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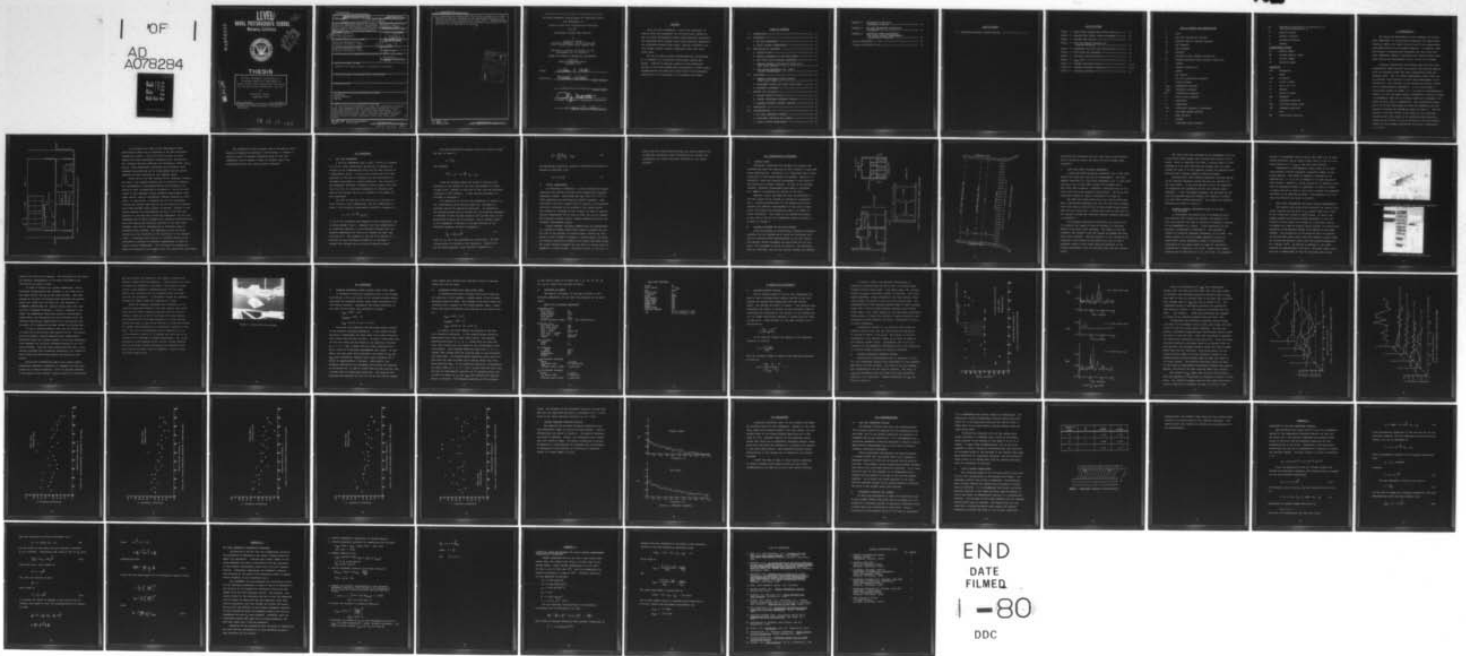
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THESIS

Hot Wire Anemometer Investigation Of
Turbulence Levels And Development Of
Liquid Crystal Flow Visualization Techniques
For The Rectilinear Cascade Test Facility

by

William R. Miller

September 1979

Thesis Advisor:

M.D. Kelleher

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Hot Wire Anemometer Investigation Of Turbulence Levels
And Development Of
Liquid Crystal Flow Visualization Techniques
For The
Rectilinear Cascade Test Facility

by

William R. Miller
Lieutenant Commander, United States Navy
B.S., United States Naval Academy 1969

Submitted in partial fulfillment of the
requirement for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the
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September 1979

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ABSTRACT

Using hot wire anemometry, a base line turbulence intensity level was determined for the Rectilinear Cascade at the U.S. Naval Postgraduate School Turbopropulsion Laboratory. The turbulence with straight inlet guide vanes was compared to the turbulence without guide vanes. Results indicated a uniform though slightly greater turbulence level when using guide vanes.

The use of liquid crystal thermography was investigated as a technique for visualizing flow across cascade test blades. Methods of applying crystals to and resistance heating of the blade surface were investigated in bench tests. Recommendations are made which should lead to the successful application of the technique in the cascade wind tunnel.

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LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|------------|--|
| A | area |
| B | hot wire calibration constant |
| c_p | specific heat at constant pressure |
| d | bar diameter |
| D | wire diameter |
| dB | decibels |
| h | convective heat transfer coefficient |
| \bar{h} | average convective heat transfer coefficient |
| I | current |
| k | thermal conductivity |
| L | length |
| M | bar spacing |
| N | hot wire calibration exponent |
| P | electric power |
| P_{ATM} | atmospheric pressure |
| P_{BAR} | barometric pressure |
| Δp | differential pressure |
| Q | rate of heat transfer |
| R | resistance |
| T | temperature |
| %TI | turbulence intensity, percentage |
| u' | root mean square velocity |
| U | mean velocity |
| V | voltage |
| x | turbulence decay distance |

| | |
|------------|--|
| α_0 | temperature coefficient of resistivity of hot wire referenced to T_0 |
| γ | specific weight |
| μ | dynamic viscosity |
| ν | kinematic viscosity |
| ρ | density |

DIMENSIONLESS GROUPS

| | |
|------------|------------------------|
| Nu | Nusselt number |
| \bar{Nu} | Average Nusselt number |
| P_r | Prandtl number |
| Re | Reynolds number |

Subscripts

| | |
|----------|------------------------|
| ATM | atmospheric |
| b | blade |
| corr | corrected |
| DC | direct current |
| g | gas (i.e., air) |
| Hg | mercury |
| L | based on length |
| man | manometer |
| o | reference condition |
| RMS | root mean square value |
| STD | standard conditions |
| w | wire |
| ∞ | free stream condition |

I. INTRODUCTION

The design and development of more advanced gas turbine axial compressors by the National Aeronautics and Space Administration (NASA) will result from the use of new computational tools made possible by the modern computer. As computer codes are written to describe more accurately the fluid flow past axial compressor blading, comparisons are needed between calculated results and experimental data to verify the programs.

Obtaining experimental verification data for flow field computational codes requires very careful and detailed measurements not generally made when doing conventional blade performance tests. The U.S. Naval Postgraduate School (NPS) has an unusually large facility in which such measurements can be carried out. This facility is the Cascade Wind Tunnel located at the Turbopropulsion Laboratory. In this wind tunnel, a rectilinear cascade of blades (i.e., an array of two-dimensional blades, all with the same profile, representing a section through a turbomachine blade row at constant radius but "unwrapped" and layed out flat) can be investigated. The Cascade Wind Tunnel has a 750 HP fan which draws air from the atmosphere and discharges it through the cascade as shown in Figure 1. The test section of the wind tunnel is ten inches in the blade span direction and sixty inches in the blade-to-blade direction. Velocities up to Mach 0.4 can be achieved in the test section. Details of the cascade installation are given in References 1, 2, and 3.

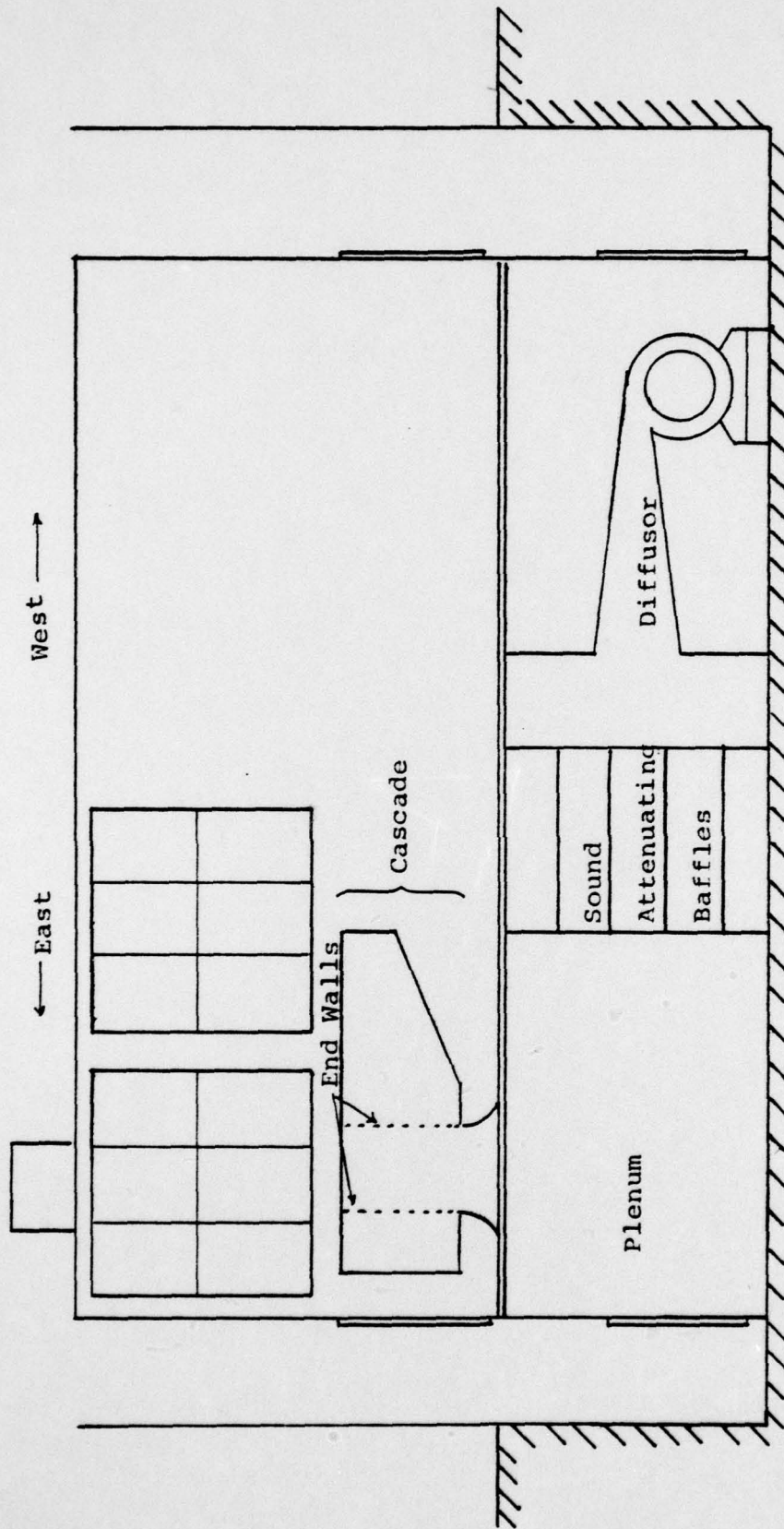


Figure 1. RECTILINEAR CASCADE WIND TUNNEL FACILITY

It is planned that much of the experimental study envisioned by NASA will be conducted on the NPS rectilinear cascade wind tunnel. Data will first be taken on blade shapes with known performance characteristics, specifically the National Advisory Committee for Aeronautics (NACA) 65-A₁₀ series. With measurement techniques thus validated, newly designed blade profiles can be investigated and the results compared to those predicted by new computer codes.

Before any of the NASA studies can be conducted, however, the flow in the cascade facility must be verified as meeting the requirements of two-dimensionality and periodicity required by NASA, as specified in Reference 4. While the wind tunnel is well equipped to make pneumatic measurements, NASA needs several items of information normally obtained by other means. In particular, a knowledge of the flow turbulence entering the cascade test section and the location of specific test blade boundary layer regimes is desired. Because it can readily measure the instantaneous velocity of the flow and separate it into mean and fluctuating components, the hot wire anemometer can be used to measure the turbulence characteristics. Since the laminar and turbulent portions of the test blade boundary layer can be characterized by different rates of convective heat transfer, the temperature along the blade surface will vary according to the conditions of the boundary layer. A technique which results in different colors being reflected by surfaces at different temperatures is known as Liquid Crystal Thermography. This technique is proposed as a means of visualizing the boundary layer flow across the test blades.

The objectives of this research were to develop hot wire methods of measuring turbulence in the cascade, to conduct a baseline survey of cascade turbulence using the hot wire anemometer, and to develop a means of boundary layer flow visualization using the liquid crystal technique.

