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NASA CR-135277
PWA-5540

EXPERIMENTAL CLEAN COMBUSTOR PROGRAM
TURBULENCE CHARACTERISTICS OF COMPRESSOR DISCHARGE FLOWS

by

P. S. Follansbee and R. R. Dils

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney Aircraft Group
Commercial Products Division

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PRATT & WHITNEY AIRCRAFT GROUP

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Reference: Contract NAS3-19447, Modification 1

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16. Abstract

The results of turbulence measurements at the entrance to the diffuser duct of a large gas turbine are presented in this report. Hot film and hot wire measurements were conducted over a compressor discharge temperature range of 450K (idle) to 608K (rich approach). It was found that the turbulent intensity at the I.D. (25 percent span) and mid span locations increases gradually from 6 ±1 percent at idle to 7 ±1 percent at approach; the turbulent intensity at the O.D. (75 percent span) location increases from 7.5 ±0.5 percent at idle to 15 ±0.5 percent at approach. The energy in the velocity waves is uniformly distributed over a 0.1 to 5 kHz bandwidth and the cut-off frequency is not a strong function of the engine operation. The axial length of the fourier components within this bandwidth varies from 0.021 to 1.05m. The turbulence near the diffuser O.D. is of sufficient amplititude and scale to affect the flow to the front end sections of the burner.

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FOREWORD

This document describes the work performed by the Commercial Products Division, Pratt & Whitney Aircraft Group of United Technologies Corporation under the Turbulence Measurement Addendum to Phase III of the Experimental Clean Combustor Program. This final report was prepared in accordance with Modification No. 1 to National Aeronautics and Space Administration, Lewis Research Center Contract NAS3-19447. This report has been assigned Commercial Products Division, Pratt & Whitney Aircraft Group internal report number PWA-5540.

Appreciation is expressed for the contributions made by Mr. Howard P. Grant of the Dynamic Measurements Development and Support Group at Pratt & Whitney Aircraft.

TABLE OF CONTENTS

		Page
SUMMARY		1
INTRODUCTION		2
CHAPTER I	PROGRAM DESCRIPTION	3
	A. Phase III ECCP Program	3
	B. Turbulence Measurement Program	3
CHAPTER II	EQUIPMENT AND EXPERIMENTAL PROCEDURES	4
	A. Test Engine and Combustor	4
	B. Probe Description and Location	8
	C. Data Acquisition System	8
	D. Calibration Procedures	13
	E. Data Reduction Procedures	19
CHAPTER III	RESULTS AND DISCUSSION	23
CHAPTER IV	CONCLUSIONS	35
REFERENCES		36
DISTRIBUTION		37

LIST OF ILLUSTRATIONS

Figure	Title	Page
1	Cross Sectional Schematic of the JT9D-7A Reference Engine	5
2	Experimental Engine, X-686, With Bifurcated Ducts Installed	5
3	P-6 Test Cell Layout	6
4	Cross Section of Experimental Clean Combustor Program Phase III Vorbix Combustor	7
5	Location of Turbulence Probes	9
6	Wedge Type Probe	11
7	Stator 4 Probe Adaptor	12
8	Wire Probe	12
9	Dependence of Probe Resistance on Temperature	13
10	Dependence of Quiescent Environment Bridge Voltage on Temperature	15
11	Experimental Arrangement for Anemometer Velocity Calibrations	16
12	Anemometry Probe Velocity Calibrations	17
13	Wedge Probe Transfer Function	18
14	Block Diagram of Data Reduction System	21
15	Dependence of Turbulence on Engine Operation	27
16	Test 1, Probe 3 (Wedge Type) Power Spectral Density Function for Idle Condition at 25 Percent Span	27
17	Test 3, Probe 1 (Wedge Type) Power Spectral Density Function for Approach Power Condition at 25 Percent Span	28
18	Test 3, Probe 2 (Wedge Type) Power Spectral Density Function for Idle Condition at 75 Percent Span	28

LIST OF ILLUSTRATIONS (Cont'd)

Figure	Title	Page
19	Test 3, Probe 4 (Wedge Type) Power Spectral Density Function for Approach Power Condition at 75 Percent Span	29
20	Test 1, Probe 3 (Wedge Type) Spectral Distribution for Idle Condition at 25 Percent Span	29
21	Test 3, Probe 1 (Wedge Type) Spectral Distribution for Idle Condition at 25 Percent Span	30
22	Test 3, Probe 2 (Wedge Type) Spectral Distribution for Idle Condition at 75 Percent Span	30
23	Test 3, Probe 4 (Wedge Type) Spectral Distribution for Approach Power Condition at 75 Percent Span	31
24	Test 3, Probe 2 (Wedge Type) Spectral Distribution for Idle Condition at 75 Percent Span	33
25	Test 3, Probe 4 (Wedge Type) Spectral Distribution for Idle Condition at 75 Percent Span	34
26	Test 3, Probe 4 (Wedge Type) Spectral Distribution for Idle Condition at 75 Percent Span	34

LIST OF TABLES

Table	Title	Page
I	Probe Types and Locations	10
II	Dependence of Turbulent Intensity on Engine Operation, Test 1	24
III	Dependence of Turbulent Intensity on Engine Operation, Test 2	24
IV	Dependence of Turbulent Intensity on Engine Operation, Test 3	25
V	Engine Test Conditions	26
VI	Turbulence Characteristics of Compressor Discharge Flows	32

SUMMARY

The results of turbulence measurements at the entrance to the diffuser duct of a JT9D gas turbine engine are presented in this report. A series of hot film and hot wire measurements were made with state-of-the-art probes over the range of engine operating conditions permitted by the probe endurance. The measurements were made in the experimental JT9D-20 engine X686 used for the Phase III Experimental Clean Combustor Program. Three engine tests were conducted from Idle (T_4 = 450K) to rich approach (608K). Several features of the turbulence in the diffuser duct were documented:

1. The turbulent intensity at the I.D. (25 percent span) and midspan locations increases gradually from 6 ±1 percent at idle to 7 ±1 percent at approach; the turbulent intensity at the O.D. (75 percent span) location increases from 7.5 ±0.5 percent at idle to 15 ±0.5 percent at approach.

2. The energy in the velocity waves is uniformly distributed over a 0.1 to 5 kHz bandwidth. The axial length of the fourier component within this bandwidth varies from 0.021 to 1.05 m.

3. The cut-off frequency of the turbulence (−3 db) is approximately 3 kHz and is not a function of the engine operation. Above the cut-off frequency, the fourier components of the wave decrease at a rate proportional to $f^{-2.5\pm0.1}$. Ninety percent of the energy of the waves is contained within a 0.1 to 5 kHz bandwidth.

4. Determination of the origin of the high level of turbulence at the diffuser O.D. requires further information on the development of the turbulence along the diffuser.

5. The turbulence at the diffuser O.D. is of sufficient amplitude and scale to affect the flow to the front end sections of the burner.

INTRODUCTION

The objective of this addendum to the Phase III Experimental Clean Combustor Program was to conduct a series of measurements in order to document the turbulence characteristics of the compressor discharge flows within a JT9D engine. This report describes the program conducted and the results. The turbulent intensity and scale are of interest to advanced lean burning prevaporized-premixed combustor designs because of their potential effect on the fuel prevaporization and premixing near the entrance of a combustor and attendant changes in emissions performance.

This report is organized in four chapters. A summary of the program plan and schedule is presented in Chapter I. Chapter II contains a description of the experimental JT9D engine and turbulence measurement probes used for the program work and a description of the test and analysis procedures. The turbulence program results are discussed in Chapter III and the concluding remarks are presented in Chapter IV.

CHAPTER I

PROGRAM DESCRIPTION

A. PHASE III ECCP PROGRAM

The turbulence program addendum was conducted concurrently with the latter stages of the Experimental Clean Combustor Program (ECCP) Phase III, which is described in a separate report [Reference 1].

The ECCP Phase III program, consisted of a detailed evaluation of a low pollution combustor, fuel system, and fuel control concept in a JT9D engine. The general objective was to demonstrate significant pollution reductions with an advanced combustor which meets the performance, operation, and installation requirements of the engine. The test program included steady-state and transient pollution and performance evaluations. Details of the work are contained in Reference 1. The turbulence measurements were made during the acceleration/deceleration test portion of the ECCP program.

B. TURBULENCE MEASUREMENT PROGRAM

The turbulence measurement program was conducted during the second half of 1976. A series of hot film and hot wire measurements were made with state-of-the-art probes over the range of engine operating conditions permitted by the endurance of the sensing probes.

The program was accomplished in four tasks: Task I, Instrumentation, included the procurement, fabrication, and calibration of the required hot wire/hot film type probes; Task II, Testing and Data Acquisition, with the engine operating in a steady-state mode and at power levels ranging from sub-idle to the maximum consistent with the probe design; Task III, Data Analysis; and Task IV, Reporting.

CHAPTER II

EQUIPMENT AND EXPERIMENTAL PROCEDURES

A. TEST ENGINE AND COMBUSTOR

Experimental JT9D-20 engine X-686 was used as the test vehicle for the Phase III Experimental Clean Combustor Program and the turbulence measurement addendum program. A detailed description of the engine is available in reference 1; a cross sectional schematic of a JT9D-7A reference engine is shown in Figure 1.

