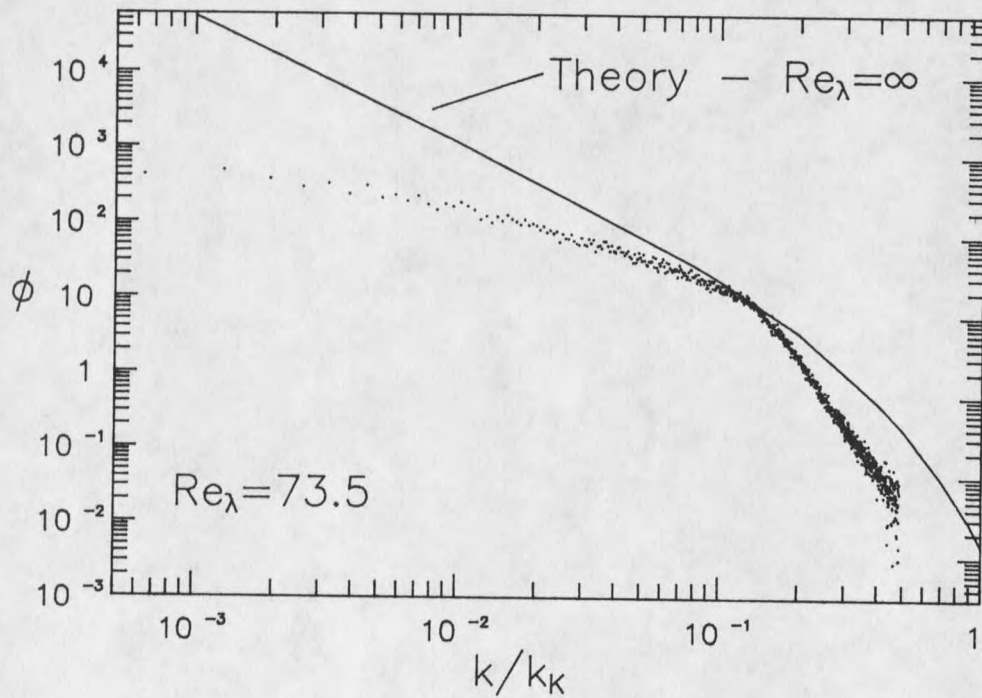


Figure 39. Non-Dimensional Spectrum at $y/\delta = .293$.

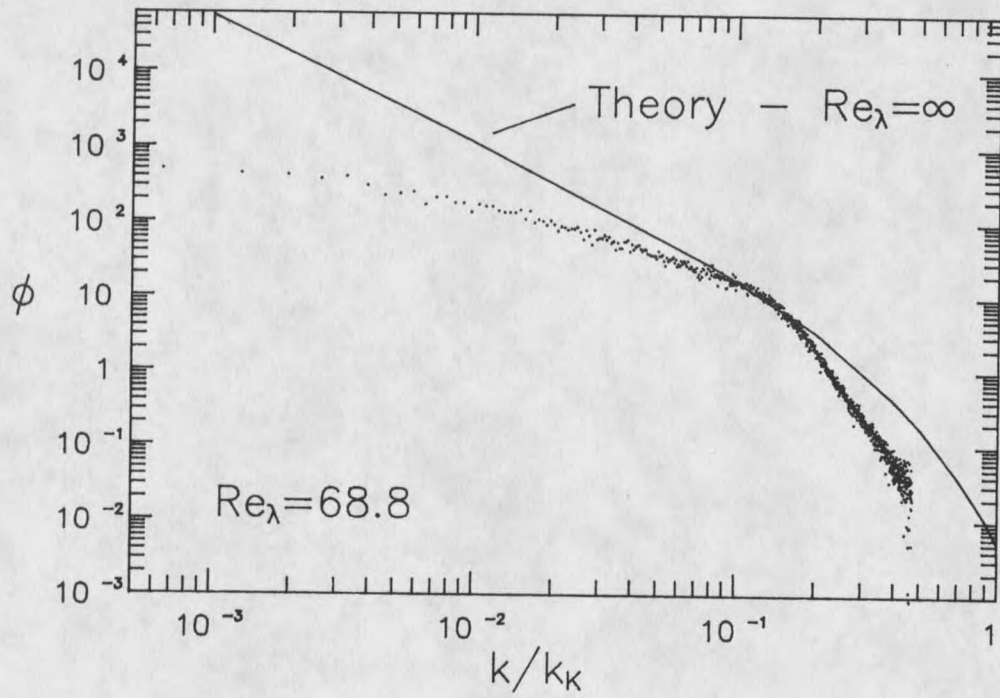


Figure 40. Non-Dimensional Spectrum at $y/\delta = .334$.

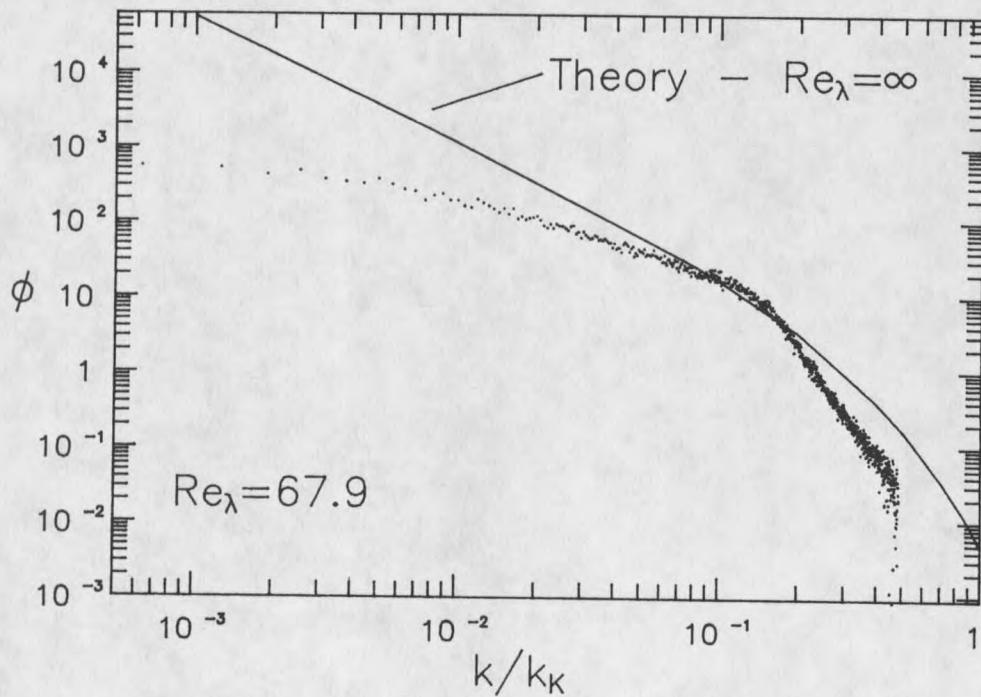


Figure 41. Non-Dimensional Spectrum at $y/\delta = .374$.

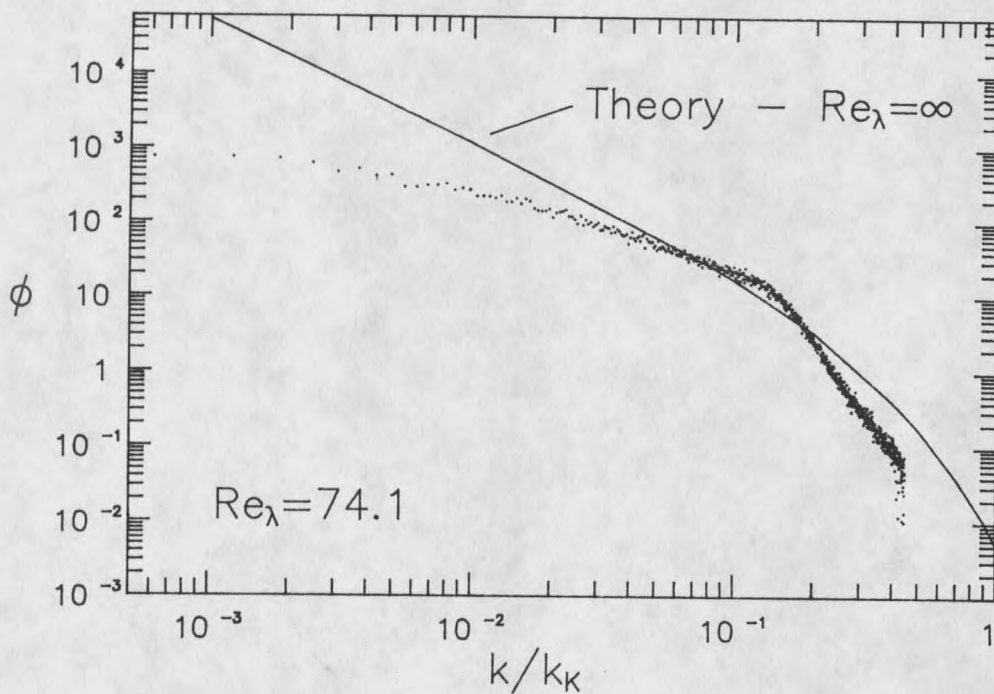


Figure 42. Non-Dimensional Spectrum at $y/\delta = .415$.