II. BACKGROUND

A. HOT WIRE ANEMOMETRY

A hot wire anemometer uses a small (0.00015 in diameter by 0.05 in. long) electrically heated wire to measure the velocity of an incompressible fluid and the mass velocity of a compressible fluid. As fluid flows across the wire, heat generated in the wire is dissipated to the surrounding environment principally by forced convection. The circuitry of the anemometer contains a feedback control bridge which maintains the wire at a constant temperature by adjusting the current flow through the wire in response to the amount of heat dissipated.

The rate of heat loss from the wire is a function of fluid velocity, fluid temperature, and wire temperature as given in the following relationship (derived in Appendix A):

$$Q = (A^* + B^* U^{\frac{1}{N}}) (T_w - T_g)$$

A^* and B^* are constants which depend on fluid properties, and N varies between 2 and 3. Assuming the fluid temperature to be relatively constant, a fluid velocity increase past the constant temperature hot wire will increase the heat loss from the wire. The tendency to cool the wire results in a decrease in wire resistance followed by an increase in current flow through the wire from the control bridge.

The heat generated by passing electrical current through the wire is equal to

$$Q = I^2 R_w$$

and therefore

$$I^2 R_w = (A^* + B^* U^{\frac{1}{N}}) (T_w - T_g)$$

Since the voltage across the bridge is directly proportional to the current in the wire, measurement of bridge voltage gives a measure of the rate of heat loss and therefore a measure of flow velocity. A more detailed discussion is provided by Reference 5.

The capability of the hot wire anemometer to respond to the instantaneous fluid velocity makes the instrument an excellent device for measuring turbulence. By segregating the measures signal into an average and a fluctuating component, a knowledge of both the mean velocity and the RMS value of the fluctuating velocity can be obtained. The DC voltage output of the anemometer is related to the mean velocity by the following equation, derived in Appendix A:

$$V_{DC}^2 = V_o^2 + BU^{\frac{1}{N}} \quad (1)$$

where V_o , B , and N are determined by calibration. The RMS voltage output is related to the turbulence intensity by the following equation, (also derived in Appendix A):

$$\frac{u'}{U} = \frac{2N V_{DC}}{V_{DC}^2 - V_0^2} V_{RMS} \quad (2)$$

The percentage turbulence intensity calculated and plotted is defined in Reference 6 as:

$$\%TI = 100 \frac{u'}{U} \quad (3)$$

B. LIQUID THERMOGRAPHY

As described in Reference 7, liquid crystals are organic compounds that exhibit brilliant color changes over discrete temperature bands. These bands may vary from 1°C to 50°C in width depending upon the specific crystals selected. Once calibrated, the color changes allow an observer to distinguish individual isotherms on the surface of the coated object. The location of isotherms or the location of areas of rapidly varying temperatures can be used to infer location of laminar and turbulent boundary layers, laminar separation points, and turbulent reattachment points.

Liquid crystals available commercially are encapsulated in a polyvinyl alcohol binder which serves to extend the useful life of the crystals to several years, reduces the variations of color caused by changes in viewing angle, and makes the crystals relatively insensitive to normal and shear forces. The liquid crystals proposed for use come in a slurry which is sprayed on a black surface. The black surface is necessary to

ensure that all light passing through the liquid crystal film is absorbed, preventing light reflected by the surface from interfering with color variations reflected by the liquid crystals.

III. DESCRIPTION OF APPARATUS

A. CASCADE STATUS

Reference 1 describes the cascade as originally constructed and shows the condition of flow through it after some minor modifications. Reference 2 is a detailed study of flow conditions in the plenum beneath the cascade. Figure 13 in Reference 2 shows the physical arrangement of the plenum at the beginning of current research. As part of the current research, pneumatic measurements were made by Lieutenant R.C. Moebius to establish the quality of the flow.

Moebius' survey confirmed the flow non-uniformity in the test region of the cascade as reported in References 1 and 2. Several modifications to the cascade wind tunnel entrance and numerous rearrangements of the turning vanes within the plenum were subsequently made in an effort to obtain uniformity. The status of the cascade and plenum at the time of the hot wire anemometer baseline surveys is as shown in Figure 2.

B. CASCADE ALIGNMENT FOR HOT WIRE SURVEYS

Since the purpose of establishing a baseline turbulence intensity for the cascade was to serve as a reference with which to evaluate future modifications to the wind tunnel, the simplest cascade alignment was maintained for all surveys. This alignment is shown in Figure 3. The end-walls were set vertically and all test section blading was removed.

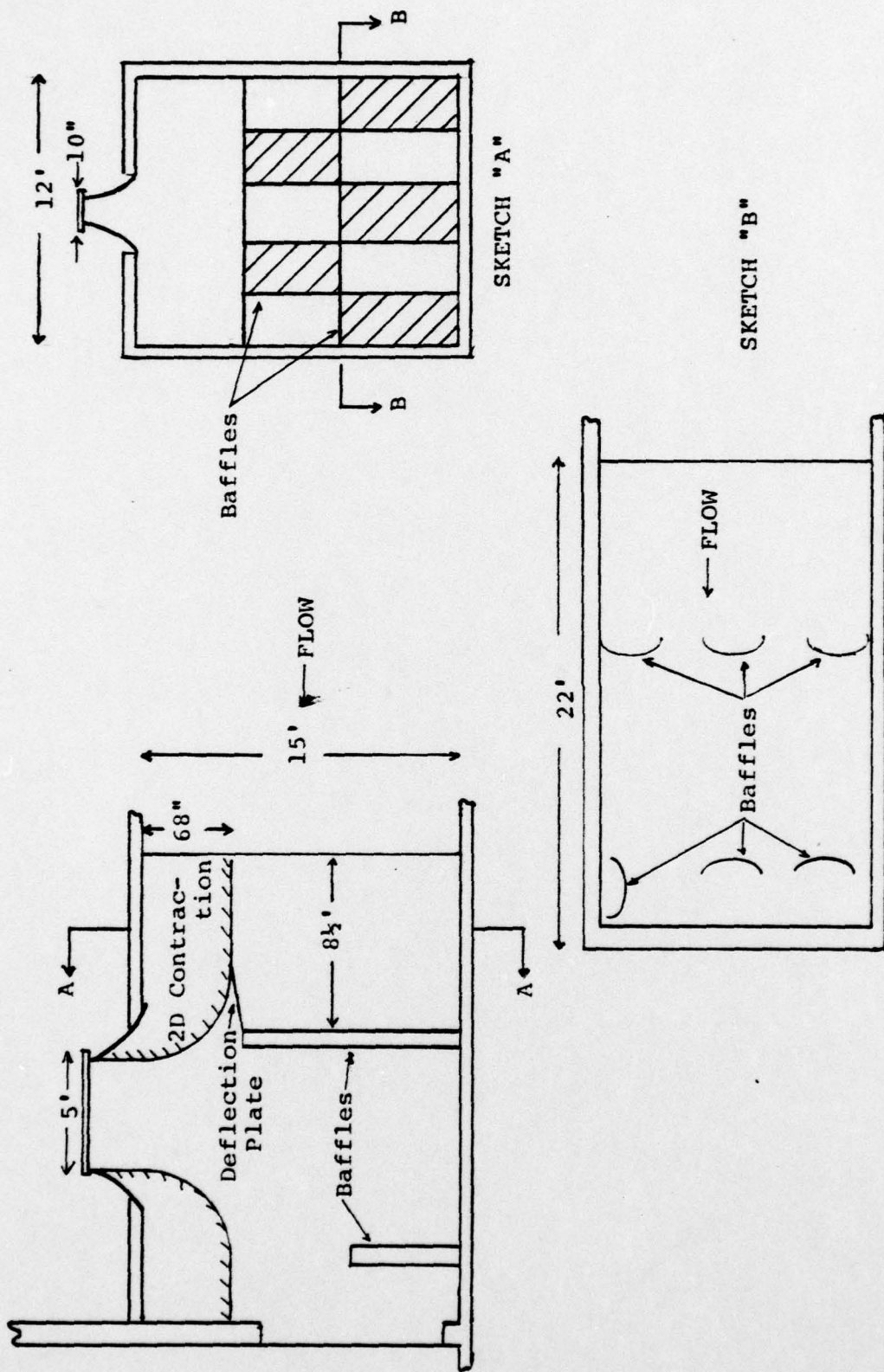


Figure 2. CASCADE WIND TUNNEL PLENUM ARRANGEMENT

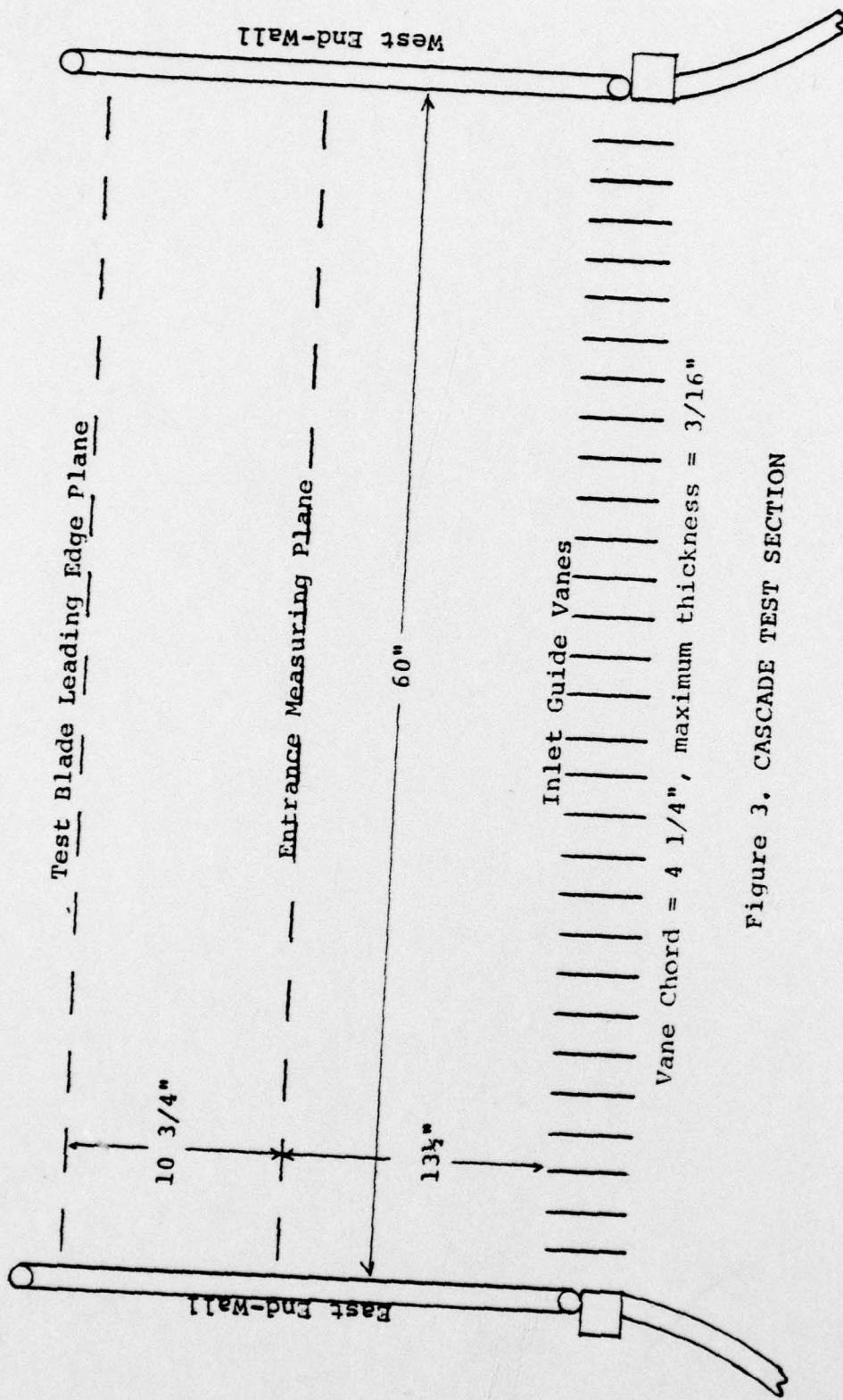


Figure 3. CASCADE TEST SECTION

One survey was conducted with the inlet guide vanes removed, while a follow-on survey was done with the straight vanes installed.