A flight-type nacelle normally was not employed for either experimental or production JT9D engine testing. A cylindrical core engine exhaust nozzle was used in place of the plug-type flight design; a pair of bifurcated fan ducts was used in place of the annular fan duct. The fan and core nozzle areas were sized to provide aerodynamic characteristics equivalent to the flight nacelles. The bifurcated fan ducts facilitate installation of special instrumentation and test hardware, and are readily removed for access to the core engine. The instrumented engine shown with the bifurcated fan ducts installed and ready for test is shown in Figure 2.

The engine was run in the P-6 test stand in an ambient inlet indoor test cell located at the Pratt & Whitney Aircraft facility in Middletown, Connecticut. The cell contains the instrumentation and data processing equipment required for the automatic temperature recording system and low-emission combustor development programs. The facility is equipped with a monorail engine handling system to facilitate movement of the engine into and out of the test cell. A schematic view of the test cell layout is shown in Figure 3. All engine controls, data logging, and computer face equipment are located in the test cell control room.

Cross section drawings of the Phase III Vorbix (vortex burning and mixing) combustor is shown in Figure 4. The Vorbix concept incorporates two burning zones separated axially by a high velocity throat section. The pilot zone is a conventional swirl-stabilized, direct-injection combustor employing thirty fuel injectors. It is sized to provide the required heat release rate for idle operation at high efficiency. Emissions of carbon monoxide and unburned hydrocarbons are minimized at idle operation conditions primarily by maintaining a sufficiently high pilot zone equivalence ratio to allow complete burning of the fuel.

At high power conditions, the pilot exhaust equivalence ratio was reduced as low as 0.3 (including pilot dilution air) to minimize formation of oxides of nitrogen. The minimum equivalence ratio for the pilot zone was determined by the overall lean blowout limits, combustion efficiency, and the need to maintain sufficient pilot zone temperature to vaporize and ignite the main zone fuel. Main zone fuel was introduced through fuel injectors located at the outer wall of the liner downstream of the pilot zone discharge location. Sixty fuel injectors were used. Main zone combustion and dilution air was introduced through sixty swirlers positioned on each side of the combustor. A more extensive description of the equipment, hardware and test procedures is found in the companion ECCP Final Report [Reference 1].

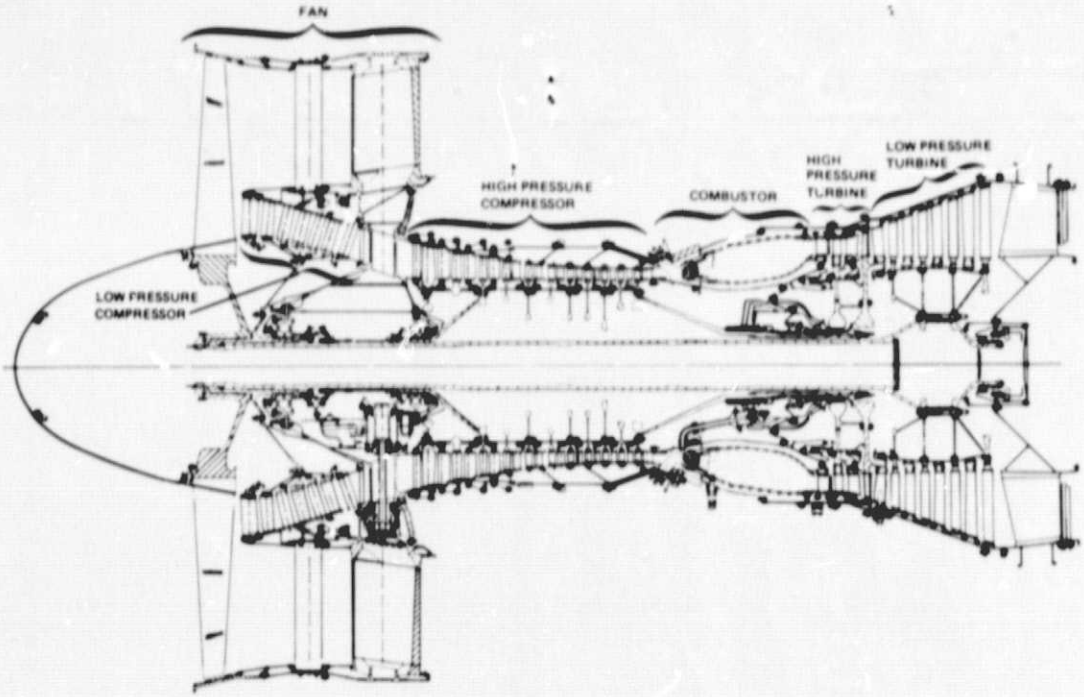

Figure 1 *Cross Sectional Schematic of the JT9D-7A Reference Engine*

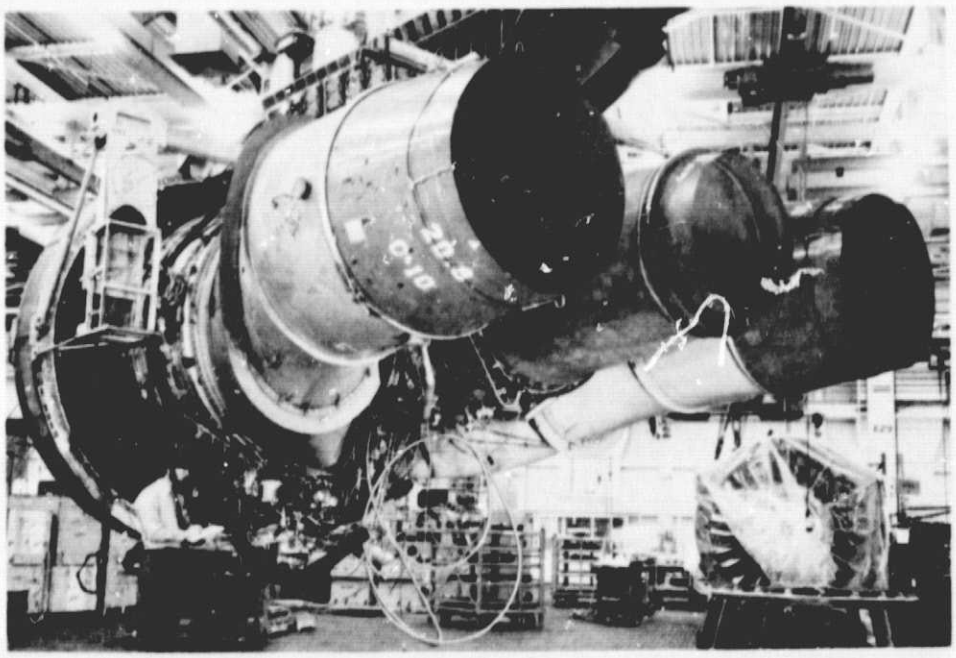

Figure 2 *Experimental Engine, X-686, With Bifurcated Ducts Installed* *(X-43208)*

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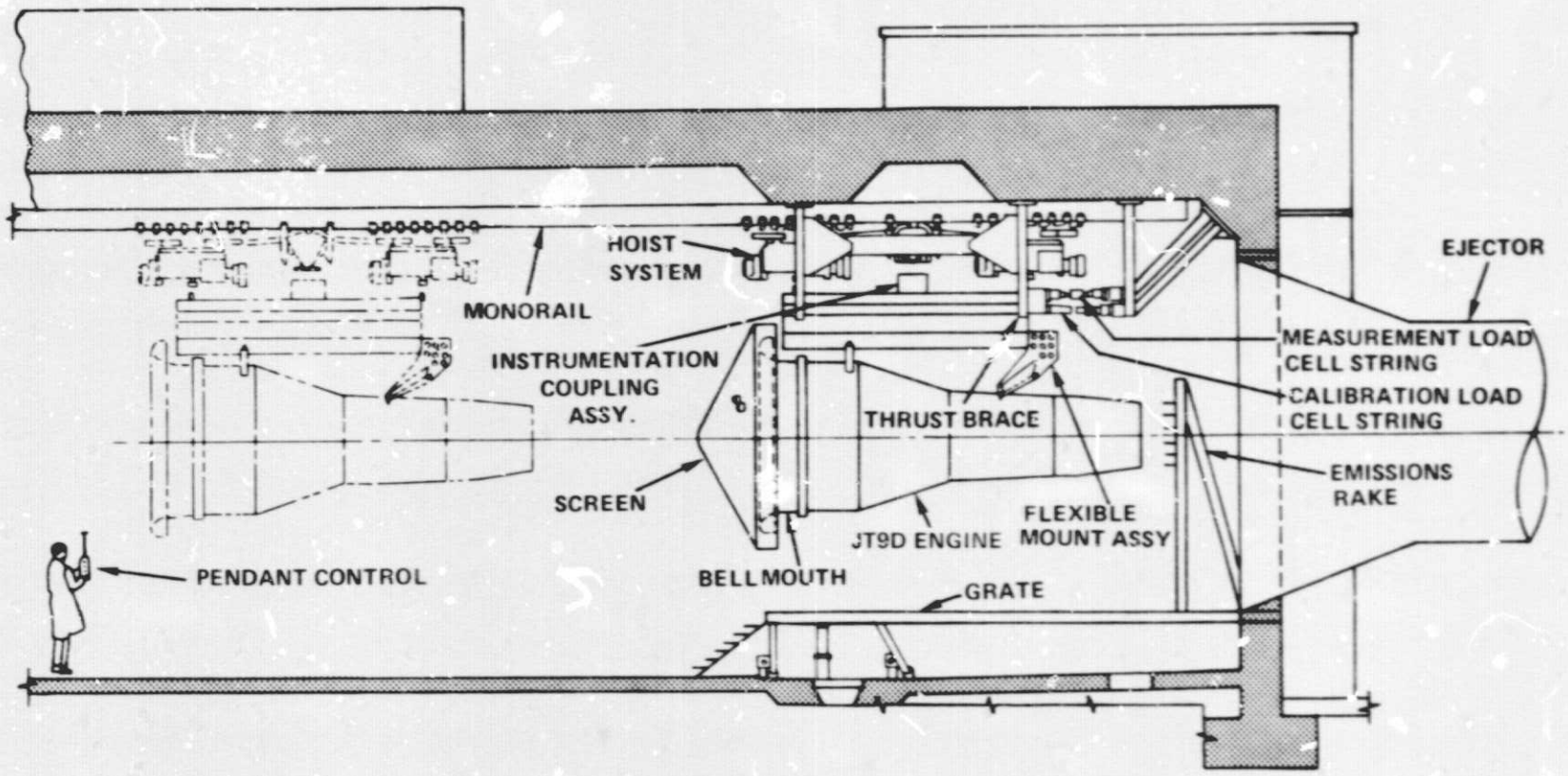