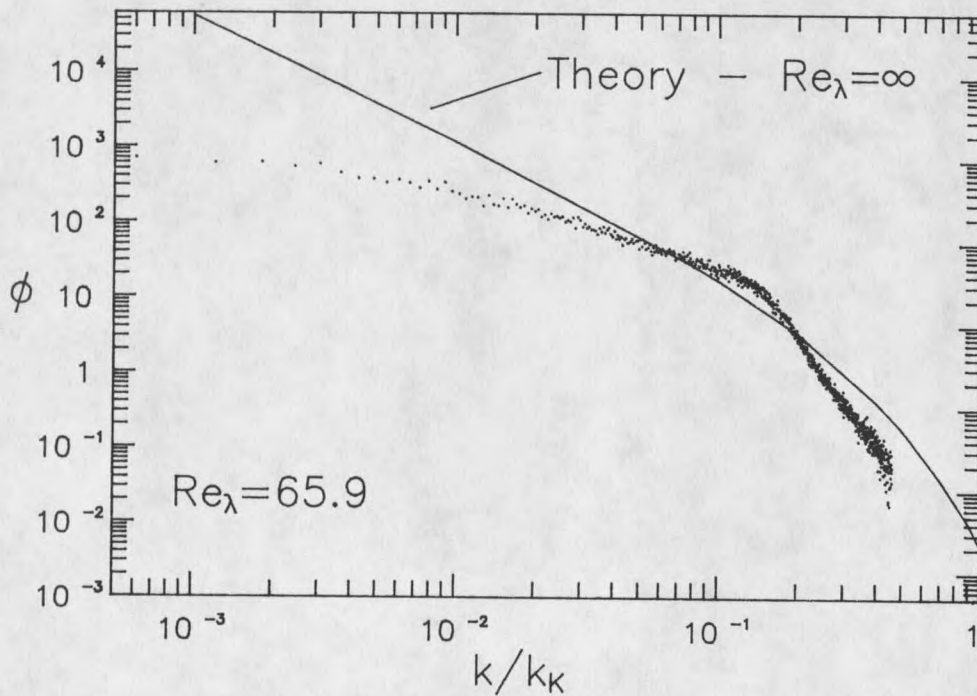


Figure 43. Non-Dimensional Spectrum at $y/\delta = .445$.

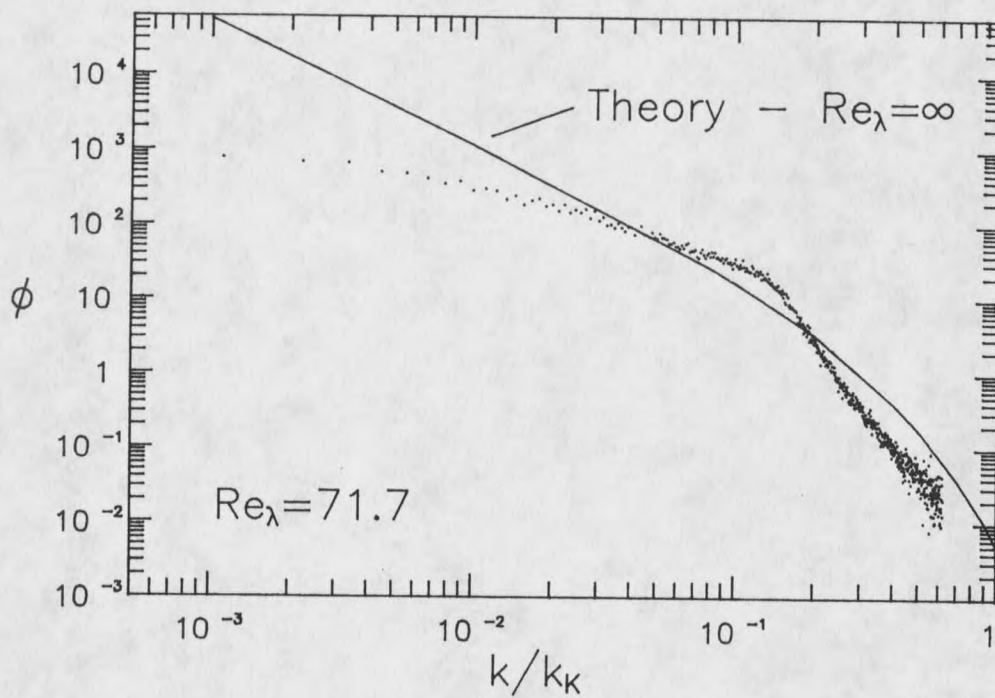


Figure 44. Non-Dimensional Spectrum at $y/\delta = .496$ (# 1).

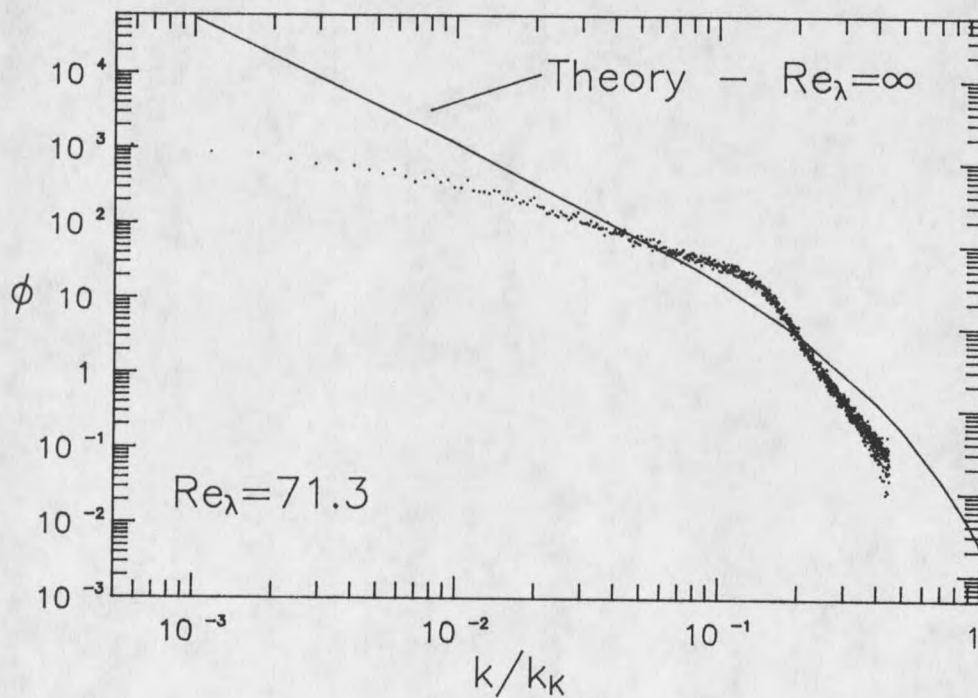


Figure 45. Non-Dimensional Spectrum at $y/\delta = .496$ (# 2).

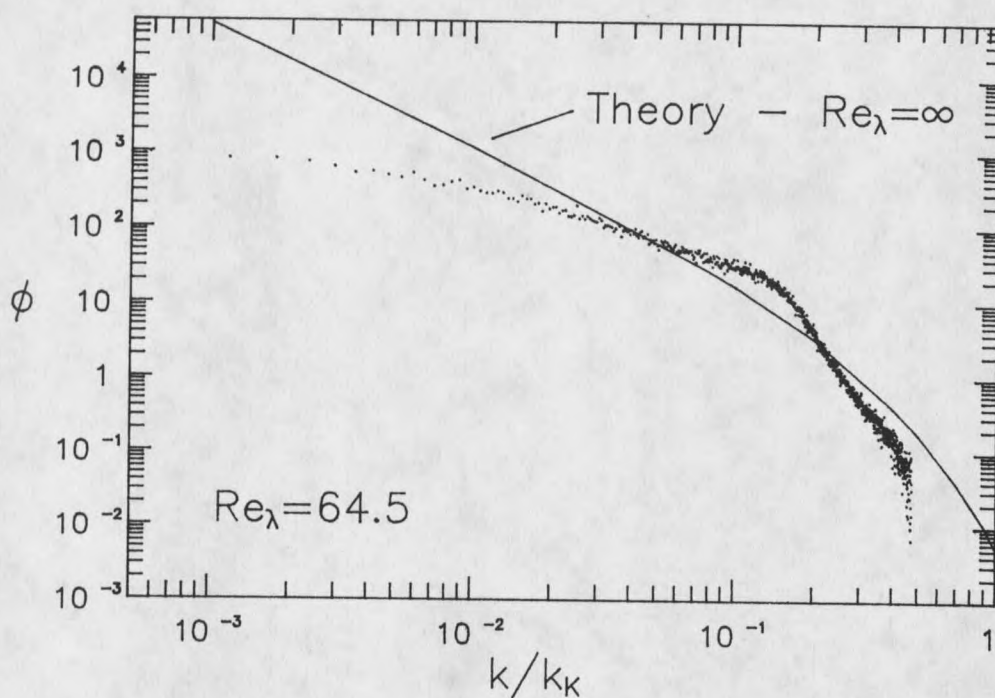


Figure 46. Non-Dimensional Spectrum at $y/\delta = .536$.