C. DISA TYPE 55D00 UNIVERSAL ANEMOMETER

A DISA type 55D00 universal anemometer with a DISA 55F31 single wire probe was used for all measurements. The anemometer consisted of a DISA 55D0L anemometer unit, a DISA 55D25 auxiliary unit, a DISA 55D30 digital DC voltmeter and a DISA 55D35 RMS voltmeter. Reference 8 describes each of the above units and gives operating instructions. The units were connected together as shown in Reference 8 on page 19.

The DISA type 52B01 sweep drive unit and the DISA type 55H01 transversing mechanism with the DISA type 51C01 stepper motor were used to position the hot wire probe during surveys made from the front wall. Surveys made from the back wall of the cascade utilized the installed traverse assembly described in Reference 1.

For permanent recording of the data, the input to the DC voltmeter was coupled to the red channel of a Hewlett-Packard 7132A strip chart recorder. The output of the RMS voltmeter was coupled to the red channel of another HP-7132A strip chart recorder. The blue channel of both recorders was connected to the output of the sweep drive unit so that a permanent record of the linear span-wise position of the voltage measurement could be recorded along with the voltage itself.

The 55F31 probe was connected to the anemometer unit via a DISA 55A44 probe support and a fifteen foot type RG 58 C/U cable. Prior to inserting the probe, a locally made 1/4 inch diameter by 12.5 inch long tube was slipped over the probe support to allow it to fit properly through the standard front and back wall traverse assembly mounting brackets.

Existing front wall traverse assemblies had been designed for standard pneumatic probes and were not suitable for hot wire probes. It was also desired to have the capability of conducting both pneumatic and hot wire surveys simultaneously. A twin arm support assembly was designed for use with the standard mounting brackets but capable of holding the DISA 55H01 traverse mechanism. The support and traverse mechanism are shown in Figure 4.

D. SPECTRAL DYNAMICS CORPORATION MODEL SD 330 REAL TIME ANALYZER

To investigate the possibility of frequencies within the turbulent flow through the cascade, the model SD 330 real time analyzer was used to observe the frequency spectrum of the anemometer unit output. A full description of the analyzer is contained in Reference 9. The analyzer is capable of providing frequency information up to 20KHz. The normal output is a plot of signal amplitude (linear or logarithmic) versus frequency (linear or logarithmic). Attenuation of the input signal in steps of 1 dB can be selected over a range of 0 to 50 dB. Output signal magnification can be specified as 0, 10, or 20 dB. All spectrum

analysis of anemometer output signals were made with an input signal attenuator and an output signal gain of 0 dB on a full scale reading of $0.1 V_{RMS}$ on the real time analyzer.

Processing of the anemometer signal input to the real time analyzer involved averaging a specified number of full signal samples. The number of samples to average can be selected as 1, 2, 4, 8, or 16 samples or 32 times any one of these values. Generally, 16 was selected as an adequate value. Once the averaging process is completed, the data is stored in memory and can be used to drive an X-Y plotter for permanent recording of the spectrum analysis. The anemometer unit and real time analyzer are shown in Figure 5.

E. TEST BLADE PREPARATION FOR LIQUID CRYSTAL THERMOGRAPHY

The cascade test blade profile selected for coating with liquid crystals was the NACA 65 A₁₀ series blade with a span of ten inches and a chord of eight inches. As one of the blades procured as original cascade equipment, it was constructed with an epoxy core covered by a thin metal casing. To prepare the blade to receive liquid crystal, an electrically conducting cover material needed to be applied to the blade surface. The resistivity of the material had to be matched to the available power supply such that electric current passing through the material could raise the surface temperature to a nominal 100°F. As derived in Appendix C, the power required was approximately 350 watts. The power supply available was a LAMBDA model LK 345A FM regulated power supply

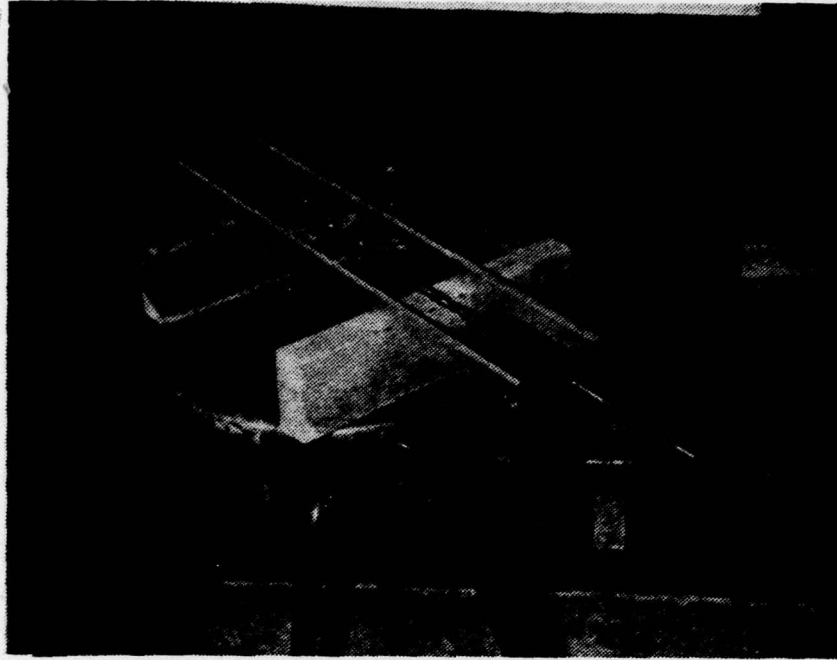


Figure 4. Twin Arm Support Assembly And Traverse Mechanism

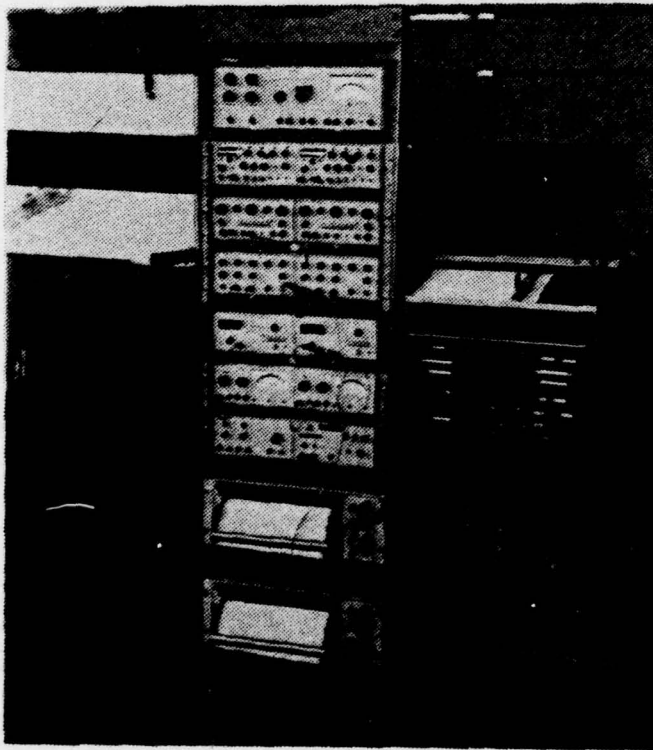


Figure 5. Anemometer And Real Time Analyzer Unit

rated at 60 volts and 10 amperes. The resistance of the covering material corresponding to the power requirements and limitations was about 10 ohms.

In order to monitor the surface temperature, copper constantan thermocouples were imbedded in the blade, one on the upper surface and one on the lower surface. They were located at the point of maximum blade thickness and approximately two inches from the blade tip, and connected to a NEWPORT LABORATORIES INC. digital output meter that read directly in degrees Fahrenheit. Prior to insertion in the blade, the temperature monitoring system of thermocouple, output meter, and connecting wire was calibrated using the Rosemount Engineering Company model 913 A calibration bath and model 920 A commutating bridge located in Halligan Hall.

To find a covering material that was thin enough not to change the blade profile once applied yet met the resistance requirements, several materials were investigated. Teledeltos paper was rejected because of its high resistance, while temsheet was initially discarded because of its 3/64 inch thickness. Four mil thick aluminized milar had a satisfactory thickness and a promising resistivity, but tended to burn through too easily when current was applied to test pieces.

Having been successfully used in the liquid crystal experiments reported by Reference 7, temsheet was again considered as a covering material. Prior to applying temsheet to the metallic blade surface, several coats of TV corona dope

and red glyptol were applied to the blade to insulate the metallic surface from the temsheet. A spray adhesive was used to attach the temsheet to the blade. Self-adhering copper strips, which served as connecting points for the power supply, were attached over the temsheet around the blade root and tip perimeters. A resistance through the temsheet between the copper strips was measured as 16 ohms.

While the temsheet resistance was acceptable, an insulation resistance reading of 390 ohms between each copper strip and the blade's metallic mounting post was unsatisfactory. Even so, a test of the blade with power applied was conducted with the blade isolated on a wooden surface. During this test, a very slight increase in potential between the copper strips resulted in a significant increase in current. The test was discontinued when a potential of 0.91 volts produced a current of 10 amperes and there was no indication of an increase in surface temperature. Due to the existence of this apparent short circuit, further development of the liquid crystal techniques was suspended until such time as the cause could be remedied. Figure 6 shows the final blade set-up.

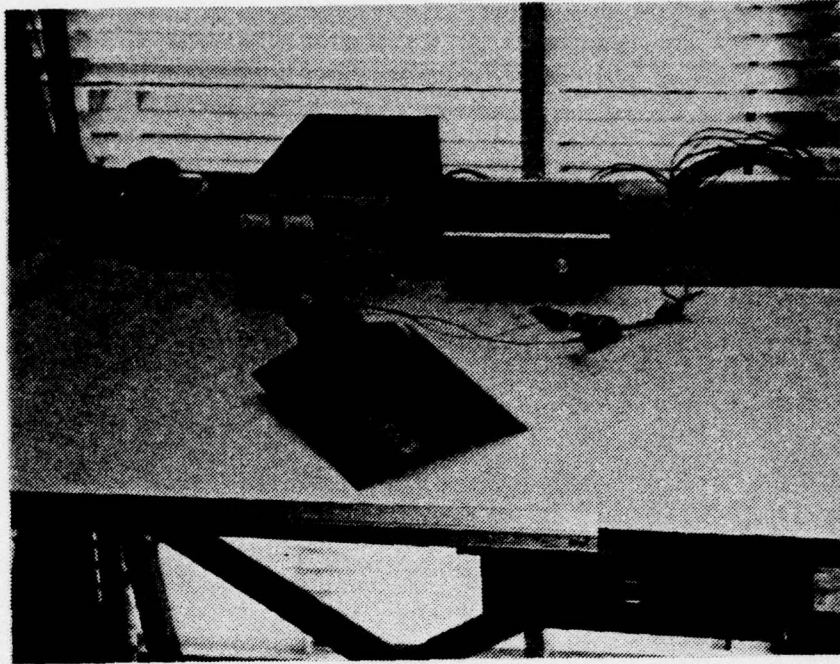


Figure 6. Test Blade And Equipment

IV. PROCEDURES

A. BASELINE TURBULENCE SURVEY WITHOUT INLET GUIDE VANES.

To establish a baseline turbulence level in the Cascade Wind Tunnel, a hot wire survey of the cascade entrance measuring plane was conducted without guide vanes installed at the wind tunnel entrance. Atmospheric and plenum conditions at the start of the survey were recorded as follows:

$$T_{\text{ATM}} = 68^{\circ}\text{F} \pm 0.5^{\circ}$$

$$T_{\text{PLENUM}} = 70^{\circ}\text{F} \pm 1^{\circ}$$

$$P_{\text{BAR}} = 29.55 \text{ in. Hg} \pm 0.05 \text{ in.}$$

The survey was conducted with the probe support mounted in the backwall traversing mechanism. In the blade-to-blade direction a measurement was taken every five inches beginning five inches from the east end-wall. At each of these positions the hot wire probe was positioned in the span-wise direction at 1, 3, 5, 7, and 9 inches from the front plexiglass wall. Thus a total of 55 discrete measurements were taken. At each point, with the probe held stationary, the values of V_{DC} and V_{RMS} were recorded by separate strip chart recorders for a period of approximately 30 seconds. Additionally, the frequency spectrum of the anemometer unit output was analyzed at the points 20, 30, and 40 inches from the east end-wall and 5 inches from the plexiglass front-wall. The analysis was conducted and recorded for both the 100 Hz and 1000 Hz ranges.

Other ranges were observed and indicated little of interest beyond the 1000 Hz range.