Figure 3 *P-6 Test Cell Layout*

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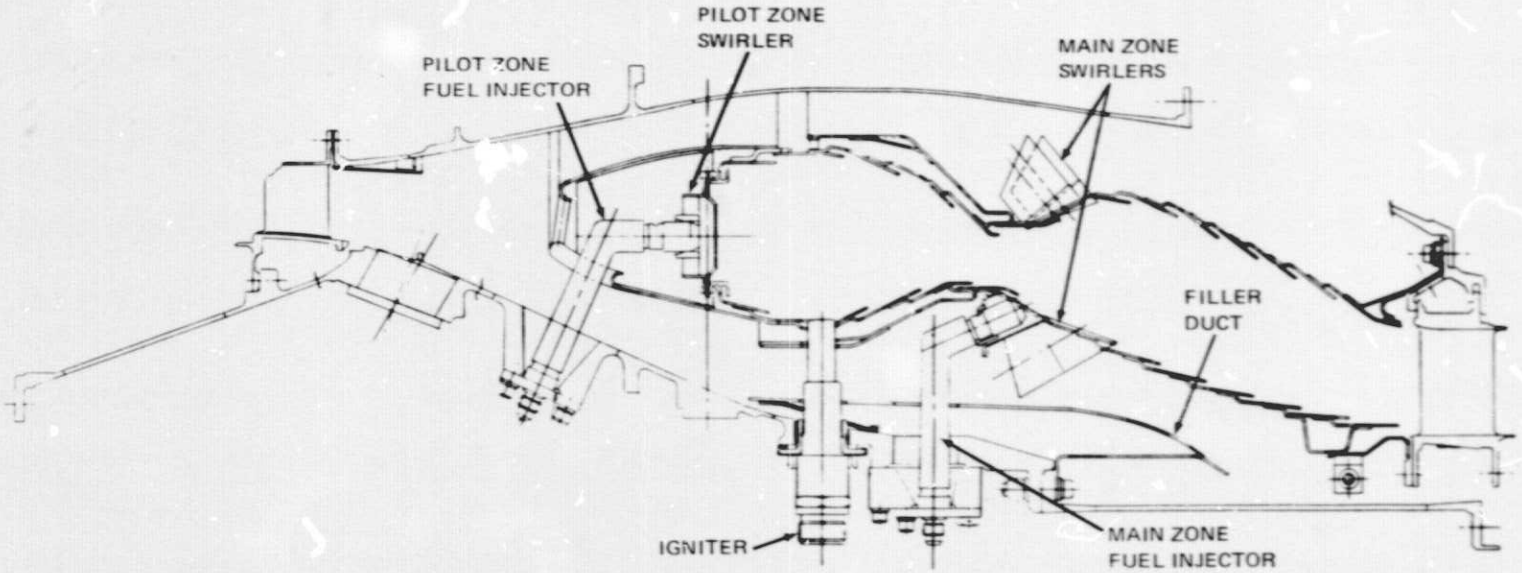

Figure 4 *Cross Section of Experimental Clean Combustor Program Phase III Vorbix Combustor*

While the two-stage Vorbix burner is a significantly different concept than the current production combustor, since compressor and burner pressure loss are the same as the bill-of-material, the measured turbulence levels in the diffuser should be representative of those in most JT9D-7 engines.

B. PROBE DESCRIPTION AND LOCATION

Turbulence measurements were conducted at six circumferential and three spanwise positions near the entrance to the diffuser. The locations of the probes are shown in Figure 5. At each circumferential position, the probes were located at 25, 50 or 75 percent span locations. Three types of wire and wedge probes were used during the tests. A summary of the probe locations and types in the three engine tests which were conducted to measure the turbulence in the diffuser is presented in Table I.

The primary devices used in the tests were wedge type probes consisting of an alumina coated platinum thin film sputtered near the leading edge of a quartz wedge (TSI 949K, Thermosystem, Inc.). A line drawing and photograph of this probe are shown in Figures 6a and 6b. A wedge probe located in a probe mounting adaptor is shown in Figure 7. Probes were retracted in the shield during installation and then inserted to a prescribed location determined from prior engine build measurements. The angular orientation of the probes was established by aligning scribe marks of the probes with the engine axis. The probes are insensitive to changes in the angle of attack within ±10 degrees of the mean flow direction.

Two types of wire probes were also used. The probes 370μ diameter stainless steel or 12μ diameter Pt-Ir wires were suspended between support posts of a TSI 1226AB probe (Figure 8). These probes were installed in the engine in the same manner as the wedge probes.

Five P_{T4} and five T_{T4} probes were located at the compressor discharge as shown in Figure 5.

C DATA ACQUISITION SYSTEM

The probes were used with a Thermosystems 1053A anenometer and the signals were recorded with a Hewlett-Packard 3960 magnetic tape recorder with frequency modulated (FM) and direct record and playback modules. Using both FM and direct record modules, it was possible to record data within a 0 to 50 kHz bandwidth. The bandwidth of the data was determined by the transfer function of the probe/lead/anenometer circuit; this transfer function was experimentally determined and used to obtain data within a 0-20 kHz bandwidth (see subsequent section). Since the diffuser turbulence was measured primarily within a 100-5,000 Hz bandwidth, the data acquisition system bandwidth did not limit or affect the turbulence measurements.

Noise levels measured in the engine prior to the test were ~0.9 mV. This electrical noise corresponded to an equivalent input noise turbulent intensity of 0.2 percent at flight idle and reduced to less than 0.1 percent as the engine thrust increased. Data was recorded after a five minute stabilization at each test point. There was no evidence of drift in the turbulence characteristics after the stabilization period.