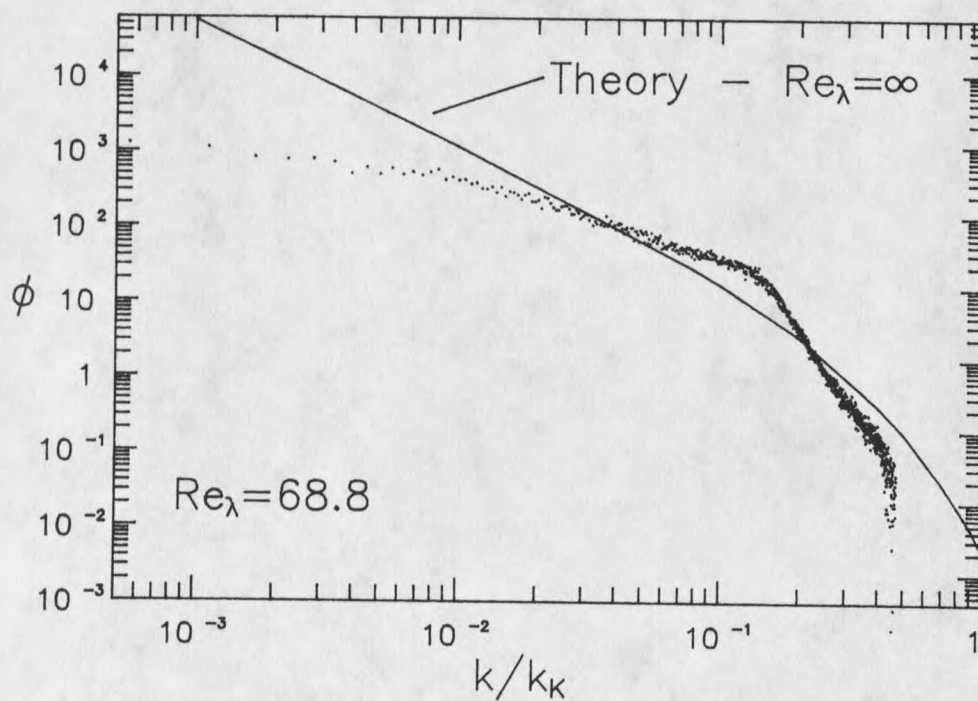


Figure 47. Non-Dimensional Spectrum at $y/\delta = .576$.

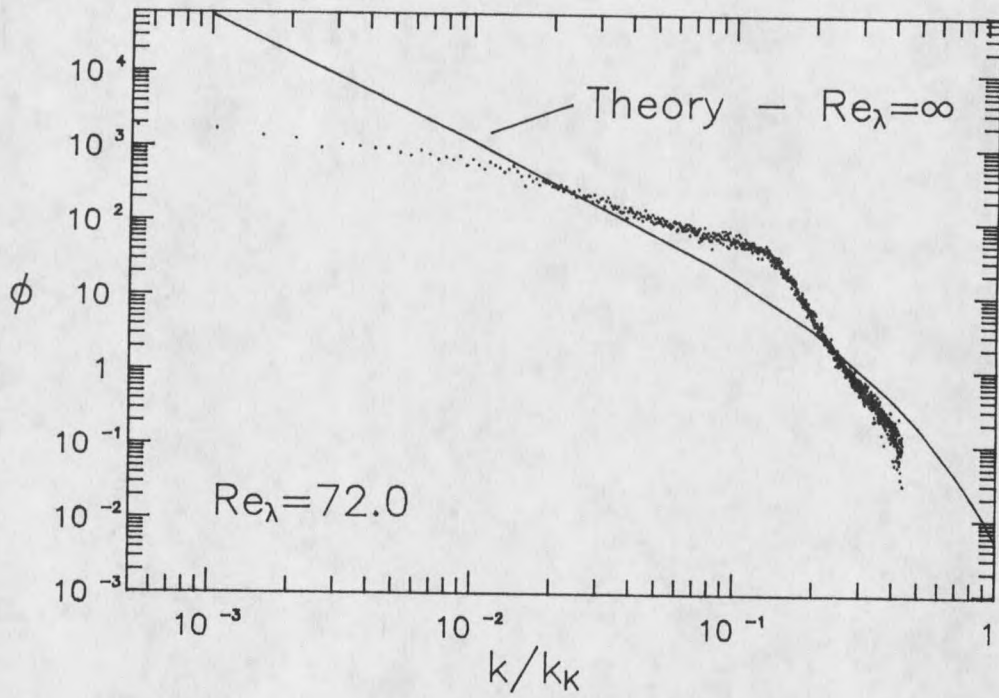


Figure 48. Non-Dimensional Spectrum at $y/\delta = .698$.

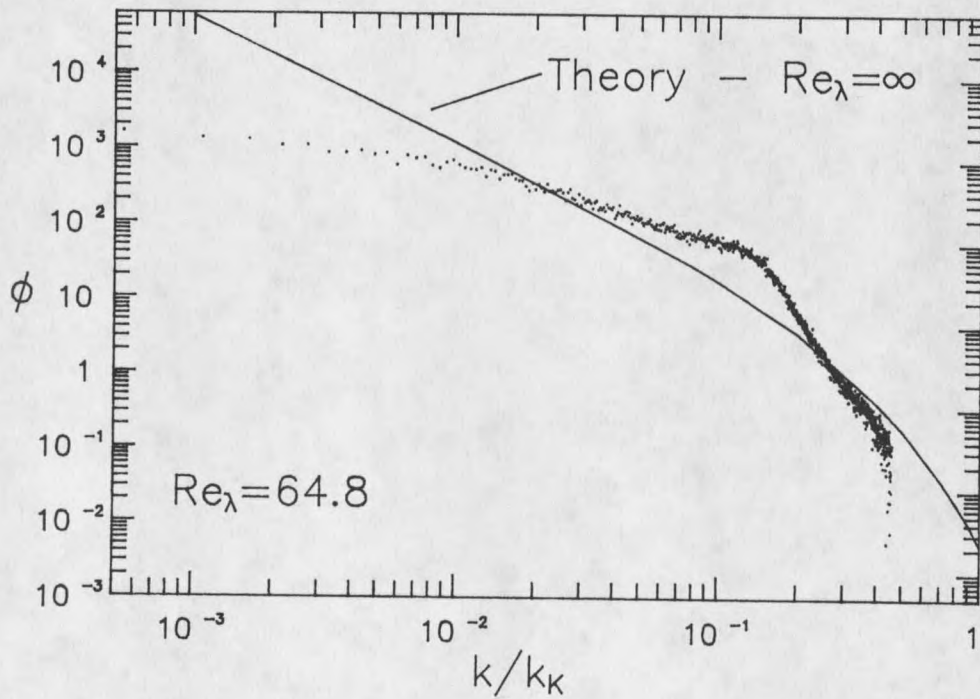


Figure 49. Non-Dimensional Spectrum at $y/\delta = .738$.

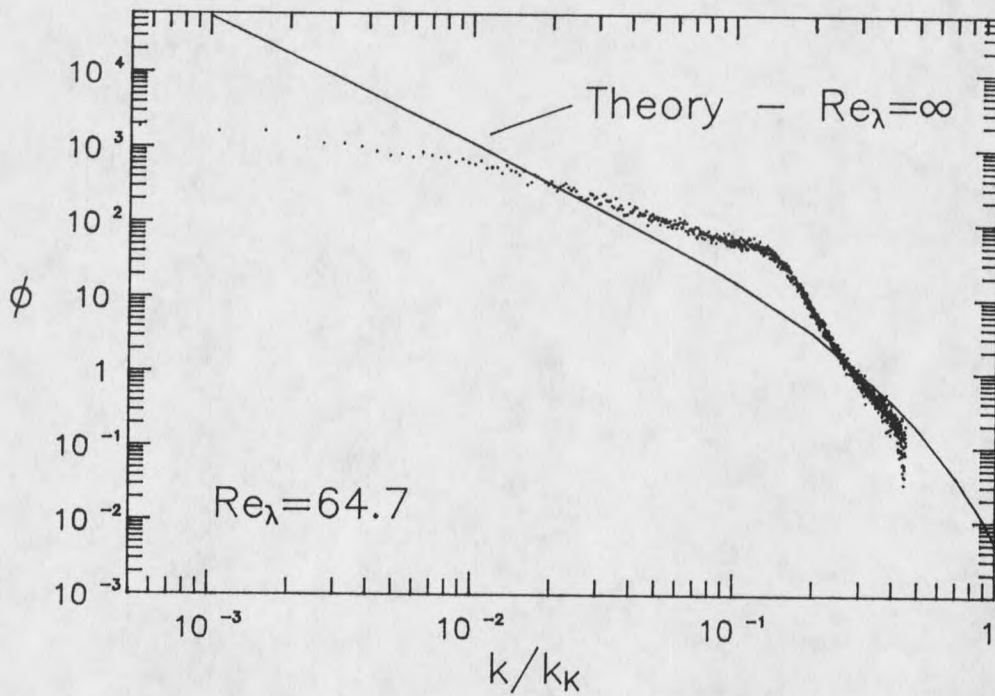


Figure 50. Non-Dimensional Spectrum at $y/\delta = .779$.