B. TURBULENCE SURVEY WITH INLET GUIDE VANES

To determine the effect straight inlet guide vanes had on turbulence in the cascade, a second survey of the entrance measuring plane was made. The straight inlet guide vanes were installed with a spacing of two inches between vanes. Atmospheric and plenum conditions were measured at the survey start as:

$$T_{\text{ATM}} = 68^{\circ}\text{F} \pm 0.5^{\circ}$$

$$T_{\text{PLENUM}} = 70^{\circ}\text{F} \pm 1^{\circ}$$

$$P_{\text{BAR}} = 28.80 \text{ in. Hg} \pm 0.05 \text{ in.}$$

As before, the probe support was mounted in the back wall traversing mechanism. In the blade-to-blade direction, measurements were taken every three inches. Odd numbered measuring positions (3, 9, 15 ... inches from the east end-wall) were aligned with the center of the corresponding guide vane spacing. Even numbered measuring positions (6, 12, 18 ... inches) were aligned with the trailing edge of the corresponding guide vane. The blade-to-blade measuring points were such that data was taken at every third spacing center and every third trailing edge. In the span-wise direction, a measurement was again taken at 1, 3, 5, 7, and 9 inches from the front wall. The grid of measurements consisted of 90 discrete points, and at each the values of V_{DC} and V_{RMS} were recorded for approximately 30 seconds. The frequency spectrum was also analyzed

on the 1000 Hz range at mid-span and 9, 21, 30, 39, 42, 48, 51, and 54 inches from the east end-wall.

C. EQUIPMENT ALIGNMENT

The specific alignment of the many controls on the Universal Anemometer and the Real Time Analyzer are as shown below:

TYPE 55D00 UNIVERSAL ANEMOMETER

Anemometer Unit

| | |
|-----------------------|--------------------------|
| HF Filter | 2 |
| Loop Control | INT |
| Bridge Ratio | 1:20 |
| Gain Adjust | 3 |
| LF Gain | High |
| Probe Resistance Ohms | 9.76 (for Probe 82779-2) |

Auxiliary Unit

| | |
|--------------------|-----------|
| High Pass Filter | OUT |
| Low Pass Filter | OUT |
| Gain - Course | 1:1 |
| Gain - Fine | Fully CCW |
| Zero Adj. - Course | 10 |
| Zero Adj. - Fine | Fully CW |
| Output | NON-INV |

RMS Voltmeter

| | |
|-------|-----|
| Range | 1 |
| Time | 0.1 |

DC Voltmeter

| | |
|-------------|-------|
| Range | 10.00 |
| Polarity | OUT |
| Normal-Hold | OUT |
| Damping | 1 |

V_{RMS} Stripchart Recorder

| | |
|------------------------------|----------------|
| Speed | 6 in/min |
| V _{RMS} Scale (red) | .01 volts/inch |
| Distance Scale (blue) | 1 inch/inch |

V_{DC} Stripchart Recorder

| | |
|-----------------------------|-------------|
| Speed | 4 in/min |
| V _{DC} Scale (red) | 1 volt/inch |
| Distance Scale (blue) | 1 inch/inch |

REAL TIME ANALYZER

| | |
|-----------------|-----------------------|
| AC/DC | AC |
| Input Range | .1 V _{RMS} |
| CAL | OPER |
| OUTPUT GAIN | 0 |
| Y DISPLAY | LOG |
| SLOPE | SPECT |
| FREQ MARKS | OUT |
| HOLD/UPDATE | OUT |
| TRANS CAPT | OUT |
| TRANS CAPT | OUT |
| MANUAL | OUT |
| INTEN MARKS | OUT |
| DIGITAL LOCATER | 000 |
| J6 | to X-Y plotter Y axis |
| J7 | to X-Y plotter X axis |

V. RESULTS AND DISCUSSION

A. CASCADE VELOCITY PROFILE

The DC voltage output of the hot wire anemometer was used to plot a mid-span mean velocity profile of the flow through the Cascade Wind Tunnel both with and without vanes. The results are shown in Figure 7. The vertical axis represents the change in velocity at the indicated blade-to-blade position referenced to the velocity at the cascade center (30 inches from either end-wall, 5 inches from the front or back wall). From equation (1) the mean velocity can be calculated as:

$$U = \left[\frac{V_{DC}^2 - V_o^2}{B} \right]^N$$

If the velocity change with respect to the reference velocity is given by

$$\Delta U = \frac{U - U_{Ref}}{U_{Ref}}$$

then the velocity change in terms of the measured quantities is given by

$$\Delta U = \left[\frac{V_{DC}^2 - V_o^2}{V_{DC_{Ref}}^2 - V_o^2} \right]^N - 1$$

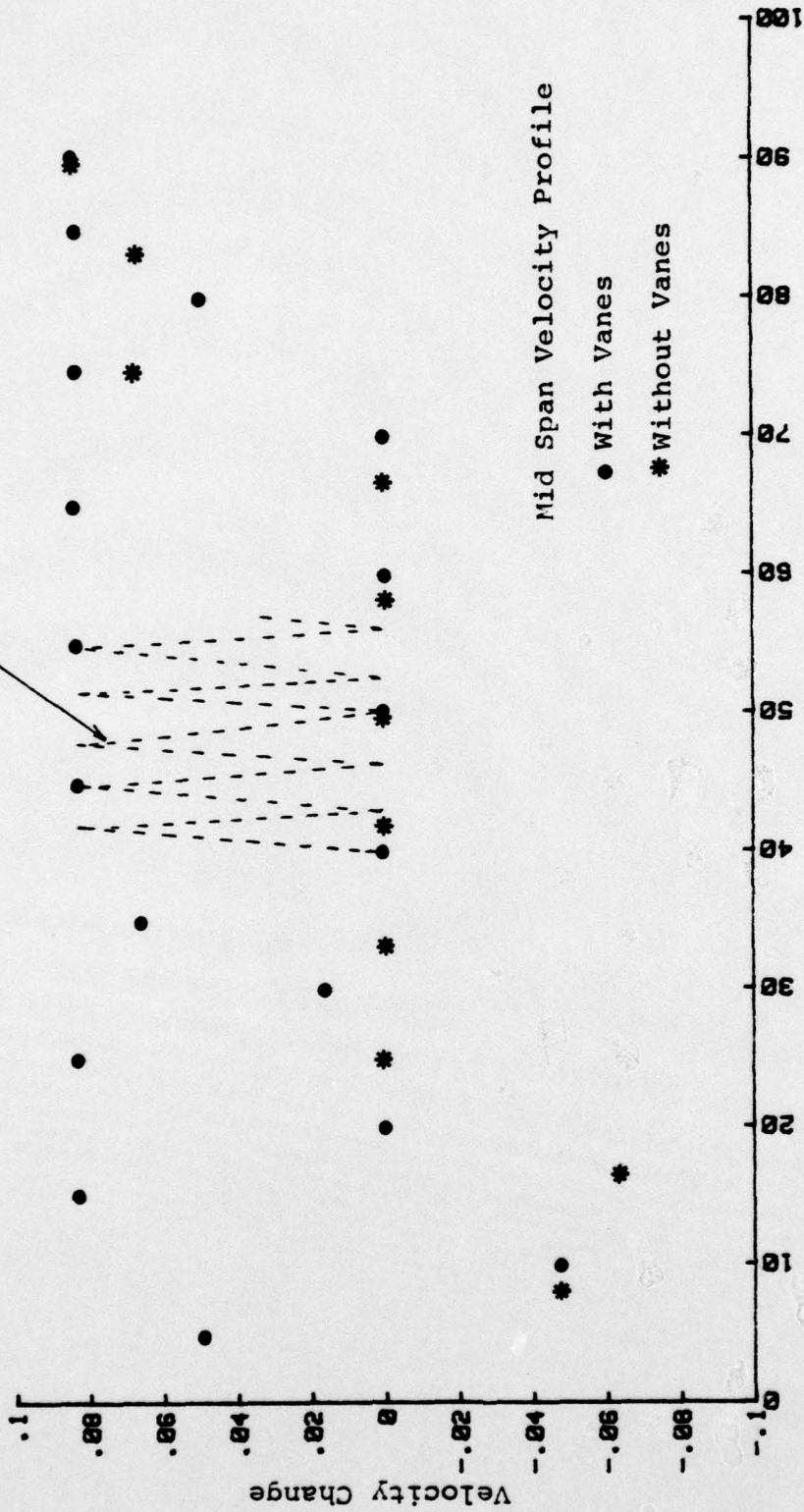
As Figure 7 shows, the velocity distribution is essentially uniform from the 25% to 65% of blade-to-blade distance without guide vanes. With guide vanes, the velocity profile presents a saw-tooth pattern as expected. The higher values represent points centered in the vane spacing, while lower values are points in line with the trailing edge. The predictability of the velocity profile seems to have a greater range (15% to 75% of blade-to-blade distance) than without guide vanes. Also, when compared to the with-vanes turbulence profile shown in Figure 10C, points of higher velocity on the with-vanes velocity profile of Figure 7 correspond to points of lower turbulence.

Interpreting changes in V_{DC} from the strip chart recording scaled at one volt per inch limits the resolution in voltage to about ± 0.05 volts. The result is that the uncertainty in the velocity change is at least as large as the velocity change itself. Furthermore, due to the non-linearity of the anemometer calibration curve, the uncertainty in velocity change increases as velocity increases.

B. CASCADE TURBULENCE INTENSITY PROFILE

Utilizing the relationship given in equations (2) and (3), the turbulence intensity was calculated for each measurement point for both surveys. The value of V_{DC} was recorded and interpreted as for the velocity profile. The value of V_{RMS} was recorded by and read from strip chart recordings scaled at 0.01 volts/inch. Typical recordings of V_{RMS} are shown in Figure 8.