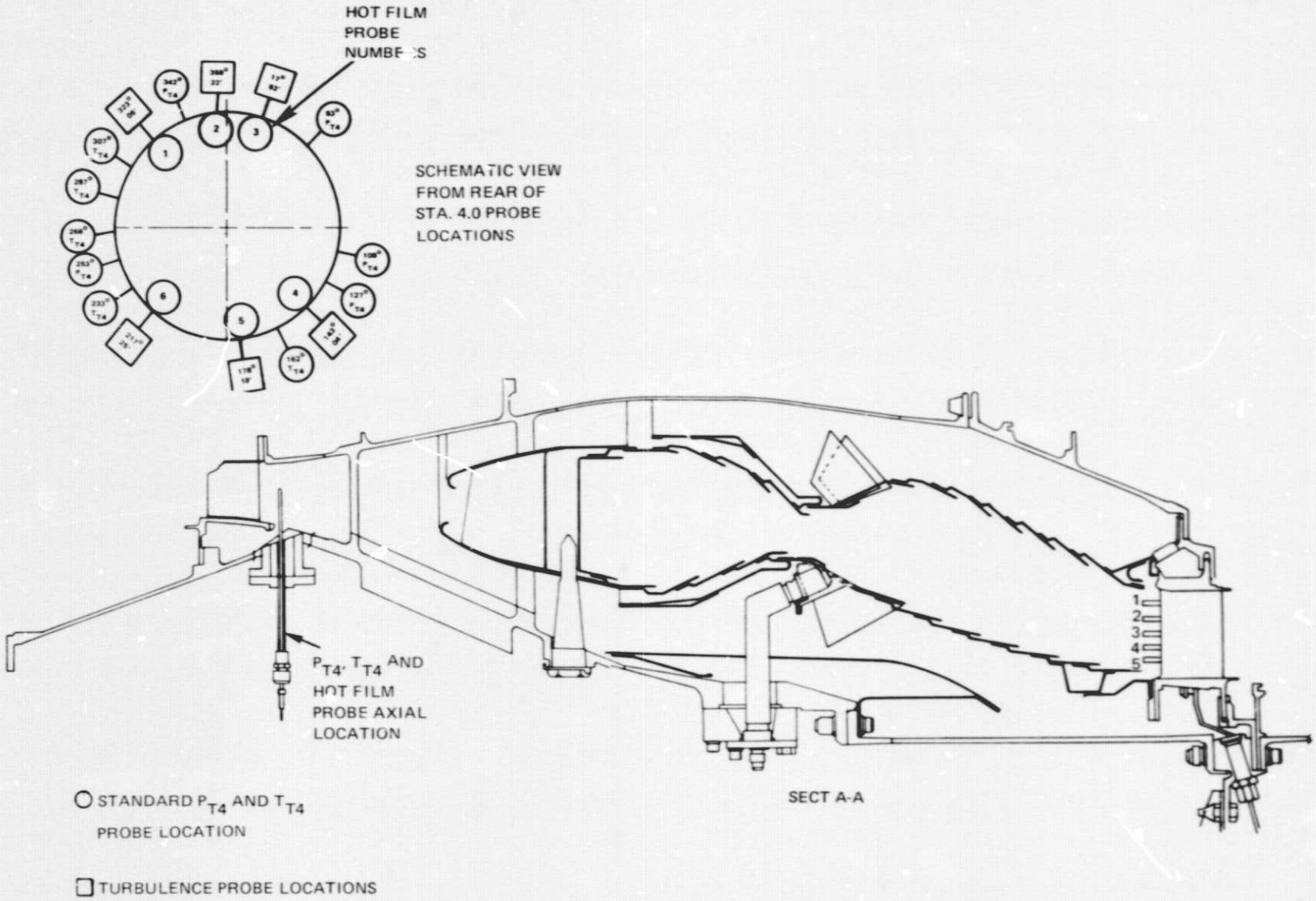

Figure 5 *Location of Turbulence Probes*

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TABLE I

PROBE TYPES AND LOCATIONS

Test No. 1

*Probe No.	Type	Angular Location	Spanwise Location (Percent)
1	370μ diameter Stainless Steel Wire Probes	323° 05′	25, 50, 75
2	TSI 949K Hot Film Probes	358° 22′	25, 50, 75
3	TSI 949K Hot Film Probes	17° 52′	25, 50, 75
4	TSI 949K Hot Film Probes	143° 04′	25, 50, 75
5	370μ diameter Stainless Steel Wire Probes	178° 18′	25, 50, 75
6	12μ Pt-Ir Wire Probes	217° 25′	25, 50, 75

Test No. 2

*Probe No.	Type	Angular Location	Spanwise Location (Percent)
1	370μ diameter Stainless Steel Wire Probes	323° 05′	25, 50, 75
2	370μ diameter Stainless Steel Wire Probes	358° 22′	25, 50, 75
3	370μ diameter Stainless Steel Wire Probes	17° 52′	25, 50, 75
4			
5	370μ diameter Stainless Steel Wire Probes	178° 18′	25, 50, 75
6	12μ Pt - Ir Wire Probes	217° 25′	25, 50, 75

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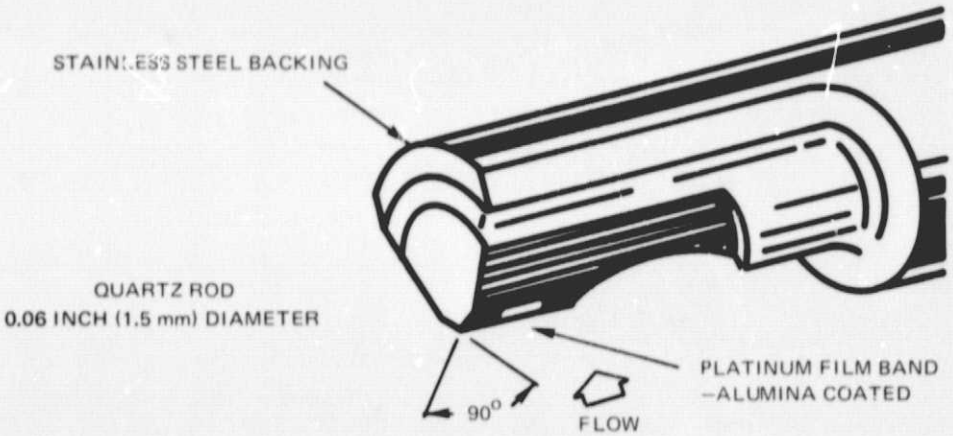
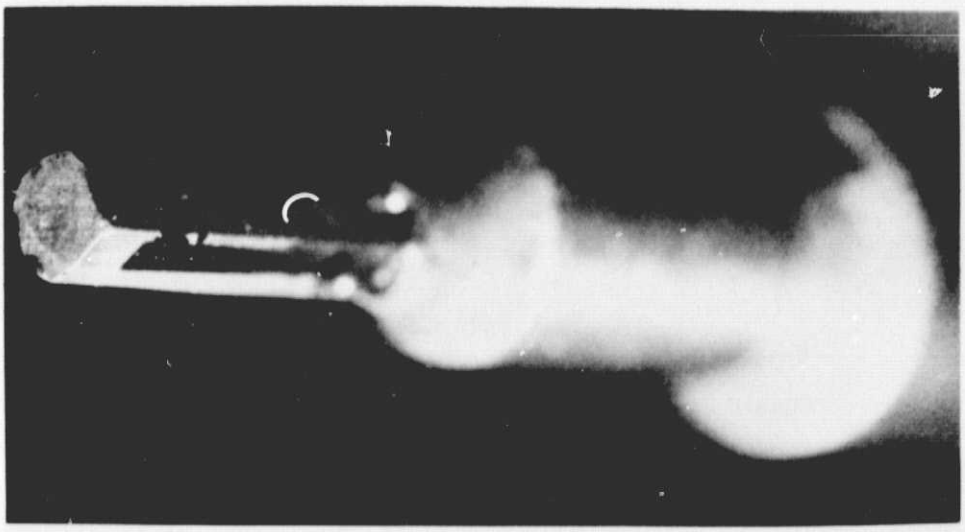
5	TSI 949K Hot Film Probe	178° 18′	25, 50, 75
6	TSI 949K Hot Film Probe	217° 25′	25, 50, 75

*See Figure 5 for Probe Location



SENSING SIZE: TWO WEDGE SURFACES EACH 0.005 INCH (0.12 mm) WIDE BY 0.04 INCH (1.0 mm) LONG

(a)



(b)

Figure 6 Wedge Type Probe (77-444-9004)

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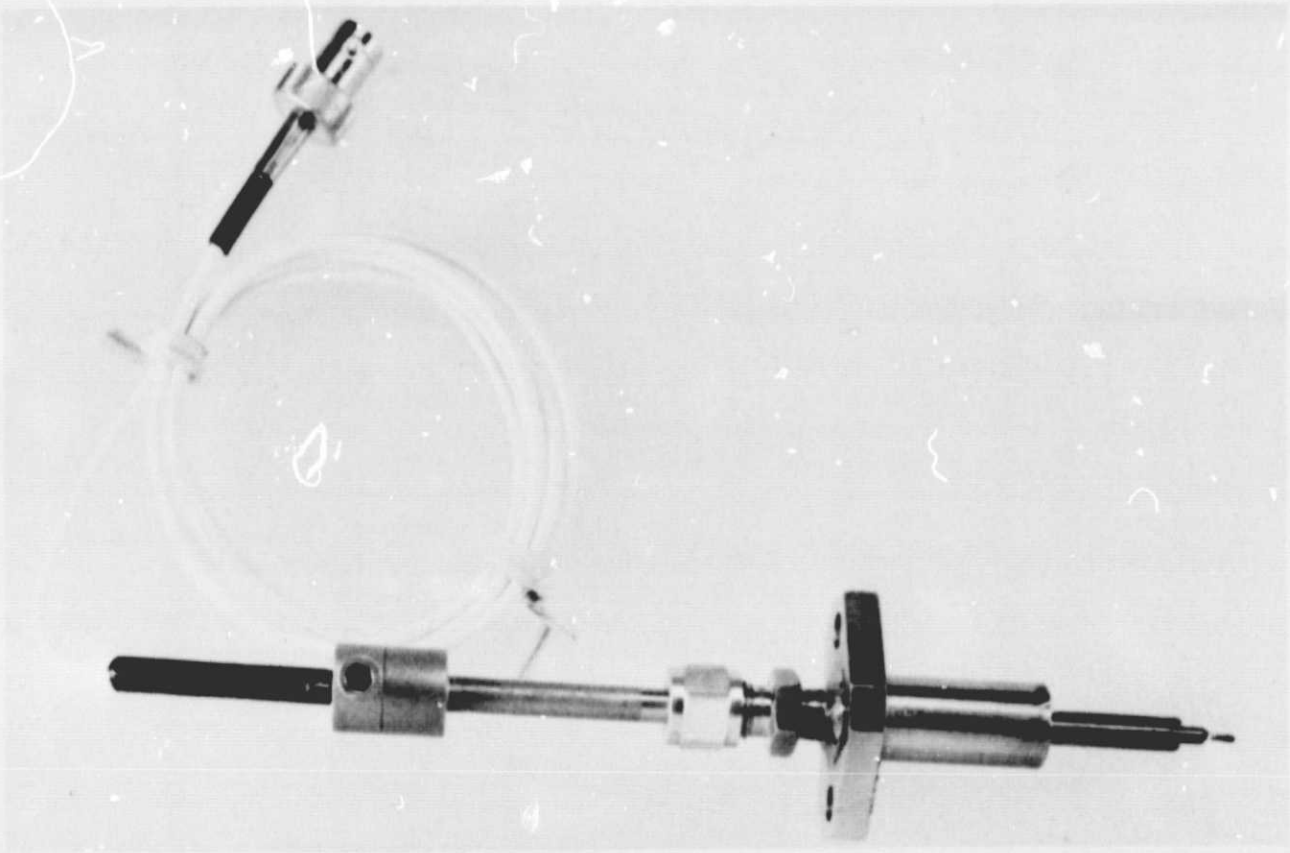