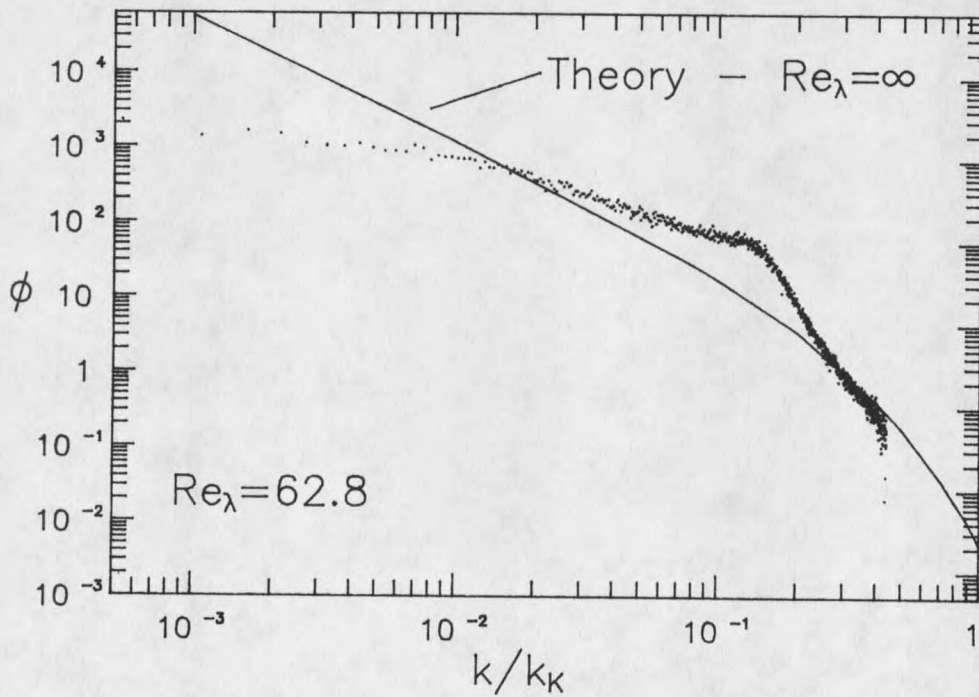


Figure 51. Non-Dimensional Spectrum at $y/\delta = .860$.

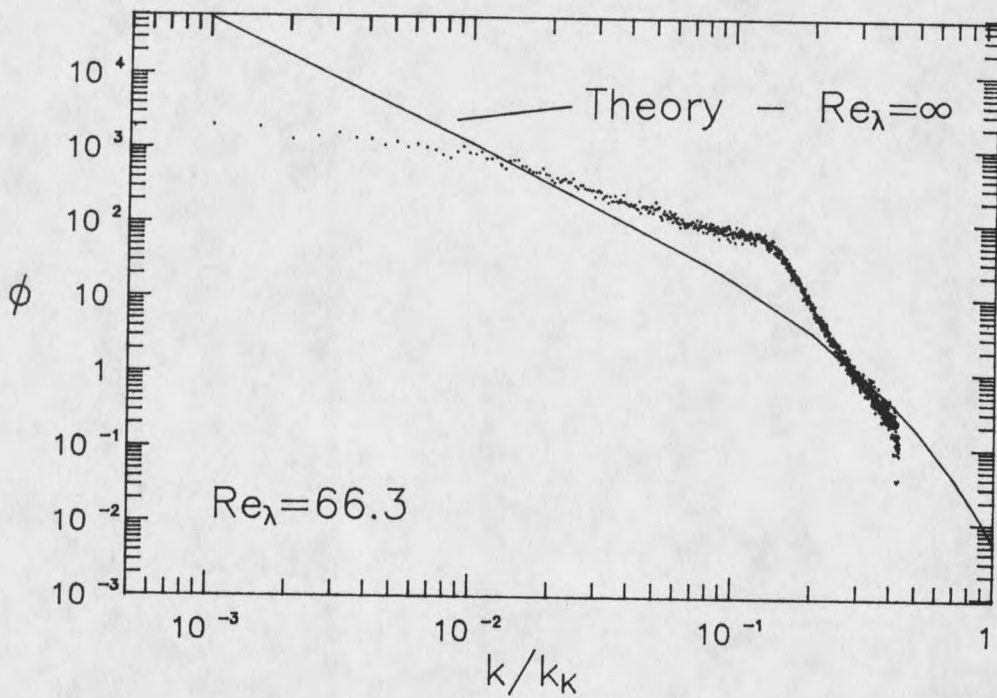


Figure 52. Non-Dimensional Spectrum at $y/\delta = .900$.

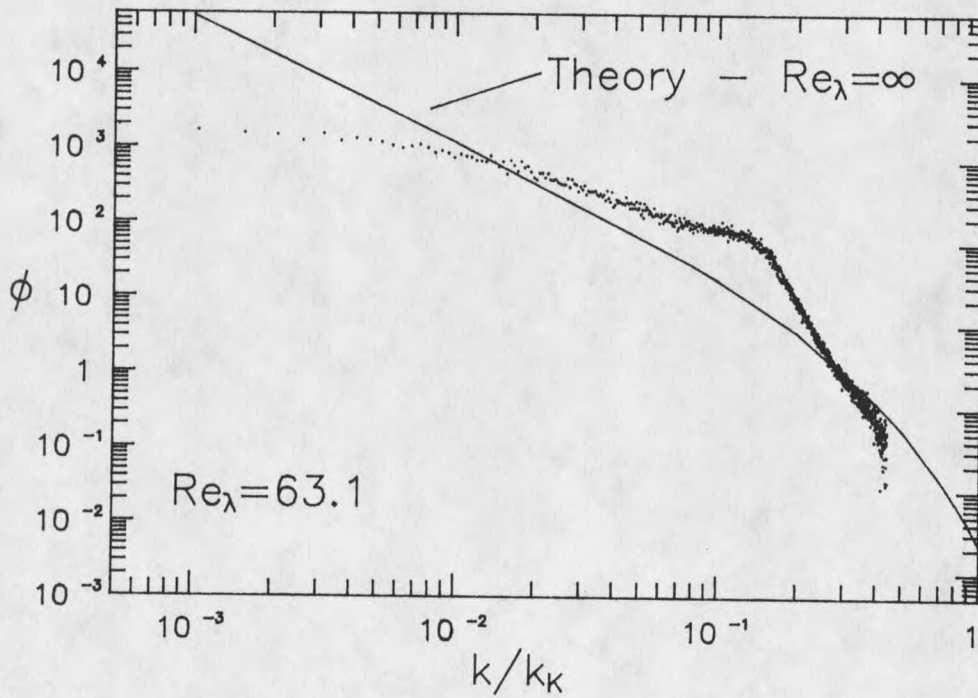


Figure 53. Non-Dimensional Spectrum at $y/\delta = .981$.

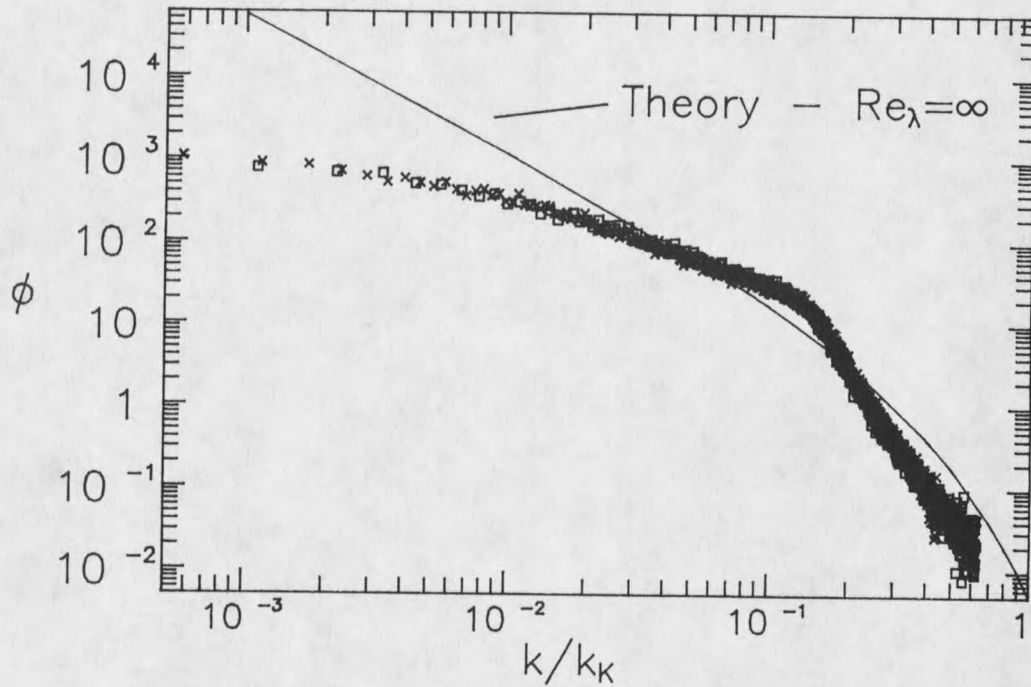


Figure 54. Comparison of Two Spectra taken at $y/\delta = .496$.