Probable distribution resulting from
vane wakes



Blade-To-Blade Distance, s
Figure 7. MID-SPAN VELOCITY PROFILE

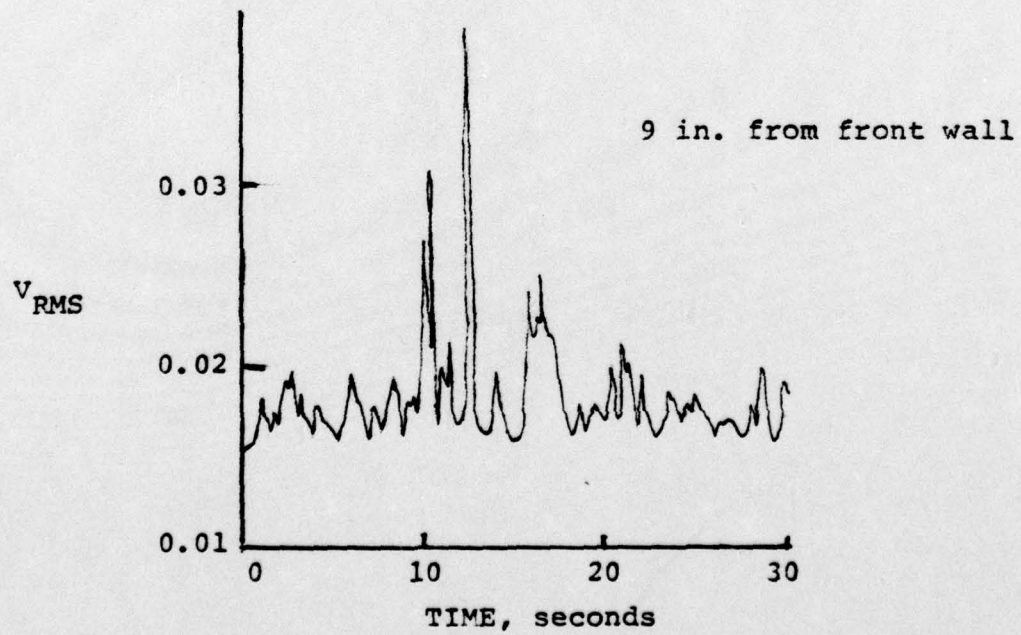
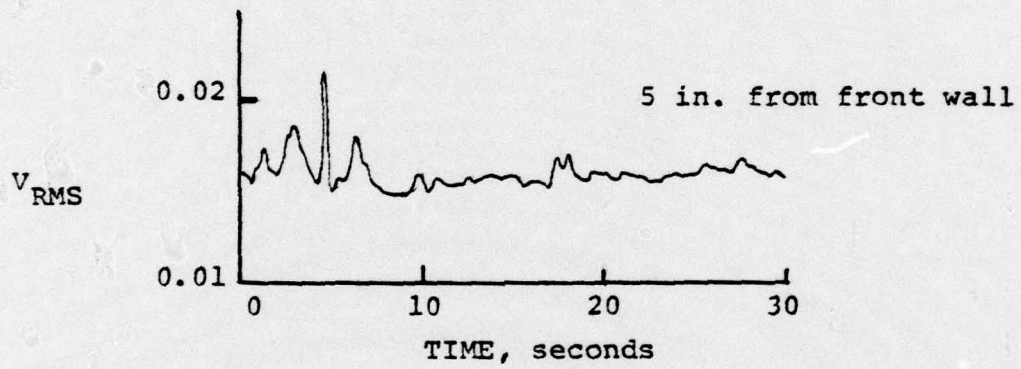
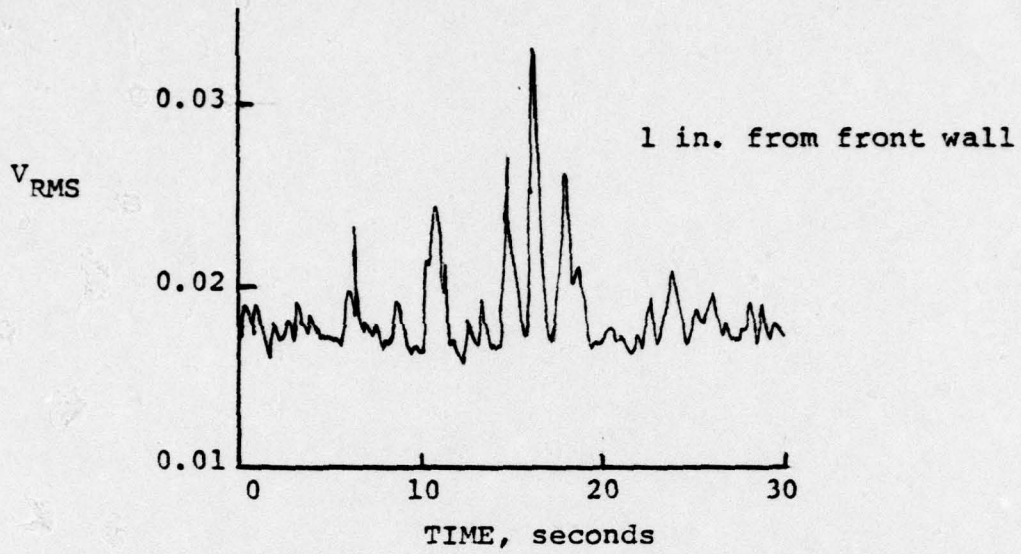
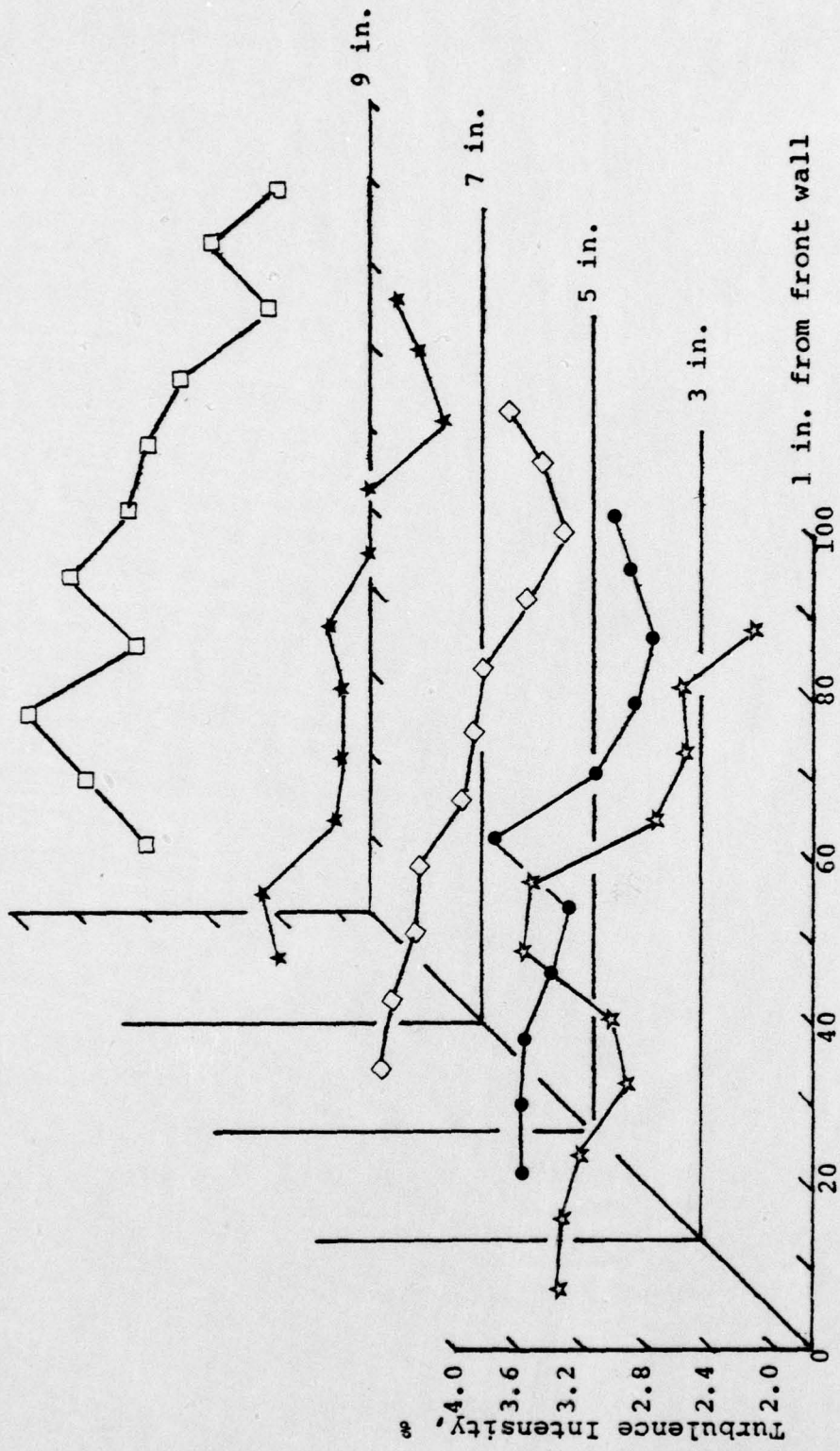


Figure 8. V_{RMS} DATA
36

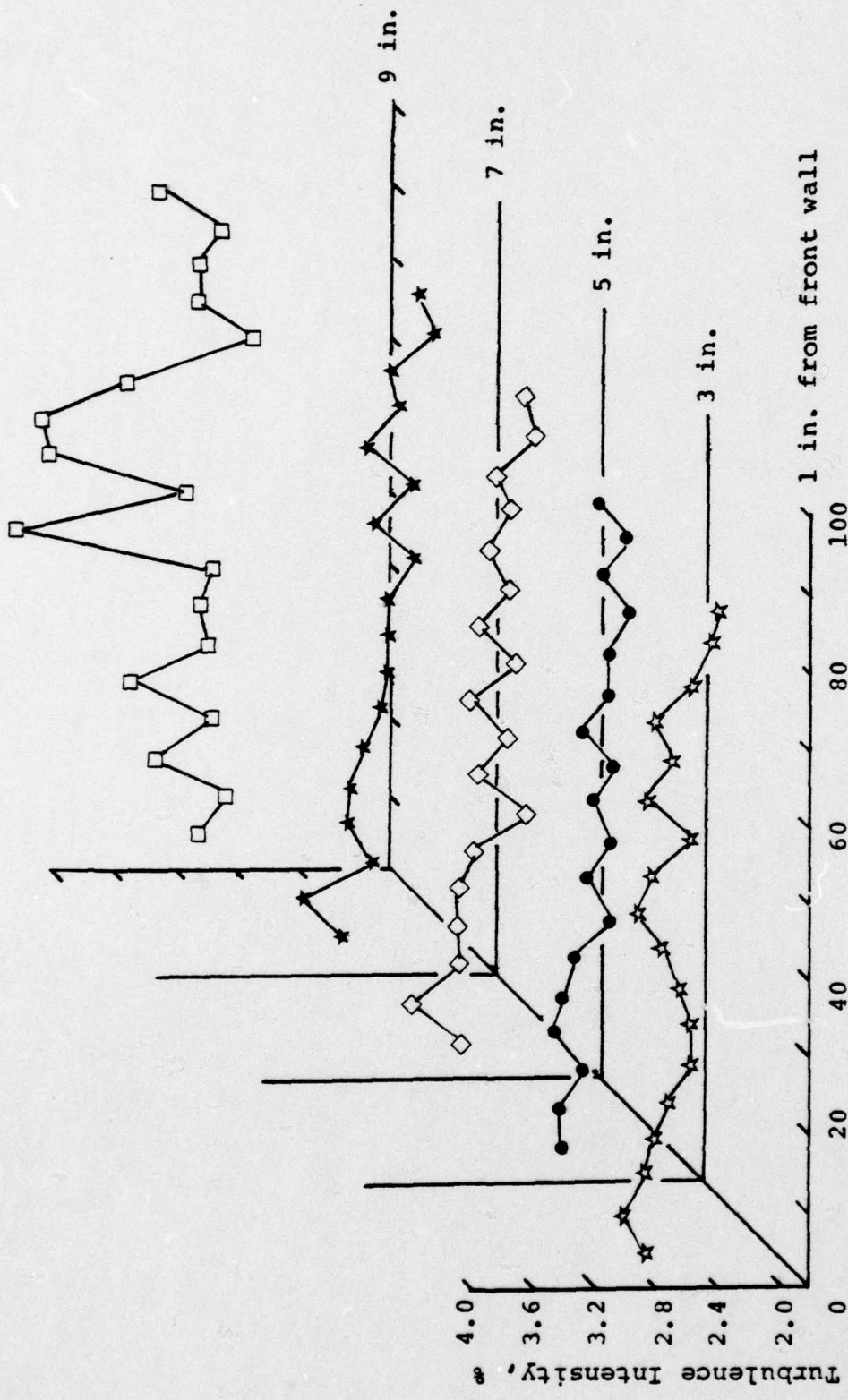
Since the fluctuations in V_{RMS} were considerably greater near the front and back walls than they were closer to mid-span, the recorded minimum and maximum values of V_{RMS} were used to infer an average value at the near wall positions. This average value of V_{RMS} was used in equation (2). The calculated values of turbulence intensity are plotted for each survey in Figure 9. The values of turbulence for the with- and without- guide vane conditions are compared in Figure 10 for various distances from the front wall.

As measured, the turbulence intensity varies between 2.0% and 3.1% at mid-span without inlet guide vanes, and from 2.36% to 3.04% with guide vanes installed. For both conditions, turbulence increases away from mid-span toward either the front or the back wall. Back wall turbulence is generally greater than turbulence at the front wall. Along the blade-to-blade direction, turbulence tends to be greatest near the east end-wall and decreases steadily toward the west end when guide vanes are not installed. With guide vanes, the turbulence profile seems to be more generally uniform in the blade-to-blade direction except near the back wall where it is highly erratic. The definite saw-tooth pattern of data is the result of measurements alternating between vane spacing centers (low points) and vane trailing edges (high points).