Figure 7 *Station 4 Probe Adaptor* *(77-441-9142)*

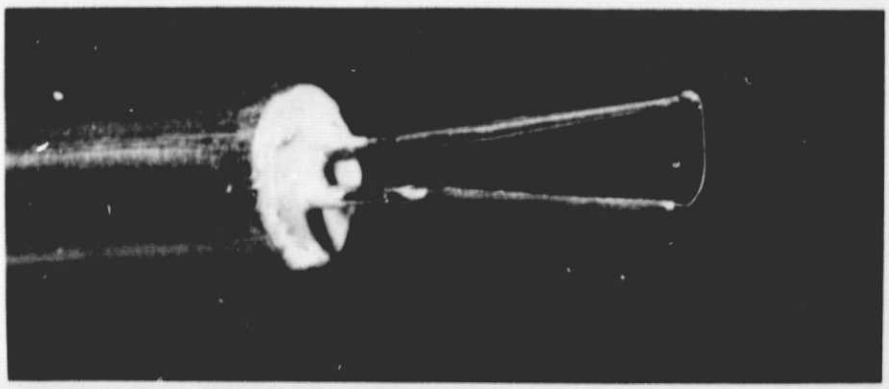

Figure 8 *Wire Probe* *(77-444-9002A)*

D. CALIBRATION PROCEDURES

The probes were subjected to a series of calibrations procedures prior to use in an engine test. The stability of the wedge probes was checked by heating the probes to 516K for approximately 30 minutes and measuring the changes in the film resistivity. Irreversible resistance changes of the probes used in the engine tests were found to be less than 0.2 percent. Typical resistances of the probes between 297K and 589K are shown in Figure 9.

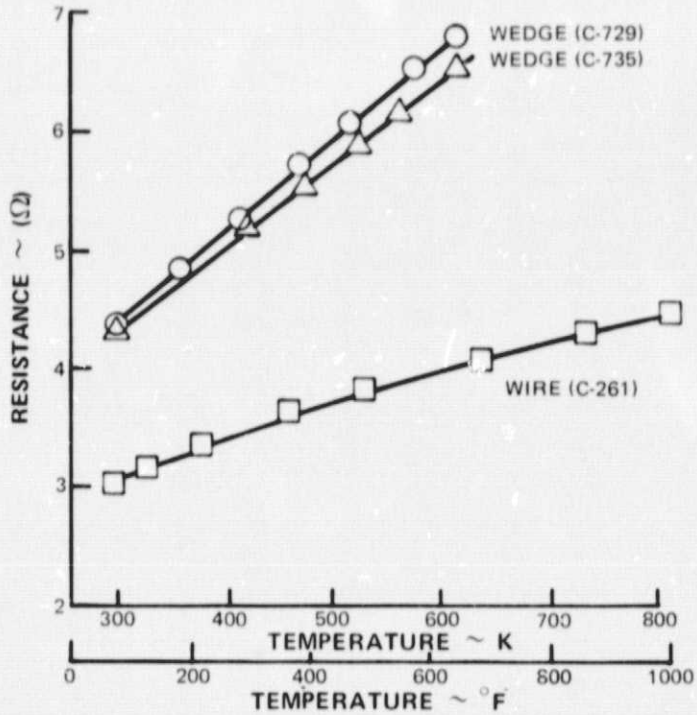

Figure 9 Dependence of Probe Resistance on Temperature

The heat transfer to a probe in a gas stream is described by the one dimensional heat balance equation at the surface of the probe,

$$hA\,(T - T_G) = \frac{R}{(R + R_b)^2}\,(E^2 - E_C{}^2) \qquad (1)$$

where h = heat transfer coefficient, KW/m^2K

A = surface area, m^2

T = average surface temperature, K

T_G = average gas temperature, K

R = sensor resistance, Ω

R_b = resistance of resistor in series with sensor in anenometer circuit, Ω

E = bridge voltage in test environment, V,

and, E_C = bridge voltage in quiescent environment, V.

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In equation 1 the left side represents the heat liberated due to convection and the right side is the heat liberated due to joulian heating. The convection heat transfer coefficient is specified by the velocity, temperature, and pressure of the environment; the general relationship is written

$$h = Ku^n$$

where $K = K[P,T]$

Substituting this expression into equation 1 and simplifying yields:

$$u^n = C[E^2 - E_C{}^2] \tag{2}$$

where $C = \dfrac{R}{KA(T - T_G)(R + R_b)^2}$

The velocity, u, and bridge voltage, E, can be separated into the steady state and wide bandwidth components, giving

$$u = \bar{u} + \tilde{u} = \bar{u}\left(1 + \frac{\tilde{u}}{\bar{u}}\right)$$

and,

$$E = \bar{E} + \tilde{E} = \bar{E}\left(1 + \frac{\tilde{E}}{\bar{E}}\right)$$

Assuming $\tilde{u}/\bar{u} << 1$ and $\tilde{E}/\bar{E} << 1$ the following simplifications apply:

$$u^n = \left[\bar{u}\left(1 + \frac{\tilde{u}}{\bar{u}}\right)\right]^n \approx \bar{u}^n\left(1 + n\frac{\tilde{u}}{\bar{u}}\right)$$

and,

$$E^2 = \bar{E}^2\left(1 + 2\frac{\tilde{E}}{\bar{E}}\right)$$

Substituting these approximations into equation 2 and simplifying yields an expression for the average velocity, u, and the turbulent intensity, $\tilde{u}/\bar{u}$, written

$$u = [C(E^2 - E_C{}^2)]^{1/n}$$

and (3)

$$\frac{\tilde{u}}{\bar{u}} = \frac{2}{n}\left(\frac{\tilde{E}\,\bar{E}}{\bar{E}^2 - E_C{}^2}\right)$$

Probe calibration consisted of determining the values of n and E_C for use in equation 3. E_C values are measured separately in a laboratory furnace. Examples of the dependence of E_C on the temperature of wedge and stainless steel wire probes are shown in Figure 10.

Taking the log of both sides of equation 2 yields

$$\log (E^2 - E_C{}^2) = n \log u - \log c$$

A log-log plot of $(E^2 - E_C{}^2)$ versus u values measured in a known velocity gas stream gives a straight line with constant slope. Although the value of C varies with temperature, pressure and overheat, ΔT, (where ΔT is defined as $T-T_G$), the slope remains constant. Therefore, ambient conditions are used for this calibration procedure. The experimental arrangement for determining the dependence of the probe voltage $(E^2 - E_C{}^2)$, on the mean velocity of a cold jet is shown in Figure 11. Example $(E^2 - E_C{}^2)$ vs. u curves are presented in Figure 12 where it is seen that the slope for a given probe is indeed constant over the experimental range of velocities.

The transfer functions of the probes also were determined in the cold jet. The output of the probes was compared with the output of a 6μ platinum wire probe which had a flat response over the bandwidth of interest. An example transfer function of a wedge probe is presented in Figure 13. These transfer functions were not found to be a strong function of Reynolds number.