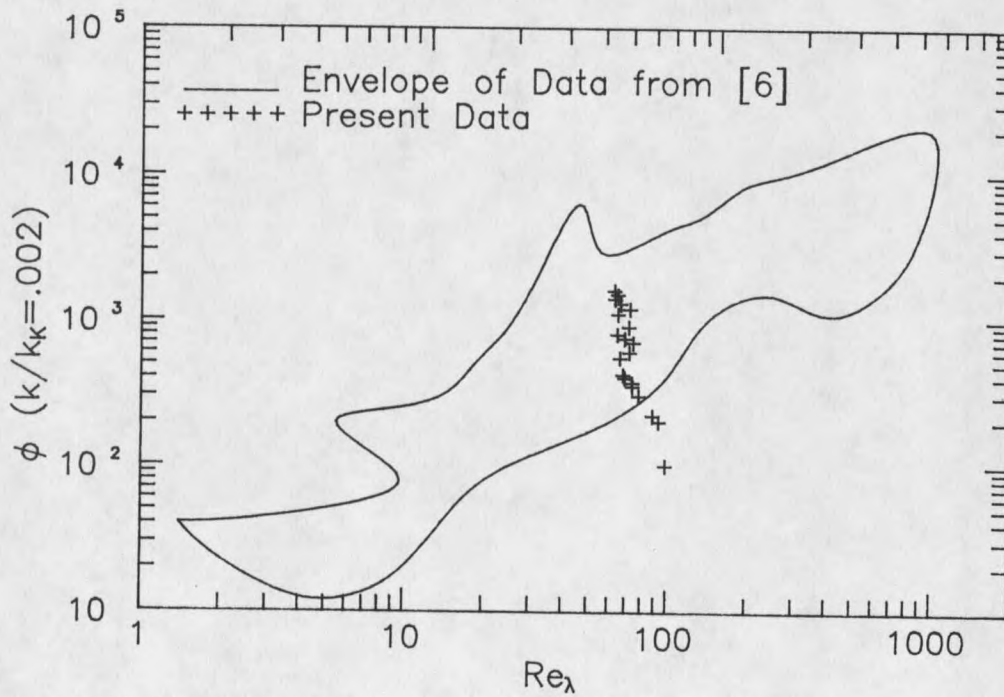


Figure 55. Reynolds Number Dependence of the Velocity Spectrum at a Low Wavenumber.

CHAPTER 4

CONCLUSIONS

Mean Flow

The distribution of mean flow properties in the boundary layer was consistent with those measured earlier in the same wind tunnel. The data showed a gradual approach to the fully turbulent flow profile expressed as $u^+ = 5 + 2.43 * \ln(y^+)$. This approach is explained if the boundary layer was in the last stages of transition for the range of Re_θ used.

The coefficients of friction were computed from the profile data on the assumption that the $d(u^+)/d(\ln(y^+))$ was constant. These coefficients of friction also showed a gradual approach to a previously measured value at a higher Re_θ , confirming that the boundary layer was transitional. However the numerical values of the coefficients of friction found are in some doubt since they were computed assuming a turbulent flow as stated above.

Wideband Measurements

The turbulent u'/u data also showed a gradual approach to a datum taken at higher Re_θ than used here. This again confirmed the transitional state of the boundary layer.

Spectral Analysis

The dissipation spectra have been measured with precision. They showed, for the first time in supersonic turbulence research, Pao's theoretically expected behavior.

The dissipation functions, as a result, were measured with a degree of scatter so low as to be unprecedented in supersonic research, as was seen when compared to previously measured dissipation functions.

The velocity spectra, for the Re_θ examined, approached the universal spectrum in a way dependent on the distance from the wall. An energy peak in the spectra is not yet explainable but the transition process is thought to be a factor.

The DPP proved to be a durable and simple-to-use sensor for obtaining supersonic turbulence data with minimal noise. Signals at frequencies exceeding 1 Megahertz (10 times the boundary layer frequency) have been obtained.

The equipment used for spectral data acquisition was adequate. A GPIB port would allow for automatic and faster data acquisition than the serial port. For computation of the FFT, a minimum of a 386SX computer with a math co-processor (calculates FFT 4 times faster) is advisable. The radix-eight program should also be developed for faster FFT calculation.

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REFERENCES CITED

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APPENDICES

APPENDIX A
BOUNDARY LAYER DATA CONVERSION PROGRAM

```

CLS
DIM dcp$(500), rms$(500)
,
,
'this program can convert both mean and fluctuating data therefore:
,
INPUT "Do you have rms data(Y/N)"; type$
,
'input file(s) section:
IF type$ = "Y" OR type$ = "y" THEN
  INPUT "Are mean and rms data in same file"; smfi$
  IF smfi$ = "N" OR smfi$ = "n" THEN
    INPUT "ENTER INPUT FILENAMES(mean,rms): ", meanfile$, rmsfile$
    LPRINT "Raw data is in: "; meanfile$, rmsfile$
    OPEN "I", #1, meanfile$
    OPEN "I", #5, rmsfile$
  ELSE
    INPUT "Enter input filename: ", infile$
    LPRINT "Raw data is in: "; infile$
    OPEN "I", #1, infile$
  END IF
ELSE
  INPUT "Enter input filename: ", infile$
  LPRINT "Raw data is in: "; infile$
  OPEN "I", #1, infile$
END IF
,
,
' output files section:
,
INPUT "Enter beginning of output filename(max 5 letters): ", out$
outmean$ = out$ + "MEA.DAT"
LPRINT "Converted data is in: "; outmean$,
OPEN "O", #2, outmean$
IF type$ = "y" OR type$ = "Y" THEN
  outfluc$ = out$ + "FLU.DAT"
  LPRINT outfluc$;
  OPEN "O", #3, outfluc$
END IF
outwall$ = out$ + "WAL.DAT"
LPRINT outwall$
OPEN "O", #4, outwall$
,
,
' information needed for converting data:
,

```

Figure 56. Boundary Layer Data Conversion Program.

```

INPUT "FOR PITOT TUBE PRES=A*VOLTS+B ENTER A,B: ", A#, B#
LPRINT "Calib. for pitot tube A,B": A#; B#
INPUT "Enter distance to C/L of probe(MILS): ", ci#
LPRINT "Wall to C/L distance is(mils): "; ci#
INPUT "ENTER SPACING THAT PROBE USED(mils): ", spcc#
LPRINT "Spacing of probe is(mils): "; spcc#
INPUT "WHAT IS THE STAGNATION PRESSURE AT THIS POINT (mm Hg)": PO#
INPUT "WHAT IS THE STAGNATION TEMPERATURE (F)": TO#
LPRINT "PO(mm Hg) and TO(F): "; PO#; TO#
,
,
' information needed only if there is fluctuating data:
,
IF type$ = "Y" OR type$ = "y" THEN
  INPUT "WHAT WAS GAIN FOR A.C. SIGNAL"; acgain#
  LPRINT "A. C. gain: "; acgain#
  INPUT "WHAT WAS NOISE LEVEL RMS(volts)": rmsni#
  LPRINT "Noise level rms(volts): "; rmsni#
  INPUT "HOW MANY SCALES WERE USED ON RMS METER"; scnum
  DIM scale$(scnum)
  LPRINT
  LPRINT "Scales on rms meter: "
  FOR i = 1 TO scnum
    INPUT "SCALE = "; scale$(i)
    LPRINT scale$(i)
  NEXT i
  LPRINT
  INPUT "What was slope for dpp (mV/psi/Vsup)": arms#
  LPRINT "Slope for dpp (mV/psi/Vsup): "; arms#
  INPUT "What was supply voltage of dpp"; vsup#
  LPRINT "Dpp supply voltage: "; vsup#
END IF
,
,
' input raw data:
,
n = 0
IF type$ = "N" OR type$ = "n" THEN
  DO UNTIL EOF(1)
    n = n + 1
    INPUT #1, dcp$(n)
  LOOP
ELSE
  IF smfi$ = "Y" OR smfi$ = "y" THEN
    DO UNTIL EOF(1)
      n = n + 1

```

Figure 56 (continued). Boundary Layer Data Conversion Program.

```

        INPUT #1, dcp#(n), rms#(n)
    LOOP
ELSE
    DO UNTIL EOF(1)
        n = n + 1
        INPUT #1, dcp#(n)
        INPUT #5, rms#(n)
    LOOP
END IF
END IF
,
,
,
' set NumPts equal to number of data points and dimension
' all needed variables to that number
,
NumPts = n
DIM U(NumPts), M(NumPts), T(NumPts), Prms#(NumPts), Pt#(NumPts)
DIM posit(NumPts), ybar(NumPts)
DIM dptopt(NumPts), dMoM(NumPts), duou(NumPts), dTot(NumPts)
,
,
' determine static pressure using last data point
' assuming it is outside of the boundary layer
,
p02# = A# * dcp#(NumPts) + B#
DIV# = p02# / P0#
,
' following curve fit for Mach number only good for 2.5<M<3.5
,
M# = (994.64088995126# * DIV# - 3201.42932903485#) * DIV#
M# = ((M# + 4551.85014460101#) * DIV# - 3759.74305873532#) * DIV#
M# = ((M# + 1995.61481604904#) * DIV# - 712.05018048908#) * DIV#
M# = ((M# + 174.507921702156#) * DIV# - 31.3326161840911#) * DIV#
M# = M# + 6.31237859982064#
PS# = P0# / (1 + .2 * M# ^ 2) ^ 3.5
PRINT "Static Pressure = ", PS#
LPRINT
LPRINT "Static Pressure: "; PS#
,
,
' close input files
,
CLOSE #1
CLOSE #5
OLDRMS# = 0
LL = 0