The values of V_{RMS} taken from the strip chart recordings can generally be considered as accurate to within ± 0.0005 volts. The inferred averages used for data taken near either front or back wall is probably accurate to within ± 0.002



Blade-To-Blade Distance, %
 Figure 9a. CASCADE TURBULENCE PROFILE WITHOUT VANES



Blade-To-Blade Distance, %

Turbulence Intensity, %

Figure 9b. CASCADE TURBULENCE PROFILE WITH VANES

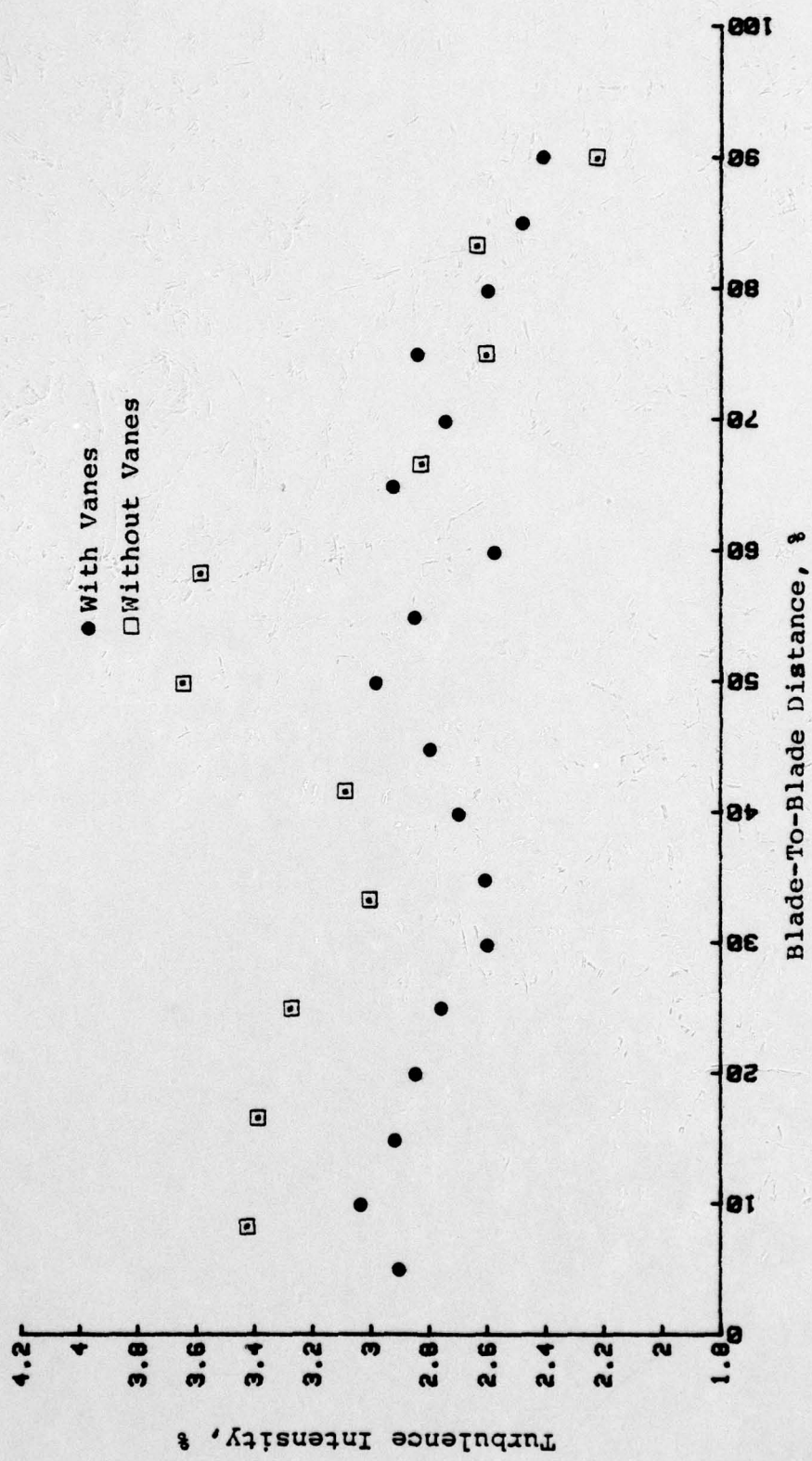


Figure 10a. CASCADE TURBULENCE COMPARISON 1" FROM WALL

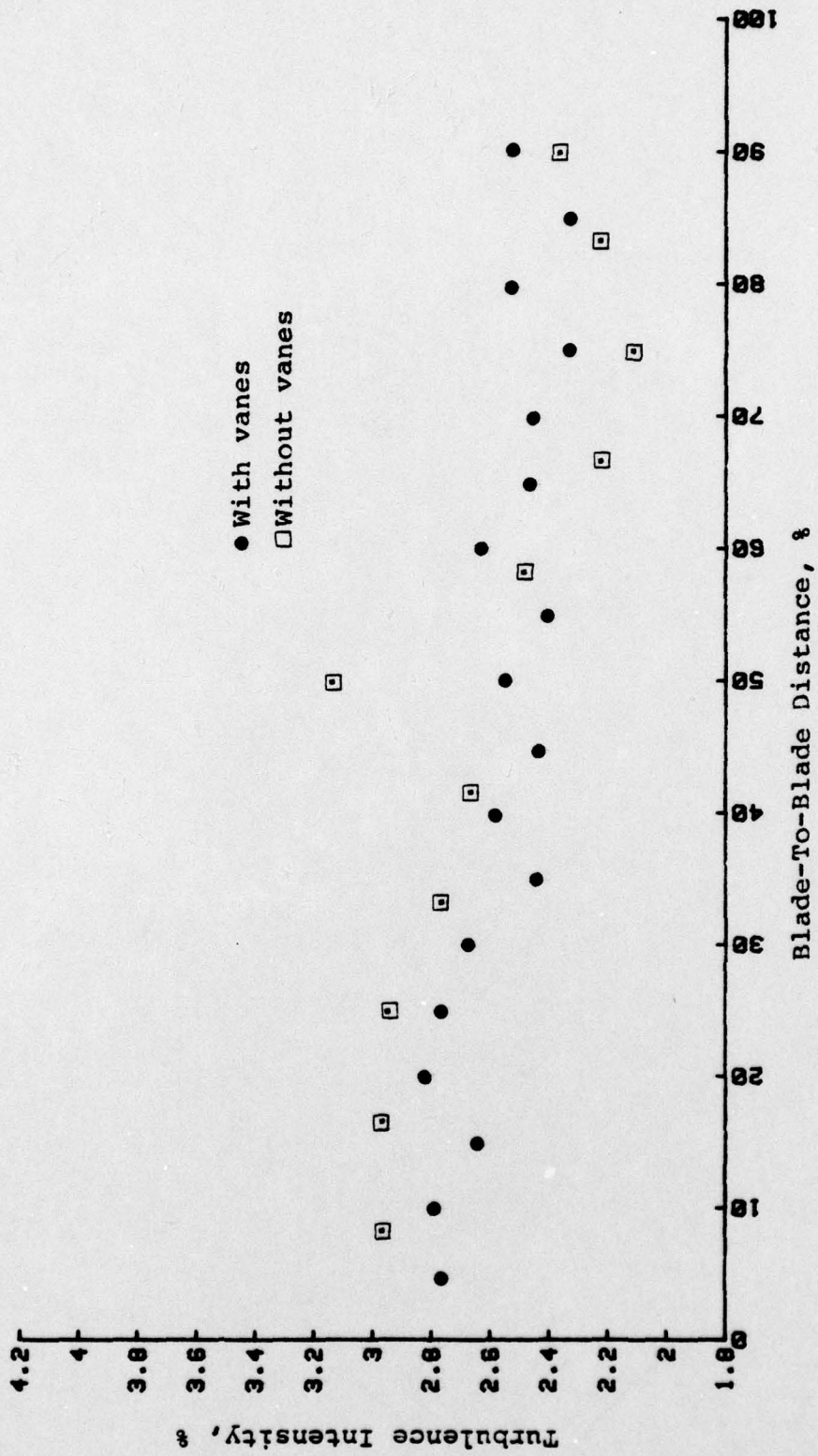


Figure 10b. CASCADE TURBULENCE COMPARISON 3" FROM FRONT WALL

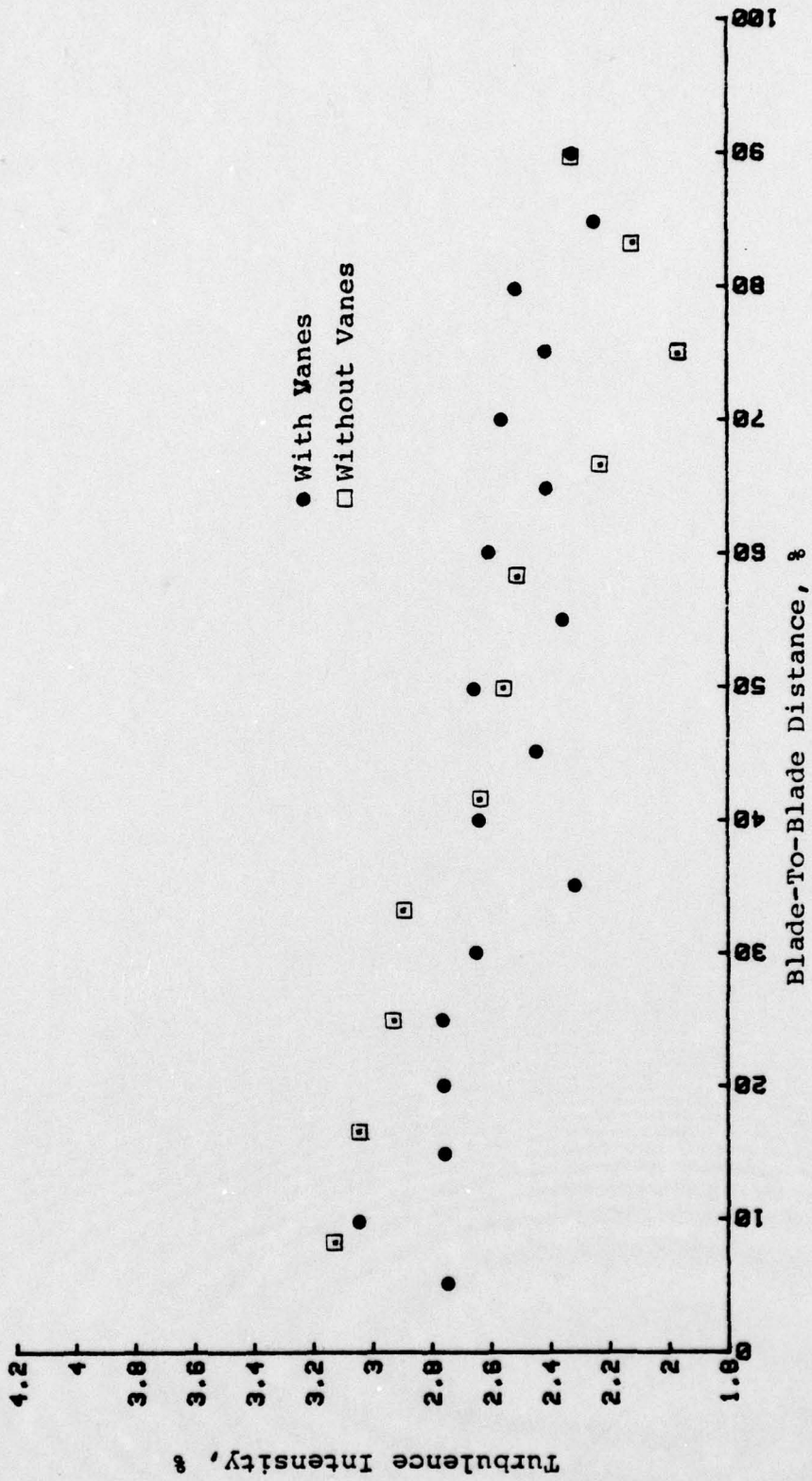


Figure 10c. CASCADE TURBULENCE COMPARISON AT MID-SPAN

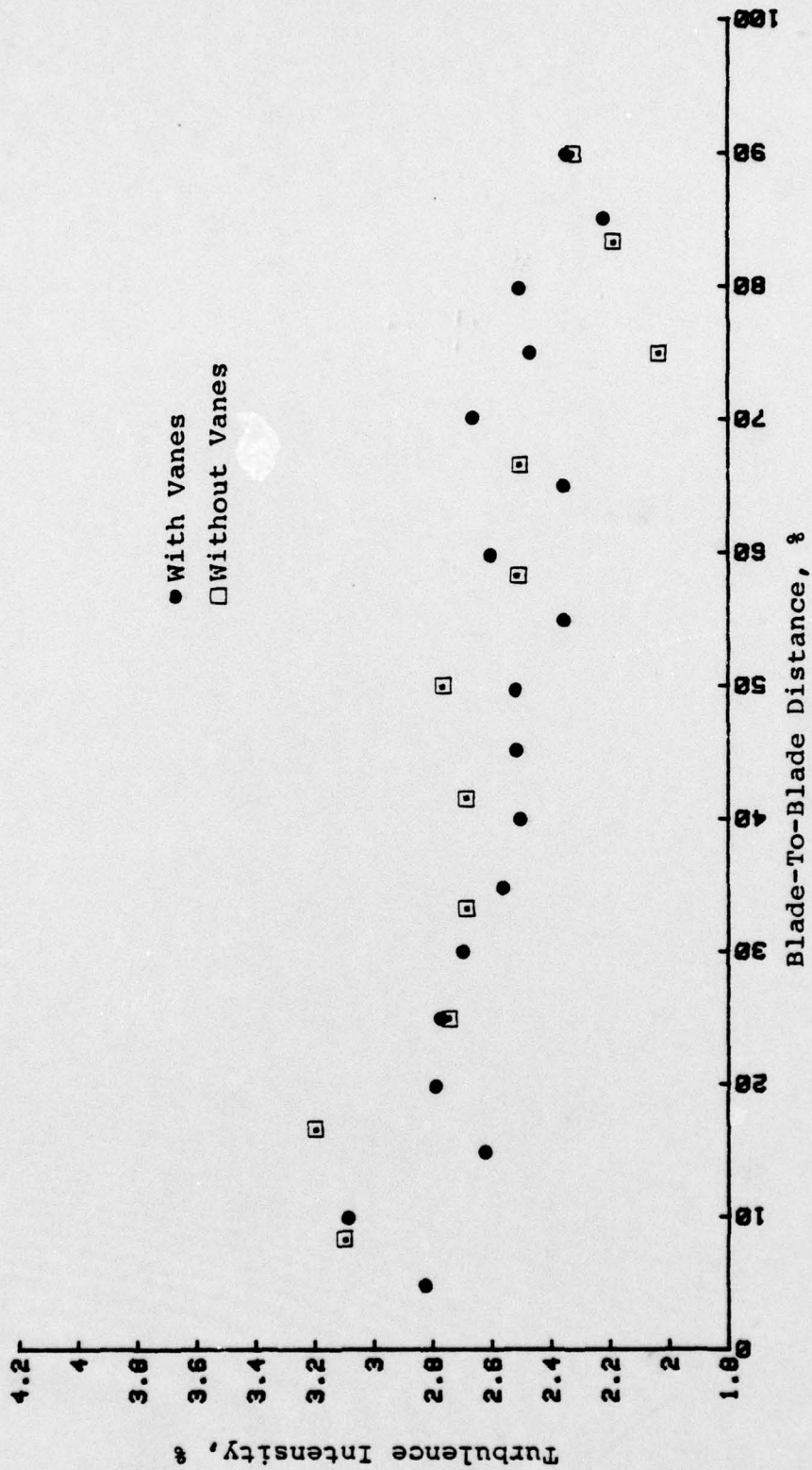


Figure 10d. CASCADE TURBULENCE COMPARISON 3" FROM BACKWALL

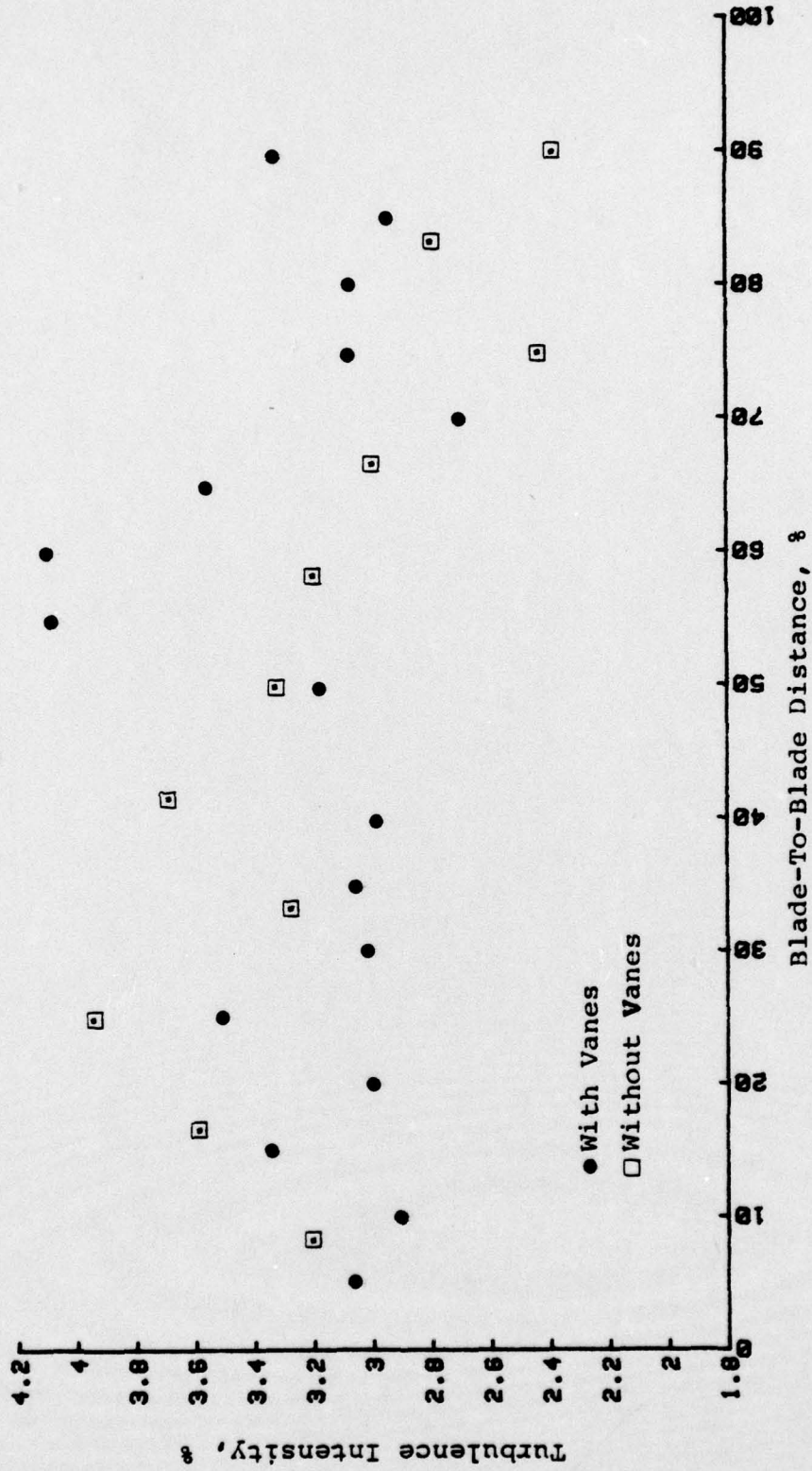


Figure 10e. CASCADE TURBULENCE COMPARISON 1" FROM BACK WALL

volts. The accuracy of the turbulence values at the one inch and nine inch span-wise positions is estimated to be $\pm 0.25\%$, while at all other span-wise positions it is $\pm 0.02\%$.

C. CASCADE FREQUENCY SPECTRUM ANALYSIS