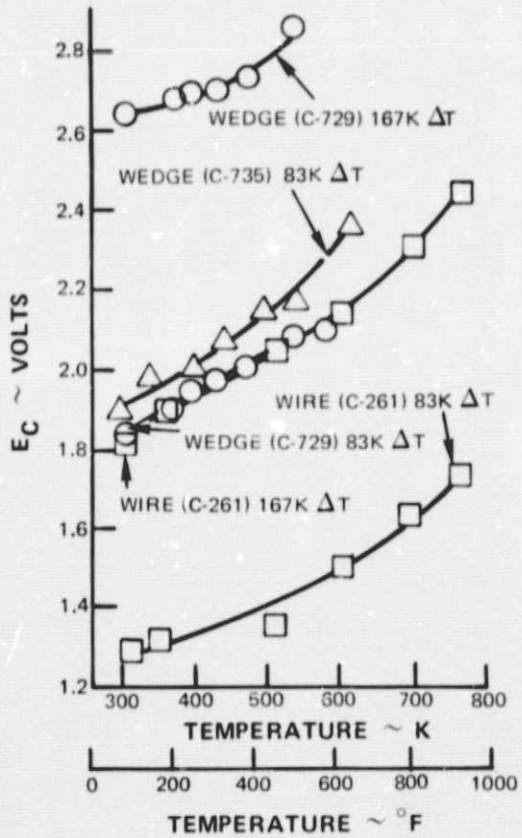

Figure 10 *Dependence of Quiescent Environment Bridge Voltage On Temperature*

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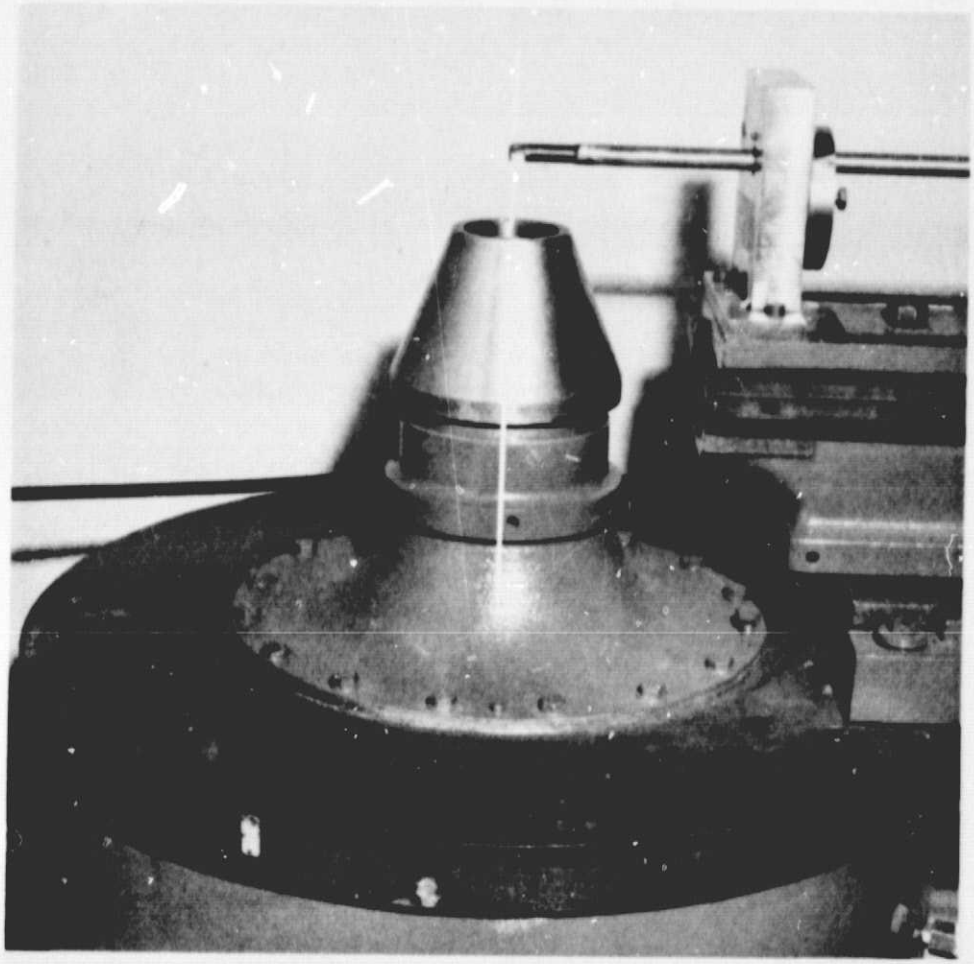

Figure 11 *Experimental Arrangement for Anemometer Velocity Calibrations* *(X-30941)*

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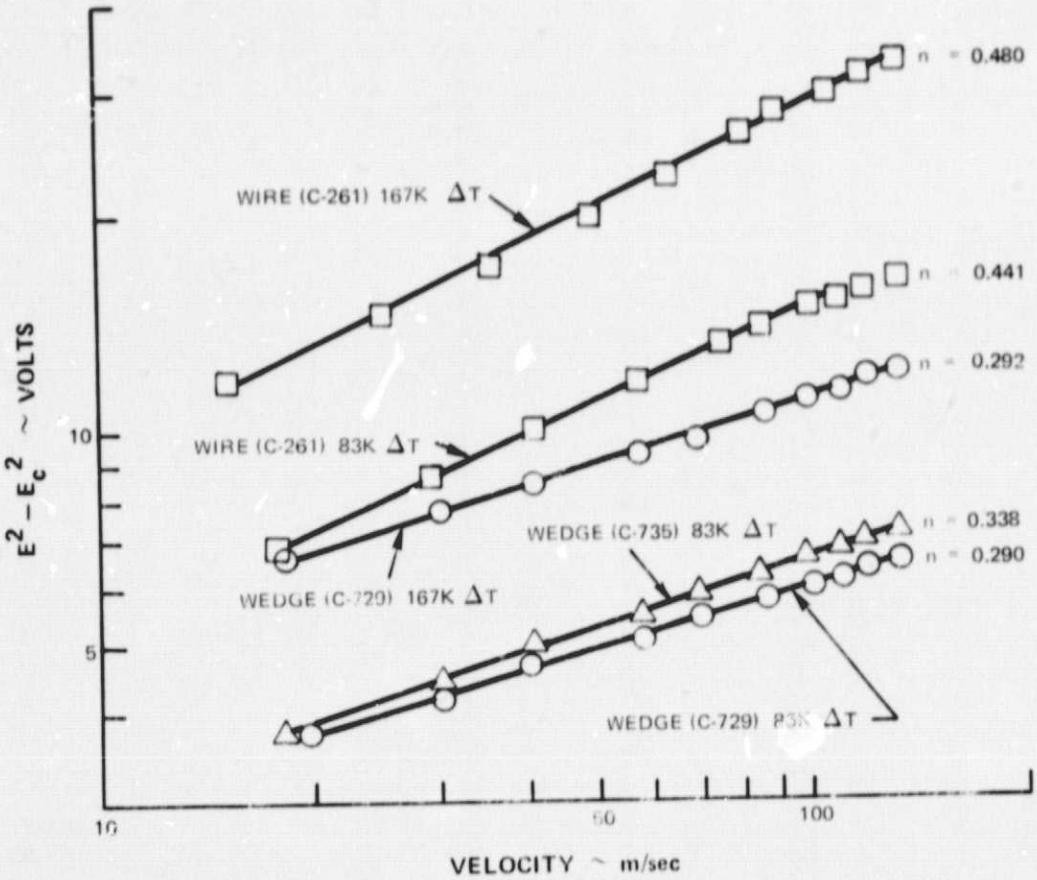

Figure 12 Anemometry Probe Velocity Calibrations

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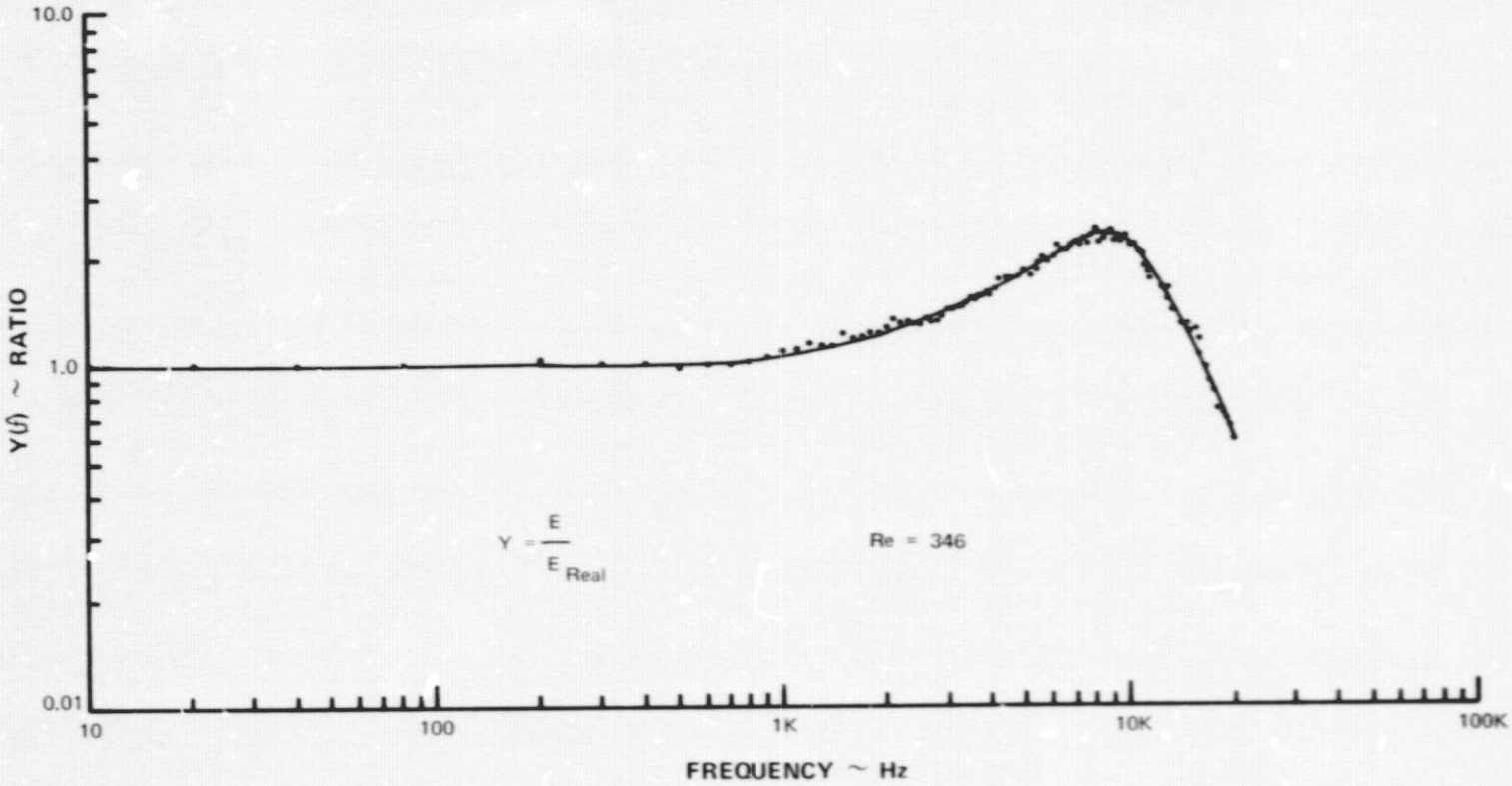