```

Figure 56 (continued). Boundary Layer Data Conversion Program.

```

posit# = cl# - spcc#
umax = 0
,
,
' start converting data
,
FOR i = 1 TO NumPts
  posit# = spcc# + posit# 'this determines position in mils
  ybar(i) = posit# 'used until boundary layer thickness is determined
  posit(i) = posit# 'it is good for case Tw=T0
  IF type$ = "Y" OR type$ = "y" THEN 'this IF statement for fluctuating data
    rms#(i) = ABS(rms#(i))
    IF 1.5 * OLDRMS# - rms#(i) < 0 THEN LL = LL + 1
    aaa# = (rms#(i) * scale#(LL)) ^ 2 - rmsn1# ^ 2
    IF aaa# < 0 THEN aaa# = 0#
    Trms# = SQR(aaa#)
    OLDRMS# = rms#(i)
    Prms#(i) = Trms# / arms# / acgain# * 51710 / vsup# ' (mm Hg)
  END IF
  Pt#(i) = A# * dcp#(i) + B# 'determine pressure (mm Hg)
  DIV# = PS# / Pt#(i)
  IF DIV# < .52822 THEN 'supersonic use Rayleigh s.s. pitot formula
    M# = (-51202179.8678269# * DIV# + 205580195.875145#) * DIV#
    M# = ((M# - 373675474.552507#) * DIV# + 406855137.997528#) * DIV#
    M# = ((M# - 295909567.682085#) * DIV# + 151801620.889262#) * DIV#
    M# = ((M# - 56542142.2090064#) * DIV# + 15508884.8955404#) * DIV#
    M# = ((M# - 3144190.97979336#) * DIV# + 468794.996351527#) * DIV#
    M# = ((M# - 50718.8483329008#) * DIV# + 3896.33578986131#) * DIV#
    M# = (M# - 208.315765009882#) * DIV# + 8.755325916119#
  ELSEIF DIV# > 1 THEN 'imaginary make = 0
    M# = 0
  ELSE
    M# = SQR(((1# / DIV# ^ (2 / 7)) - 1) * 5) 'subsonic
  END IF
  M(i) = M#
  GOSUB velocity 'm/sec
  IF U(i) > umax THEN 'this IF determines max velocity
    umax = U(i) 'in data which is assumed to be
    Ptmax = i 'Ue
  END IF
  IF type$ = "y" OR type$ = "Y" THEN 'fluctuating data only
    S# = 1.4# * M# ^ 2 ' define sensitivity coefficient
    SS# = 1.4 / .4
    SSS# = S# / (1 + .2 * M# ^ 2)
    IF M# > 1 THEN

```

Figure 56 (continued). Boundary Layer Data Conversion Program.

```

      S# = S# - (M# ^ 2 - 1#) ^ 2 / (M# ^ 2 - 1# / 7#)
      SS# = S# / .4 / M# ^ 2
      SSS# = S# / (1 + .2 * M# ^ 2)
    END IF
    dptopt(i) = Prms#(i) / Pt#(i)
    duou(i) = Prms#(i) / Pt#(i) / S#
    dTot(i) = Prms#(i) / Pt#(i) / SS#
    dMoM(i) = Prms#(i) / Pt#(i) / SSS#
  END IF
NEXT i
,
,
,
' set Ue = umax and ubl to be velocity at edge of boundar layer at .99Ue
,
Ue = umax
ubl = .99 * Ue
i = 0
,
,
' find edge of boundary layer based on ubl and using linear interpolation
,
DO WHILE U(i) < ubl
  i = i + 1
LOOP
j = i - 1
blt = posit(i) - (U(i) - ubl) / (U(i) - U(j)) * (posit(i) - posit(j))
PRINT "Ue = ", Ue
PRINT "Boundary Layer Thickness(.99Ue) = ", blt
LPRINT "Ue(m/sec)= "; Ue
LPRINT "Boundary Layer Thickness(mils) (based on .99Ue) = "; blt
,
,
' calculate ybars based on determined blt
,
FOR i = 1 TO NumPts
  ybar(i) = posit(i) / blt
NEXT i
,
,
,
' previous values based on Tw=T0 therefor ask if that is what is wanted
,
INPUT "do you want to account for wall temp=.94*T0"; wt$
IF wt$ = "y" OR wt$ = "Y" THEN
  LPRINT "Values are based on Tw=.94*T0"
  FOR i = 1 TO NumPts
    GOSUB velocity 're-do velocities based on blt

```

Figure 56 (continued). Boundary Layer Data Conversion Program.

```

      NEXT i
    ELSE
      LPRINT "Values are based on Tw=T0"
    END IF
  ,
  ,
  ' print values that may be of some interest
  ,
  Me# = M(Ptmax)
  LPRINT "Me = "; Me#
  Te# = T(Ptmax)
  LPRINT "Te(F) = "; Te# - 459.67#
  RHOE# = 133 * PS# / 287 / Te#
  ,
  ,
  'this set of calculations needed for law-of-the-wall
  ,
  MM# = .2# * Me# ^ 2
  F# = .9399999999999999#
  TW# = .9399999999999999# * (T0# + 459.67#)
  TW# = 5 * TW# / 9
  Mu# = (-5.7971299D-11 * TW# + .00000012349703#) * TW#
  Mu# = ((Mu# - .000117635575#) * TW# + 9.080124E-02) * TW# - .98601000000000001#
  MUW# = Mu# * 10 ^ -6
  RHOW# = PS# * 133 / 287 / TW#
  NUW# = MUW# / RHOW#
  K1# = SQR(MM# / F#)
  K2# = (MM# + 1#) / F# - 1#
  BB# = 2 * MM# / F#
  CC# = -K2#
  DD# = SQR(K2# ^ 2 + 4 * K1# ^ 2)
  FOR i = 1 TO NumPts
    Y = posit(i) / 1000 * .0254
    ZZ = LOG(Y * Ue / NUW#)
    ZZZ# = (BB# * U(i) / Ue + CC#) / DD#
    VV = ATN(ZZZ# / SQR(-ZZZ# ^ 2 + 1))
    Pt = Pt#(i)
    PRINT #2, posit(i); ybar(i); Pt; M(i); U(i); U(i) / Ue; T(i); T(i) / Te#
    IF type$ = "Y" OR type$ = "y" THEN
      PRINT #3, ybar; dptopt; duou; dTot; dMoM
    END IF
    PRINT #4, Y; U(i); ZZ; VV
  NEXT i
  LPRINT
  LPRINT "MEA file contains y(mils),ybar,P02(mm Hg),M,U(m/s),U/Ue,T(R),T/Te"
  LPRINT "If used FLU file contains ybar,Pt'/Pt,U'/U,T'/T,M'/M"

```

Figure 56 (continued). Boundary Layer Data Conversion Program.

```

LPRINT "WAL file contains Y,U,ZZ,V for law of the wall calculations."
CLOSE
GOTO Momthck
,
,
,
' determine velocity using  $T_w = .94 T_0$ , if this is not wanted define blt=1 mil
,
velocity:
  IF ybar(i) > .7 THEN      'this IF uses curvefit determined by
    TONEW# = T0# + 459.67#   'SWT TR 82-03
  ELSEIF ybar(i) > .05 THEN
    TONEW# = (.0615 * ybar(i) + .957) * (T0# + 459.67#)
  ELSE
    TONEW# = (.4 * ybar(i) + .94) * (T0# + 459.67#)
  END IF
  T# = TONEW# / (1# + .2# * M(i) ^ 2)  ' degrees Rankine
  T(i) = T#
  RHO# = 133 * PS# / 287 / T#
  U(i) = M(i) * SQR(T#) * 14.94062#   '14.94...=SQRT(GAMMA*R#5/9)
RETURN
,
,
' calculate momentum thickness
,
Momthck:
PRINT Ptmx
IF (Ptmx - 1) MOD 2 = 0 THEN  'even number of panels
  PRINT "even number of panels"
  Momthck = U(1) / Ue * (1 - U(1) / Ue) * Te# / T(1)
  ptmm3 = U(Ptmx) / Ue * (1 - U(Ptmx) / Ue) * Te# / T(Ptmx)
  Momthck = Momthck + ptmm3
  FOR i = 2 TO Ptmx - 1 STEP 2
    PRINT i;
    Momthck = Momthck + 4 * U(i) / Ue * (1 - U(i) / Ue) * Te# / T(i)
  NEXT i
  FOR i = 3 TO Ptmx - 2 STEP 2
    PRINT i;
    Momthck = Momthck + 2 * U(i) / Ue * (1 - U(i) / Ue) * Te# / T(i)
  NEXT i
  Momthck = Momthck / 3 * spcc#  'answer in mils
ELSE  'odd number of panels
  PRINT "odd number of panels"
  Momthck = U(1) / Ue * (1 - U(1) / Ue) * Te# / T(1)
  ptmm3 = U(Ptmx - 3) / Ue * (1 - U(Ptmx - 3) / Ue) * Te# / T(Ptmx - 3)
  Momthck = Momthck + ptmm3
  FOR i = 2 TO Ptmx - 4 STEP 2