The observed and recorded frequency spectrum did not vary appreciably among the various mid-span points. Typical distributions are shown in Figure 11. No specific frequency was found to dominate. Rather, all frequencies were present over the 0-1000 Hz range. The decay in amplitude at higher frequencies is characteristic of turbulent flow as discussed in Reference 10 and indicates the existence of turbulent eddies in a great number of sizes.

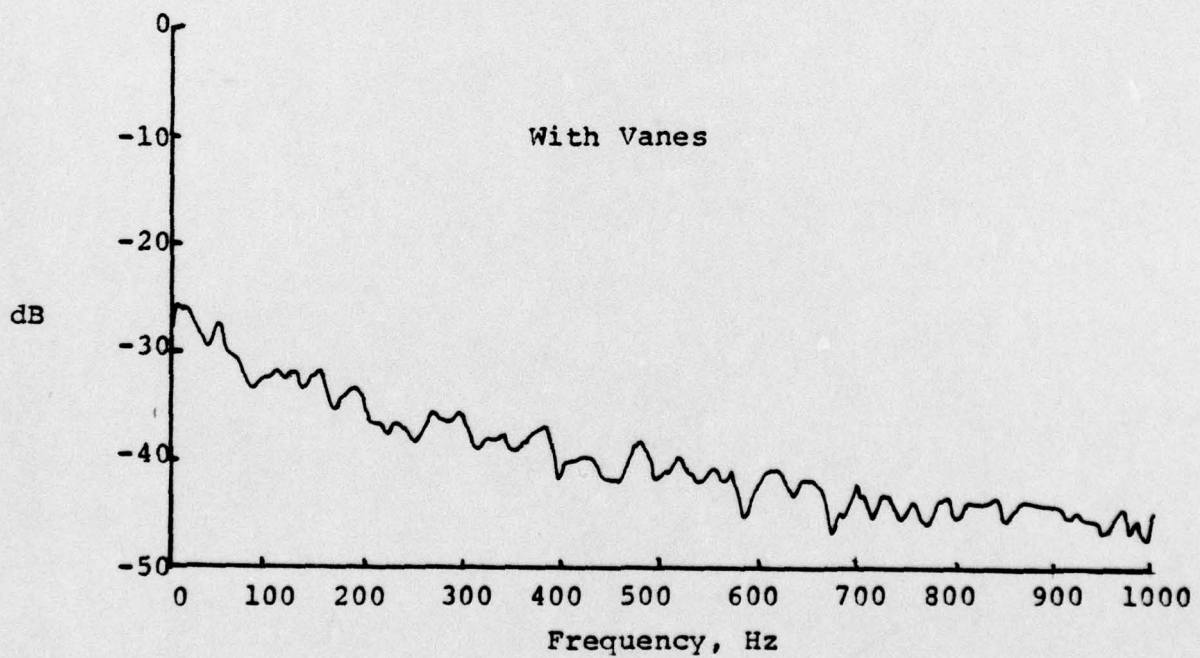
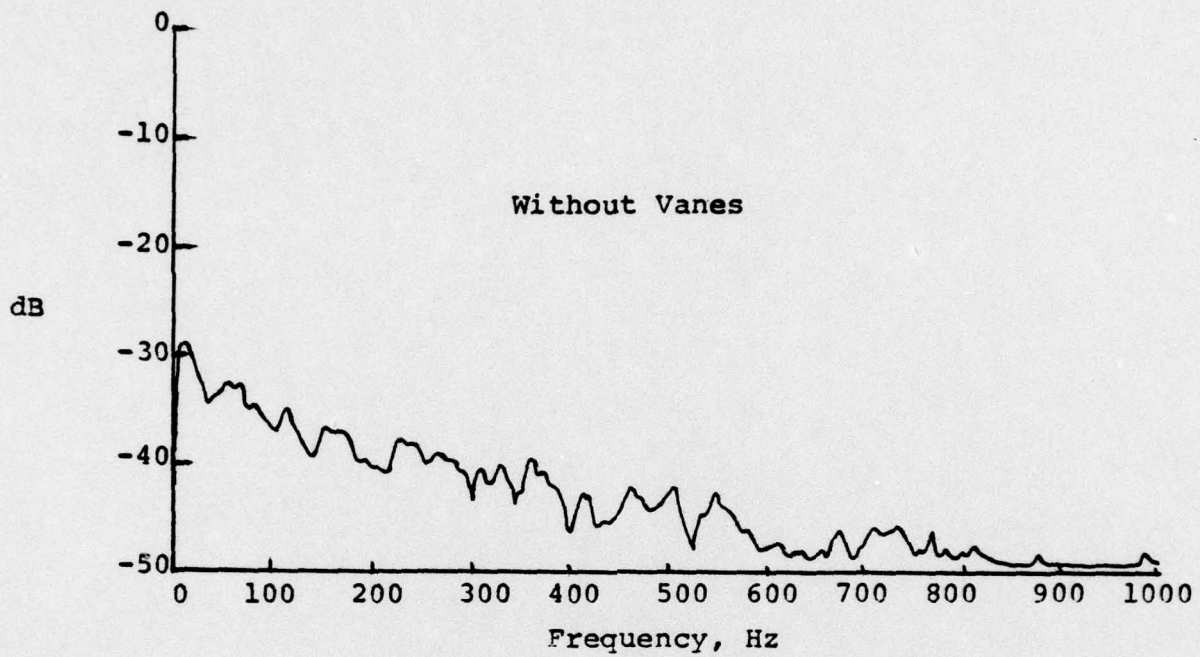


Figure 11. FREQUENCY SPECTRUM

VI. CONCLUSIONS

A baseline turbulence level for the Cascade Wind Tunnel was obtained using hot wire anemometry. Whether or not inlet guide vanes were installed ahead of the test region, the turbulence level on the blade-to-blade centerline was in the range of 2-3%. Spectral analysis of the turbulent signal showed that there was no predominant frequency present, which would have indicated the presence of a standing wave pattern in the wind tunnel plenum. Data obtained following future modifications to the cascade can be compared to the present baseline.

A start was made to apply a liquid crystal technique to observe boundary layer behavior over the test blade. Recommendations are made for how this work should continue.