Figure 13 Wedge Probe Transfer Function

E. DATA REDUCTION PROCEDURES

The properties of turbulence of most interest to the engine designer and analyst are (a) the total kinetic energy of the longitudinal turbulent fluctuations (proportional to turbulence intensity or mean deviation of the velocity; i.e., to $\sqrt{\overline{u^2}}/\bar{u}$ where u is the instantaneous magnitude of the velocity component in the streamwise direction), (b) the integral scale Λ (which is the average size of all turbulent eddies, a measure of mixing length), (c) the microscale λ (which is the average size of the smallest eddies, where viscous energy dissipation to heat takes place), and (d) the frequency spectrum of the turbulent velocity fluctuations (revealing the presence or absence of any strong disturbances at discrete frequencies). If the turbulence intensity is below 0.10 and if the frequency spectrum is relatively smooth and featureless, then only classical free turbulence is present (generated by wakes and wall friction effects far upstream). In this type of turbulence the calculation of $\sqrt{\overline{u^2}}$, λ, Λ are straight forward [Reference 2] and the interpretation clear. If the intensity is above 0.1 or the spectrum contains peaks, then phenomena other than classical free turbulence are present (e.g. wall stall, discrete vortex streets, plug flow oscillations, or other non-random mechanisms.)

These features of the velocity waves were determined from the recorded signals. First, the data were analyzed with a spectrum analyzer (Federal Scientific Model UA 500) to obtain the individual fourier components of the waves. Due to the nature of the turbulence, it was found that a full scale analyzer range of 20,000 Hz was sufficient to include all the fourier components of the turbulence. The data in the range 50 Hz to 20,000 Hz were separated into 399 components of 50 Hz bandwidth. The data was averaged for 25 seconds to obtain accurate values of the fourier coefficients.

The 399 channels of information were transferred to a PDP-11/40 mini-computer where each value was corrected for the gains or attenuations encountered during amplification, recording, and spectral analysis. The signals were also adjusted to compensate for the experimental values of the transfer function (Y(f), according to the relation

$$E_R(f) = \frac{1}{A_e} \cdot \frac{E(f)}{Y(f)}$$

where $E_R(f)$ = corrected anemometer voltage V

$E(f)$ = anemometer voltage measured with the spectrum analyzer

$Y(f)$ = anemometer transfer function

A_e = sum of gains and attenuations in the data recording and analysis circuits

The Power Spectral Density function, PSD (f), defined as

$$PSD(f) = \frac{\overline{\tilde{u}(f)^2}}{b} \qquad (4)$$

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where a superscript bar indicates a time-averaged quantity and where b is the bandwidth per channel, was computed from a combination of equations 3 and 4.

$$PSD(f) = \frac{\overline{\left[\frac{\tilde{u}(f)}{\bar{u}}\right]^2} (\bar{u})^2}{b} \tag{5}$$

$$= \frac{\overline{\left[\tilde{E}_R(f)\right]^2}}{b} \left[\frac{2}{n} \frac{\bar{E}\ \bar{u}}{(\bar{E}^2 - E_C{}^2)}\right]^2 \frac{(m/sec)^2}{Hz}$$

Where, $\bar{E}$ was determined by measuring the average D.C. voltage recorded on the FM channel. The average velocity, $\bar{u}$ was estimated from a conservation of mass analysis at the axial location of the sensors. The values of n and E_C were obtained from the probe calibrations conducted prior to the engine test. The individual PSD components were plotted as a function of frequency. The RMS value of the turbulence, Tu, or the power distribution function, $\overline{PSD}$, is defined as

$$Tu = \sqrt{\int_{f_1}^{f_n} \overline{\left[\frac{\tilde{u}(f)}{b}\right]^2} df}$$

where f_n and f_1 are the upper and lower limits of the frequency range of interest, or

$$\overline{PSD} = \sqrt{\int_{f_1}^{f_n} PSD(f)\, df}$$

where $Tu \equiv \overline{PSD}$

The turbulence intensity is defined as $Tu/\bar{u}$

The power distribution function was computed from the 399 samples of data of 50 Hz bandwidth, using the summation

$$\overline{PSD} = \sqrt{50 \sum_{i=1}^{n} PSD\ (f_i)}$$

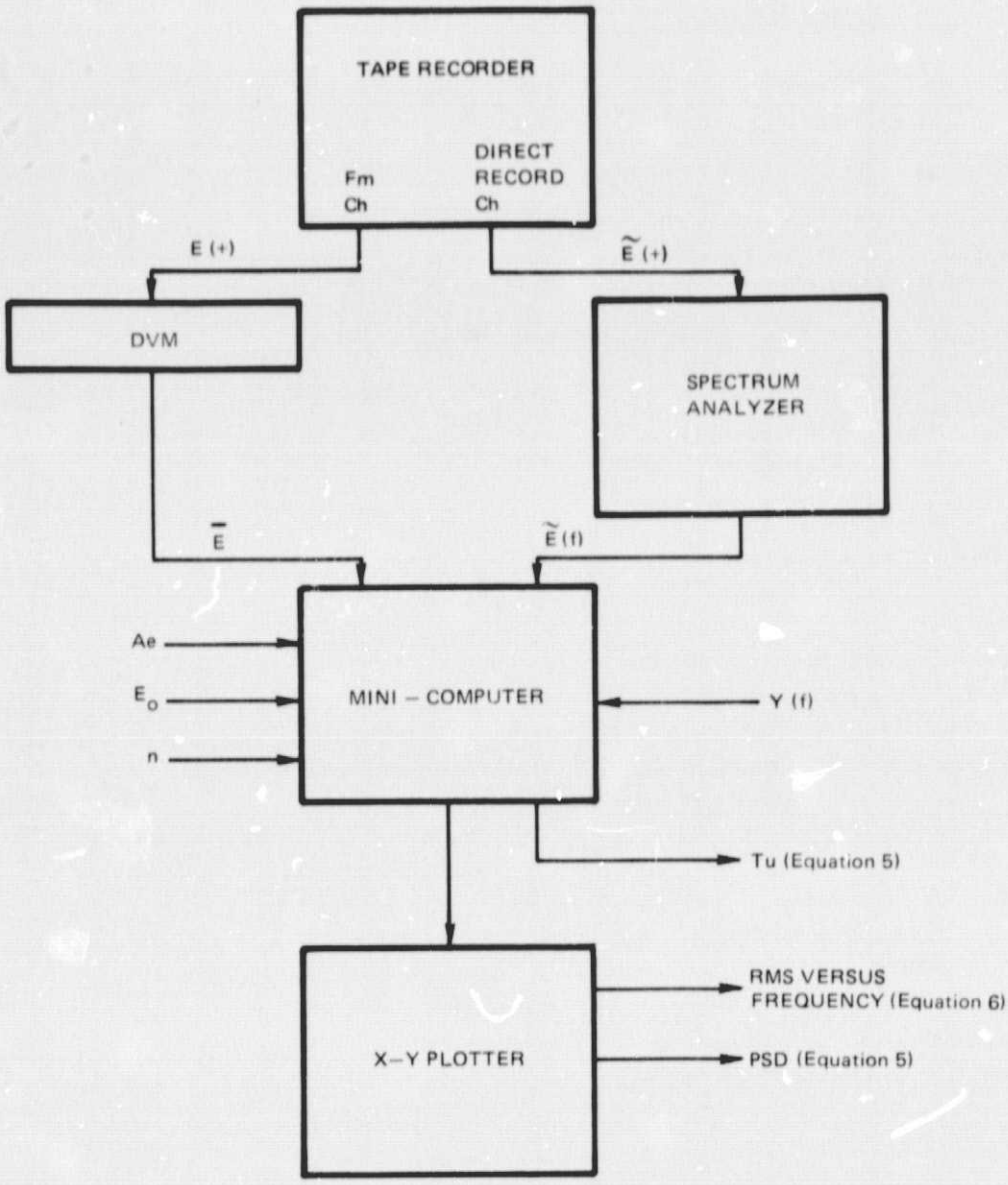

Figure 14 *Block Diagram of Data Reduction System*

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Microscale and macroscale were calculated from the power spectral density curves using the classical definitions [Reference 2].

$$\text{Macroscale} \quad \Lambda = \frac{\bar{u}}{4} \quad \frac{[\text{PSD}(100)]}{\overline{u^2}} \tag{7}$$

$$\text{Microscale} \quad \lambda = \frac{1}{\sqrt{2}\,\pi} \quad \frac{\bar{u}\,\text{Tu}}{\sqrt{\int f^2\,[\text{PSD}(f)]\,df}} \tag{8}$$

where $\bar{u}$ = mean velocity

Tu = rms turbulence level

f = frequency (Hz)

PSD (f) = power spectral density function. [PSD (f)] df is the contribution to $\overline{(\tilde{u})^2}$ of the frequencies between f and f + df.