```

Figure 56 (continued). Boundary Layer Data Conversion Program.

```

      addnum = 4 * (U(i)) / Ue * (1 - U(i) / Ue) * Te# / T(i)
      Momthck = Momthck + addnum
    NEXT i
    FOR i = 3 TO Ptmx - 5 STEP 2
      addnum = 2 * U(i) / Ue * (1 - U(i) / Ue) * Te# / T(i)
      Momthck = Momthck + addnum
    NEXT i
    Momthck = Momthck / 3 * spcc# 'answer in mils
    ptmm2 = U(Ptmx - 2) / Ue * (1 - U(Ptmx - 2) / Ue) * Te# / T(Ptmx - 2)
    ptmm1 = U(Ptmx - 1) / Ue * (1 - U(Ptmx - 1) / Ue) * Te# / T(Ptmx - 1)
    ptmm0 = U(Ptmx) / Ue * (1 - U(Ptmx) / Ue) * Te# / T(Ptmx)
    Momthck = Momthck + 3 * spcc# / 8 * (ptmm3 + 3 * (ptmm2 + ptmm1) + ptmm0)
  END IF
  ' add part of integration from wall to first data point
  trapez = (U(1) / Ue * (1 - U(1) / Ue) * Te# / T(1)) / 2 * cl#
  Momthck = Momthck + trapez
  Momthck = Momthck / 1000 * 2.54 'convert to cm
  PRINT "Momentum thickness(cm) = ", Momthck
  LPRINT "Momentum thickness(cm) = ", Momthck
  ,
  ,
  ' calculate unit Reynolds number
  ,
  T = Te# * 5 / 9 'temperature now in kelvin
  IF T < 600 THEN
    Mu = (-5.7971299D-11 * T + .00000012349703#) * T
    Mu = (Mu - .000117635575#) * T
    Mu = (Mu + 9.080124E-02) * T - .98601
    Mu = Mu * 10 ^ -6
  ELSE
    Mu = (-1.10398E-12 * T + 7.9306E-09) * T
    Mu = (Mu - .000024261775#) * T
    Mu = (Mu + .0543232) * T + 4.8856745#
    Mu = Mu * 10 ^ -6
  END IF
  V = Me# * SQR(401.8 * T)
  RePrime = PS# * 4.63415E-03 * V / T / Mu
  PRINT "Re' (1/cm) = "; RePrime
  LPRINT "Re' (1/cm) = "; RePrime
  ,
  ,
  ' calculate Re-theta
  ,
  ReTheta = RePrime * Momthck
  PRINT "Re-theta = "; ReTheta
  LPRINT "Re-theta = "; ReTheta

```

Figure 56 (continued). Boundary Layer Data Conversion Program.

APPENDIX B
LAW OF THE WALL PROGRAM

```

'
'
' input needed data from blconvl program and from curvefit of #wal.dat
'
INPUT "ENTER S"; S
INPUT "ENTER I"; I
INPUT "ENTER M-INF"; ME
INPUT "ENTER T0(F): "; T0
INPUT "ENTER STATIC PRESSURE(mm Hg): "; PS
'
' calculate needed values for law-of-the-wall
MM = .2 * ME ^ 2
TE = (T0 + 459.67) / (1 + MM)
UE = ME * SQRT(TE) * 14.94062
K1 = SQRT(MM / .94)
K2 = (MM + 1) / .94 - 1
R = S / K1 / 2.43
PRINT "R="; R
EE = K2 / SQRT(K2 ^ 2 + 4 * K1 ^ 2)
E = ATN(EE / SQRT(-EE * EE + 1))
GK = (I + E) / K1 / R - 2.43 * LOG(R)
PRINT "GK="; GK
UTAU = R * UE
TW = .94 * (T0 + 459.67)
TW = S / 9 * TW
RHOW = PS * 133 / 287 / TW
'
' calculate coefficient of friction (dimensionless)
'
Cf2 = 2 * R ^ 2 * TE / TW
PRINT "Cf = "; Cf2
MU = (-5.7971299D-11 * TW + .000000123497034#) * TW
MU = ((MU - .000117635575#) * TW + 9.080124000000001D-02) * TW - .98601
MUW = MU * 10 ^ -6
NUW = MUW / RHOW
'
' tell where to get data from
'
INPUT "ENTER INPUT FILE (WITHOUT WAL.DAT)"; A$
OPEN "I", #1, A$ + "WAL.DAT"
OPEN "O", #2, A$ + "WL2.DAT"

```

Figure 57. Law of the Wall Program.

```

,
,
' convert data from $wal.dat and store in $wl2.dat
,
DO UNTIL EOF(1)
  INPUT #1, Y, U, Z, V
  YP = Y * UTAU / NUW
  UP = UE / K1 / UTAU * (V + E)
  PRINT YP, UP
  PRINT #2, YP, UP
LOOP
CLOSE

```

Figure 57 (continued). Law of the Wall Program.

APPENDIX C
SPECTRAL ANALYSIS PROGRAM

```

' $INCLUDE: 'c:\tek\spd\include\tekspd.bi'
' $DYNAMIC
Beforecall = SETMEM(-60000)
CLS
' This program does a forward fast fourier transform on
' data pulled from the Tek 2220 oscilloscope.
'
'
'
'
' Assumptions: 4096 points taken
'
'
'
'
'
'
DIM inputre(0 TO 4095), buffer(0 TO 4095), numloc(0 TO 2047)
DIM tfim$(0 TO 1023), tfre$(0 TO 1023)
'
'
' Program assumes files for fft are in sequentially numbered filenames
' for averaging. It assumes you will give it the first part of the
' filename. I.E. if filename from oscill. is "sin1.wav" give it "sin"
'
OPEN "I", #5, "bat.dat"
INPUT #5, aa$, numave, vltdiv, secdiv, gnd, HHZ, dc$
scale = secdiv / 100
freqscl = 1 / scale / 4096
'
'
' So-called "twiddle" factors needed by program
'
numloc(0) = 0: numloc(1) = 4: numloc(2) = 2: numloc(3) = 6
numloc(4) = 1: numloc(5) = 7: numloc(6) = 3: numloc(7) = 5
FOR i = 4 TO 10
    GOSUB twiddle
NEXT i
ppn# = 3.141592653589793# / 2048
FOR p = 1 TO 511
    pN# = ppn# * p
    tfre$(p) = COS(pN#)
    tfim$(p) = -SIN(pN#)
    tfre$(1024 - p) = -tfim$(p)
    tfim$(1024 - p) = -tfre$(p)
NEXT p

```

Figure 58. Spectral Analysis Program.

```

tfre#(512) = COS(ppn# * 512)
tfim#(512) = -tfre#(512)
,
,
' Begin fft analysis
,
FOR jj = 1 TO numave
    CLS
    IF jj < 10 THEN
        bb$ = RIGHT$(STR$(jj), 1)      'ave. 1 - 9
    ELSEIF jj < 100 THEN
        bb$ = RIGHT$(STR$(jj), 2)      'ave. 10 - 99
    ELSEIF jj < 1000 THEN
        bb$ = RIGHT$(STR$(jj), 3)      'ave. 100 - 999
    ELSE
        bb$ = RIGHT$(STR$(jj), 4)      'ave. 1000 - 9999
    END IF
    finame$ = aa$ + bb$ + ".wav"
    PRINT "Working on file :"; finame$
,
,

    CALL bfiletof(finame$, 0, status%)
    CALL bwftoarr(0, inputre(0), status%)
    CALL bfreewf(0, status%)
    avenum = 0
    FOR i = 0 TO 4095
        inputre(i) = inputre(i) - gnd
        avenum = avenum + inputre(i)
    NEXT i
,
,

' This sequence subtracts out the mean so that the DC component
' does not overshadow the rest of the spectrum.
,

    IF dc$ = "Y" OR dc$ = "y" THEN
        avenum = avenum / 4096
    PRINT "ave : "; avenum
    FOR i = 0 TO 4095
        inputre(i) = inputre(i) - avenum
    NEXT i
    END IF
,
,

'compute fft
,

    FOR i = 1 TO 11
        Lcnt = 0

```

Figure 58 (continued). Spectral Analysis Program.

```

      g = (4096 / 2 ^ i)
      FOR k = 0 TO 4095 STEP 2 * g
        FOR j = 0 TO g / 2 - 1
          rcnt = k + j
          tempre1 = inputre(rcnt)
          tempim2 = inputre(rcnt + g * 3 / 2)
          IF Lcnt = 0 THEN
            tempre2 = inputre(rcnt + g)
            tempim1 = inputre(rcnt + g / 2)
            inputre(rcnt) = tempre1 + tempre2
            inputre(rcnt + g / 2) = tempim1 + tempim2
            inputre(rcnt + g) = tempre1 - tempre2
            inputre(rcnt + g * 3 / 2) = -tempim1 + tempim2
          ELSE
            tempre2 = inputre(rcnt + g / 2)
            tempim1 = inputre(rcnt + g)
            locat = numloc(Lcnt)
            tr2 = tempre2 * tfre#(locat) - tempim2 * tfim#(locat)
            ti2 = tempim2 * tfre#(locat) + tempre2 * tfim#(locat)
            inputre(rcnt) = tempre1 + tr2
            inputre(rcnt + g / 2) = tempim1 + ti2
            inputre(rcnt + g) = tempre1 - tr2
            inputre(rcnt + g * 3 / 2) = -tempim1 + ti2
          END IF
        NEXT j
        Lcnt = Lcnt + 1
      NEXT k
    NEXT i
  ,
  ,
  , scaling factor and find amplitudes
  ,
    b0 = inputre(0)
    b1 = inputre(1)
    buffer(0) = buffer(0) + (ABS(b0 + b1) / 2) ^ 2 'divide by 2 just for convenience at end
    buffer(1) = buffer(1) + (ABS(b0 - b1) / 2) ^ 2
    FOR i = 2 TO 4094 STEP 2
      buffer(1 + i / 2) = buffer(1 + i / 2) + (inputre(i) ^ 2 + inputre(i + 1) ^ 2)
    NEXT i
  ,
  ,
  ,
    CLOSE
  NEXT jj
  ERASE inputre, tfre#, tfim#
  DIM spec(0 TO 2048)
  ,