VII. RECOMMENDATIONS

A. HOT WIRE ANEMOMETRY METHODS

The methods utilized were basic and straightforward. The nonlinear system was adequate for the measurements that were made, and its use greatly simplified the mechanics of equipment set-up and calibration. It is recommended that a linearized anemometer system be developed to simplify taking multiple-wire measurements and to allow use of available automatic correlation equipment.

During preliminary measurements and familiarization, it became evident that the geared tooth drive traversing mechanism supplied by DISA did not always provide positive traction. Slip became a major problem and precluded accurate data taking with continuous span-wise traverses. To at least alleviate part of this problem, it is recommended that a sensing unit be mounted on one arm of the twin arm support assembly. By so doing, the actual position of the probe could be recorded instead of the current method of recording the value of the stepper motor drive voltage.

B. TURBULENCE VARIATION AND CONTROL

To meet the requirements of NASA, the turbulence level at the cascade leading edge plane must be variable up to 6%. Reference 11 discusses methods of generating turbulence using a square mesh grid constructed of round bars. Since a bar-spacing to bar-diameter ratio of 5 or less is suggested,

it is recommended that several ratios be investigated. For simplicity, initial investigation should be done using bars which run in the span-wise direction only and fit into a frame which can be positioned at various heights above the inlet guide vanes.

To achieve an intensity of 6% at the leading edge plane, Reference 11 indicates that a ratio of turbulence decay distance to bar spacing in the range of 10 to 15 is needed. To meet these recommendations, one of the grids proposed in Table 1 should be constructed and then positioned a distance equal to 10M upstream of the leading edge plane. While measuring the turbulence intensity, the grid should be moved closer to or farther away from the leading edge plane until 6% turbulence is achieved.

C. LIQUID CRYSTAL THERMOGRAPHY

This technique seems to be one which would be very useful for flow visualization in the Cascade Wind Tunnel. Two problems, however, must first be addressed. The electrical short circuit between the temsheet and the metallic surface must be corrected. It is recommended that either the entire metallic covering of the blade now being used be removed, or that a new blade be manufactured entirely of a nonconducting material. The accuracy of the blade geometry with the temsheet covering must also be restored. The construction of a new blade with a reduced perimeter would permit the temsheet thickness to restore the blade to its original dimensions.

| NUMBER OF BARS | $\frac{M}{d}$ | d INCHES | M INCHES |
|----------------|---------------|----------|----------|
| 20 | 3 | 0.723 | 2.169 |
| 20 | 2 | 0.968 | 1.935 |
| 25 | 1 | 1.176 | 1.176 |

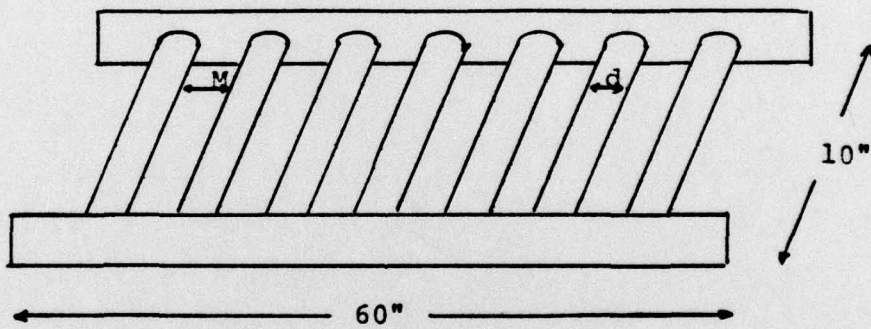


Table 1. TURBULENCE GENERATOR SPECIFICATIONS

Alternatively, the present blade could have its surface depth reduced by an amount equal to the temsheet thickness. This latter option will require the removal and reinstallation of the thermocouples.

APPENDIX A

DERIVATION OF HOT WIRE ANEMOMETER FORMULAS

Heat transfer from heated wire of a hot wire anemometer depends on the temperature difference between the wire and the fluid (air), the physical dimensions and material properties of the wire, and the physical properties and flow characteristics of the fluid. Empirically, the heat transferred from the wire can be expressed as a function of Prandtl and Reynolds numbers. One such relation is given in Reference 12 as

$$\text{Nu} = 0.42 \text{Pr}^{0.26} + 0.57 \text{Pr}^{0.33} \text{Re}^{0.50}$$

Since the properties of the air flowing through the cascade are essentially constant, the following form is assumed for the heat transfer relationship

$$\text{Nu} = A' + B' \text{Re}^{\frac{1}{N}} \quad (\text{A1})$$

From Newton's law of cooling, the heat removed from the wire is

$$Q = h A (T_w - T_g) = h (\pi DL) (T_w - T_g) \quad (\text{A2})$$

Expressing the Nusselt number definition as

$$\text{Nu} k = h D$$

and using it to substitute (A1) into (A2) gives

$$Q = L k \pi (A' + B' Re^{\frac{1}{N}}) (T_w - T_g) \quad (A3)$$

Since the material properties of the wire and the air are basically constant, and the dimensions of the wire do not change, (A3) can be expressed as

$$Q = (A^* + B^* U^{\frac{1}{N}}) (T_w - T_g)$$

With the anemometer operated in the constant temperature mode,

$$T_w - T_g = \text{constant}$$

therefore

$$Q = A'' + B'' U^{\frac{1}{N}} \quad (A6)$$

The heat generated in the wire is given by

$$Q = I_w^2 R_w \quad (A7)$$

For the wire to remain at a constant temperature, the heat generated must equal the heat removed, thus

$$I_w^2 R_w = A'' + B'' U^{\frac{1}{N}} \quad (A8)$$

The wire resistance is given by Reference 5 as:

$$R_w = R_o + \alpha_o R_o (T_w - T_o) \quad (A9)$$

All the values on the right side are constants, therefore R_w is a constant. Multiplying both sides of (A8) by R_w gives

$$I_w^2 R_w^2 = A^2 R_w + B^2 R_w U^{\frac{1}{N}} \quad (A10)$$

Using Ohm's law, (A10) reduces to

$$V^2 = A + BU^{\frac{1}{N}}$$

and, when the velocity is zero,

$$V_o^2 = A$$

which leads to

$$V^2 = V_o^2 + BU^{\frac{1}{N}} \quad (A11)$$

To consider the effect of changes in the velocity on the voltage, both sides of (A11) are differentiated with respect to time:

$$\frac{d}{dt} (V^2) = \frac{d}{dt} (V_o^2) + \frac{d}{dt} (BU^{\frac{1}{N}})$$

$$2V \frac{dv}{dt} = \frac{B}{N} U^{\frac{1}{N}} \frac{1}{U} \frac{du}{dt}$$

Since $BU \frac{1}{N} = v^2 - v_0^2$,

$$2v \frac{dv}{dt} = \frac{v^2 - v_0^2}{N} \frac{1}{U} \frac{du}{dt}$$

Rearranging gives

$$\frac{du/dt}{U} = \frac{2NV}{v^2 - v_0^2} \frac{dv}{dt} \quad (A12)$$

Taking the root mean square of the differential terms of (A12):

$$u' = \left[\frac{1}{T} \int_0^T \left(\frac{du}{dt} \right)^2 \right]^{\frac{1}{2}}$$

$$v_{\text{RMS}} = \left[\frac{1}{T} \int_0^T \left(\frac{dv}{dt} \right)^2 \right]^{\frac{1}{2}}$$

given

$$\frac{u'}{U} = \left[\frac{2NV}{v^2 - v_0^2} \right] v_{\text{RMS}} \quad (A13)$$

APPENDIX B

HOT WIRE ANEMOMETER CALIBRATION PROCEDURES

Calibration of the hot wire was accomplished following the procedures of Reference 8 and using a Thermo-System Inc. model 1125 calibrator. A Meriam type W model 30EB25 30-inch water manometer was used in conjunction with the calibrator to the pressure differential across the 0.150 inch diameter orifice. Atmospheric temperature and barometric pressure were obtained at the start of the calibration from a standard Fortin barometer at the calibration site.

The anemometer unit was prepared for calibration following the operating procedures on pages 15 and 16 of Reference 8. The velocity of air through the calibrator orifice was regulated using the flow regulator control. The pressure regulator control on the calibrator was set so that the manometer read 30 inches of water with the flow regulator fully open. During calibration, the flow through the orifice and across the hot wire was adjusted to give several manometer readings. At each calibration point the manometer reading and the corresponding hot wire V_{DC} were recorded. Generally, half the calibration points were taken with a rising manometer, and half were taken with a falling manometer.

Reduction of the calibration data consisted of determining the true velocity corresponding to each manometer pressure. Data reduction was as follows:

1. Convert atmospheric temperature to degrees Rankine.
2. Correct barometric pressure for temperature and latitude.

$$P_{ATM} (\text{"Hg}) = P_{BAR} - \text{Temp. Corr.} - \text{Lat. Corr.}$$

$$\text{Lat. Corr.} = .0235$$

3. Compute density of air

$$\rho_{ATM} (\text{lbm/ft}^3) = \gamma_{Hg} P_{ATM} / [(12) (R) (T_{ATM})]$$

$$R = 53.34 \text{ ft-lbf/lbm } ^\circ R$$

$$\gamma_{Hg} \approx 846 \text{ lbf/ft}^3$$

4. Correct manometer pressure to standard conditions

$$\Delta P_{CORR} (\text{"H}_2\text{O}) = \Delta P_{MAN} \frac{P_{STD}}{P_{ATM}}$$

$$P_{STD} = 29.92 \text{ "Hg}$$

5. Compute the velocity corresponding to the corrected manometer pressure by using Figure 2A of Reference 13 or by using the following equation derived from this figure:

$$U (\text{ft/s}) = 10 \cdot [0.4975 \log(\Delta P_{CORR}) + 1.8249]$$

log is to the base 10.

6. Correct the velocity to standard conditions

$$U_{CORR} (\text{ft/s}) = U \left[\frac{T_{ATM}}{T_{STD}} \right]^{1/2}$$

$$T_{STD} = 529.7 \text{ R}$$

7. Correlate the values of V_{DC} to the corresponding values of U_{CORR} by linear regression or other suitable techniques. The basic relation between U_{CORR} and V_{DC} is given by

$$V_{DC}^2 = A + B U_{corr}^{\frac{1}{N}}$$

where $A = V_0^2$

and $2 \leq N \leq 3$

APPENDIX C

ELECTRICAL POWER REQUIREMENTS FOR LIQUID CRYSTAL THERMOGRAPHY VISUALIZATION TECHNIQUES.

Assume turbulence flow of air over a flat plate eight inches long, ten inches wide, having a surface area of 160 square inches. Plate surface temperature is to be 100°F. Air flow is at 275 ft/s and 70°F. The film temperature for property evaluation is taken as 85°F. Property values for air are therefore as follows:

$$\mu = 0.0449 \text{ lbm/h-ft}$$

$$k = 0.1528 \text{ BTU/h-ft-}^\circ\text{F}$$

$$C_p = 0.240 \text{ BTU/lbm }^\circ\text{F}$$

$$P_r = 0.708$$

$$\rho = 0.0728 \text{ lbm/ft}^3$$

$$\nu = 1.714 \times 10^{-4} \text{ ft}^2/\text{s}$$

For the turbulent flow specified, the correlation of equation 5-81 of Reference 14 is used

$$\overline{NU}_L = \frac{\bar{h}L}{k} = P_R^{1/3} \left(0.037 \text{ Re}_L^{0.8} - \frac{1700}{2} \right)$$

This yields an average convective heat transfer coefficient of

$$\bar{h} = 0.01 \text{ BTU/s-ft}^2\text{-}^\circ\text{F}$$

Equating the heat generated in the blade by the electrical current to the heat removed by convection gives

$$\text{Power} = I^2 R = \bar{h} A (T_b - T_\infty) = VI$$

which leads to

$$I_{\min} = \frac{\bar{h} A (T_b - T_\infty)}{V_{\max}} = \frac{\text{Power}}{V_{\max}}$$

and

$$R_{\max} = \frac{\bar{h} A (T_b - T_\infty)}{I_{\min}^2} = \frac{\text{Power}}{I_{\min}^2}$$

The power requirement is calculated as

$$\text{Power} = \bar{h} A (T_b - T_\infty) = 351 \text{ watts}$$

For a power supply rated at a maximum output potential of 60 volts, current and resistance requirements are

$$I_{\min} = 5.8 \text{ amps}$$

$$R_{\max} = 10.2 \text{ ohms}$$

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