```

Figure 58 (continued). Spectral Analysis Program.

```

,
' unscramble fft results
,
i = 11
GOSUB twiddle
FOR i = 2 TO 2048
    spec(numloc(i - 1)) = SQR(buffer(i) / 2 / numave)    'gives Vrms
NEXT i
spec(0) = SQR(buffer(0) / numave / 2)
spec(2048) = SQR(buffer(1) / numave / 2)
,
,
' Open file to write to , take ave. of spectrum
' and compute frequency spacing based on delta t.
,
OPEN "0", #2, aa$ + bb$ + "spc.dat"
zmod = vltdiv / 2048    'here makes up for dividing by 2 for conven.
FOR i = 0 TO 2048
    freq = i * freqsc1
    spec(i) = spec(i) * zmod
    rms = rms + spec(i) ^ 2
    PRINT #2, freq * 1000 ^ (- (HHZ - 1)), spec(i)
NEXT i
CLOSE
rms = SQR(rms)
PRINT "RMS = "; rms
END
,
,
,
twiddle:
,
    NN = 2 ^ i
    FOR j = 1 TO NN / 2 - 1
        numloc(NN - 2 * j) = numloc(NN / 2 - j)
    NEXT j
    FOR j = 1 TO NN - 1 STEP 2
        IF j < NN / 2 THEN
            numloc(j) = 2 * numloc(2 * j)
        ELSE
            numloc(j) = NN - numloc(j - 1)
        END IF
    NEXT j
RETURN

```

Figure 58 (continued). Spectral Analysis Program.

APPENDIX D
NOISE REMOVAL AND INTEGRAND CALCULATION PROGRAM

```

PRINT "This program provides the integrand of Iu."
PRINT "It also stops converting the data when the noise exceeds the voltage."
DO
INPUT "Continue?"; a$
IF a$ = "n" OR a$ = "N" THEN EXIT DO
INPUT "Enter signal data file to be converted "; a$
a$ = ".\" + a$ + "100spc.dat"
INPUT "Enter noise data file to be used "; d$
d$ = ".\" + d$ + "100spc.dat"
INPUT "Enter data file to dump to "; b$
b$ = ".\int\" + b$ + ".dat"
OPEN "I", #1, a$
INPUT #1, f1, v, f2, v
CLOSE #1
bw = f2 * 1000000!
OPEN "I", #1, a$
OPEN "O", #2, b$
OPEN "I", #4, d$
PRINT "The data file will contain freq(MHz),Vrms(w/o noise),Iu(f^2*Vrms^2)"
DO UNTIL EOF(1)
    INPUT #1, f, v
    f = f * 1000000
    INPUT #4, dmy, n
    IF n > v THEN EXIT DO
    v = v ^ 2 - n ^ 2
    IF f < 246950 THEN
        v = v / 1233 ^ 2
        ' this if-statement takes care of
        ' gain for oscilloscope
    ELSE
        v = v / (1302.87 - .000282932# * f) ^ 2
    END IF
    Iu = f ^ 2 * v / bw
    v = SQR(v)
    f = f / 1000000
    PRINT #2, f, v, Iu
    i = i + 1
LOOP
CLOSE
LOOP

```

Figure 59. Noise Removal and Integrand Calculation Program.

APPENDIX E
SPECTRAL NON-DIMENSIONALIZATION PROGRAM

```

DIM f(2000), pp(50), T(50), u(50), M(50)
DIM v(2000)
' This program converts #int.dat files to dissipation function.
,
OPEN "I", #1, "pasmea.dat"
FOR k = 1 TO 50
    INPUT #1, a, b, pp(k), M(k), u(k), a, T(k), a
NEXT k
CLOSE
OPEN "D", #3, "..\spec\dissip\diss.dat"
INPUT "use file"; z$
IF z$ = "Y" OR z$ = "y" THEN
    OPEN "I", #4, "cond.dat"
END IF
DO
    IF z$ = "N" OR z$ = "n" THEN
        INPUT "continue"; a$
        IF a$ = "N" OR a$ = "n" THEN EXIT DO
        INPUT "Enter file to be converted "; a$
    ELSE
        IF EOF(4) THEN EXIT DO
        INPUT #4, a$
        PRINT a$;
    END IF
    b$ = a$
    a$ = "..\spec\int\" + a$ + ".dat"
    IF z$ = "N" OR z$ = "n" THEN
        INPUT "Enter position in mils "; posi
    ELSE
        INPUT #4, posi
        PRINT posi;
    END IF
    PRINT #3, posi / 247.2082;
    k = (posi - 22.5) / 5 + 1
    k = INT(k)
    PRINT k
    PRINT pp(k), M(k), u(k), T(k)
    IF z$ = "N" OR z$ = "n" THEN
        INPUT "Enter supply voltage "; sv
    ELSE
        INPUT #4, sv
        PRINT sv
    END IF
    arms# = .0000982#      'V/psi/Vsup
    ,
    OPEN "I", #1, a$

```

Figure 60. Spectral Non-Dimensionalization Program.

```

,
ps = 15.5984          'mm Hg
Tk = T(k) * 5 / 9      'in Kelvin now
pp2 = pp(k) ^ 2
M2 = M(k) ^ 2
s = 1.4 * M2 - (M2 - 1) ^ 2 / (M2 - 1 / 7)
s2 = s ^ 2
mu = -5.7971299D-11 * Tk ^ 4 + .00000012349703# * Tk ^ 3
mu = mu - .000117635575# * Tk ^ 2 + .09080125# * Tk - .98601 ' kg/s/m
mu = mu * .000001
rho = ps * 133.322368421# / 287 / Tk          'kg/m^3
nu = mu / rho                                'm^2/s
PRINT "nu (m^2/s) "; nu
INPUT #1, f(1), v(1), i
INPUT #1, f(2), v(2), i
bw = f(2) * 1000000!
f(2) = bw
ppr = v(2) * 51.71 / arms# / sv
rms = rms + ppr ^ 2 + (v(1) * 51.71 / arms# / sv) ^ 2
v(2) = ppr ^ 2 / bw
ppr = v(2) * bw ^ 2
dis = ppr * bw / 2
pprold = ppr
j = 3
DO UNTIL EOF(1)
  INPUT #1, f(j), v(j), i
  f(j) = f(j) * 1000000!
  ppr = v(j) * 51.71 / arms# / sv
  rms = rms + ppr ^ 2
  v(j) = ppr ^ 2 / bw
  ppr = v(j) * f(j) ^ 2
  dis = dis + (ppr + pprold) * bw / 2
  oprold = ppr
  j = j + 1
LOOP
ii = j - 1
dis = dis + pprold * bw / 2
rms = SQR(rms)
CLOSE #1
Iu = dis / pp2 / s2
dis = dis * 60 * nu / s2 / pp2 * 3.141592654# ^ 2
PRINT "Viscous dissipation function (m^2/s^3)"; dis
PRINT #3, dis;
ue3 = 636.0276 ^ 3
rms = rms / pp(k)
del = .2472082 / 1000 * 25.4

```

Figure 60 (continued). Spectral Non-Dimensionalization Program.

```

dis = dis * del / ue3
PRINT dis
PRINT #3, dis;
PRINT "Pt'/Pt"; rms
PRINT #3, rms;
rms = rms / s
PRINT "u'/u="; rms
PRINT #3, rms;
lam = rms * u(k) / 2 / 3.141592654# / SQR(Iu)
kk = (dis * ue3 / del) ^ .25 * nu ^ -.75
PRINT kk
PRINT #3, kk;
uk = kk * nu
RE = rms * u(k) * lam / nu      'Re - lambda = u' * lambda / nu
PRINT "RE = "; RE
lam = lam * 100      'lam (cm)
PRINT #3, uk; lam; RE
b$ = "..\spec\dissip\" + b$ + ".dat"
OPEN "0", #2, b$
FOR j = 2 TO ii
    phi = v(j) * u(k) / 2 / 3.141592654# / nu / uk
    wv = 2 * 3.141592654# * f(j) / u(k) / kk
    PRINT #2, wv, phi
NEXT j
CLOSE #2
PRINT
LOOP
CLOSE

```

Figure 60 (continued). Spectral Non-Dimensionalization Program.

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