The minicomputer in the block diagram of Figure 14 provided the means to accomplish this standard calculation, since all the quantities of equations (7) and (8) were already available in the minicomputer. This procedure is exactly equivalent to that used in Reference 3 in which analog signals proportional to u and du/dt are processed as follows:

a) $\lambda = u \left[\sqrt{\bar{u}}^{\,2} / \sqrt{\overline{du/dt}^2}\right]$

b) Λ is obtained by playing the tape into an autocorrelator to obtain a plot of autocorrelation versus time delay (τ). The integral scale is equal to the time delay at which autocorrelation vanishes (τ_o) multiplied by stream velocity (u).

The availability of the minicomputer and the use of equations (7) and (8) provided better accuracy (less reprocessing of raw analog signals).

CHAPTER II

RESULTS AND DISCUSSION

Three engine tests were conducted to measure the turbulence levels in the diffuser. A summary of the test points is presented in Tables II through IV with the diffuser duct temperature. A complete description of the engine and diffuser performance parameters is presented in Table V. As seen in Table II, all three types of probes were used in Test 1. Probes 1 and 6 failed immediately at the first idle point. Probe 5 remained partially intact, although it was damaged and provided erratic and aphysical data; the probe failed completely at the first approach point. Probe 4 also generated erratic data which was not reproducible when the engine was returned to idle. The problem appeared to be due to a ground loop.

Probes 2 and 3 provided reliable data throughout the engine test; a summary of the turbulent intensities are presented in Table II. While the probe 3 data was more reproducible at idle than the probe 2 data, both sets of data are in reasonable agreement. There appears to be a gradual increase in the turbulent intensity with engine thrust.

The diffuser gas temperature in Test 1 was limited to 616 K, the maximum operating temperature of the wedge probes. In Test 2, the stainless steel and Pt-IR wire probes were used in an attempt to obtain data above 616 K T_{T4}. The anemometers were set for operation at a climb T_{T4} of 736 K and the engine was started, idled for 5 minutes and immediately accelerated to the climb test point. Probe 6 (Pt-Ir) was destroyed during installation; the remaining probes were intact after the idle engine equilibration. Probes 1, 2 and 3 broke during acceleration to the climb test point. At the climb test point, probe 5 failed and the test was terminated.

Test 3 was more successful. Six wedge probes were used to obtain turbulence data from idle ($T_{T4} \approx 450$ K) to approach ($T_{T4} \approx 616$ K). Probes 3 and 5 were unstable, apparently due to intermitent connections at the probe, but the remaining probes provided reliable, reproducible test data during the entire engine test.

At the 25 percent span position, the data are in agreement with the initial data; again, there appears to be a gradual increase in the turbulence with engine thrust. The turbulent intensity is not a strong function of the engine thrust. At the 75 percent span position, the turbulence level is higher at each test point and shows a much more marked dependence on the engine thrust level (Figure 15). The approach value of ~ 15 percent was unexpected.

The PSD functions of the velocity waves measured at all the locations and engine operation levels except for blade passing frequency were quite featureless. Example PSD functions at the 25 percent and 75 percent span location at idle and approach are shown in Figures 16 through 19. The corresponding PSD functions are shown in Figures 20 through 23. Over the entire operating range of measurements, the PSD functions were flat with a cutoff (−3 dB) frequency of approximately 3 kHz. The cutoff frequency was not a function of the engine thrust. Above 3 kHz, the PSD function is proportional to $f^{-5 \pm 0.2}$; the amplitude of the velocity fourier components decays at a rate proportional to $f^{-2.5 \pm 0.1}$. Approximately 95 percent of the power in the velocity waves is contained in frequency components below 5 kHz.

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TABLE II

DEPENDENCE OF TURBULENT INTENSITY ON ENGINE OPERATION, TEST 1

Test Point	Designation	Probe 1 S.S. Wire 323° 5′ 50% Span		Probe 2 Hot Film 358° 22′ 50% Span		Probe 3 Hot Film 17° 52′ 25% Span		Probe 4 Hot Film 143° 04′ 75% Span		Probe 5 S.S. Wire 178° 18′ 50% Span		Probe 6 Pt.-Ir. Wire 217° 25′ 50% Span	
		T_4 K	$Tu/\bar{u}$ %	T_4 K	$Tu/\bar{u}$ %	T_4 K	$Tu/\bar{u}$ %	T_4 K	$Tu/\bar{u}$ %	T_4 K	$Tu/\bar{u}$ %	T_4 K	$Tu/\bar{u}$ %
1	Idle	Failed		450	7.0	454	4.76	Erratic		Erratic		Failed	
2	Flight Idle	Failed		516	8.16	Erratic		Erratic		Erratic		Failed	
3	Approach	Failed		591	7.64	597	6.65	Erratic		Erratic		Failed	
4	Idle	Failed		456	6.59	464	4.78	Erratic		Failed		Failed	
5	Rich Approach	Failed		608	7.96	616	5.42	Erratic		Failed		Failed	
6	Idle	Failed		455	5.22	455	4.81	Erratic		Failed		Failed	

TABLE III

DEPENDENCE OF TURBULENT INTENSITY ON ENGINE OPERATION, TEST 2

Test Point	Designation	Probe 1 S.S. Wire 323° 05′ 25% Span		Probe 2 S.S. Wire 358° 22′ 75% Span		Probe 3 S.S. Wire 17° 52′ 50% Span		Probe 4 None Installed		Probe 5 S.S. Wire 178° 18′ 50% Span		Probe 6 Pt-Ir Wire 217° 25′ 25% Span	
		T_4 K	$Tu/\bar{u}$ %	T_4 K	$Tu/\bar{u}$ %	T_4 K	$Tu/\bar{u}$ %	T_4 K	$Tu/\bar{u}$ %	T_4 K	$Tu/\bar{u}$ %	T_4 K	$Tu/\bar{u}$ %
1	Climb	Failed		Failed		Failed		–	–	Erratic		Failed	

TABLE IV

DEPENDENCE OF TURBULENT INTENSITY ON ENGINE OPERATION, TEST 3

Test Point	Designation	Probe 1 Hot Film 323° 05′ 25% Span		Probe 2 Hot Film 358° 22′ 75% Span		Probe 3 Hot Film 17° 52′ 50% Span		Probe 4 Hot Film 143° 4′ 75% Span		Probe 5 Hot Film 178° 18′ 50% Span		Probe 6 Hot Film 217° 25′ 25% Span	
		T_4 K	$Tu/\bar{u}$ %	T_4 K	$Tu/\bar{u}$ %	T_4 K	$Tu/\bar{u}$ %	T_4 K	$Tu/\bar{u}$ %	T_4 K	$Tu/\bar{u}$ %	T_4 K	$Tu/\bar{u}$ %
1	Idle	461	6.83	452	7.09	Erratic		450	7.93	Erratic		459	5.87
2	Flight Idle	536	7.70	525	10.56	Erratic		520	11.03	Erratic		519	6.14
3	Approach	611	7.09	602	16.17	Erratic		597	14.17	Erratic		602	5.68
4	Idle	461	6.88	453	7.05	Erratic		447	8.08	Erratic		452	6.18

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TABLE V

ENGINE TEST CONDITIONS

	Test Pt.	Designation	T_{T4}* K	P_{T4}* 10^5 N/m^2	Average Velocity Calculated From P_{T4}/T_{T4} m/sec	F/A	N_2 RPM	Fn N
Test 1	1	Idle	450	3.71	109.3	0.0096	4941	14052
	2	Flight Idle	520	6.02	112.2	0.0106	5765	31471
	3	Approach	590	9.17	122.8	0.0140	6376	61759
	4	Idle	452	3.76	108.9	0.0095	4983	14470
	5	Rich Approach	609	9.91	128.1	0.0148	6499	70366
	6	Idle	446	3.63	107.1	0.0095	4913	13549
Test 2	1	Climb	732	18.2	139.3	0.0227	7206	169030
Test 3	1	Idle	454	3.88	110.1	0.0102	4830	16436
	2	Flight Idle	520	6.16	119.2	0.0118	5557	35177
	3	Approach	599	9.77	125.7	0.0152	6203	72284
	4	Idle	449	3.80	122.1	0.0103	4801	16018

*Measured

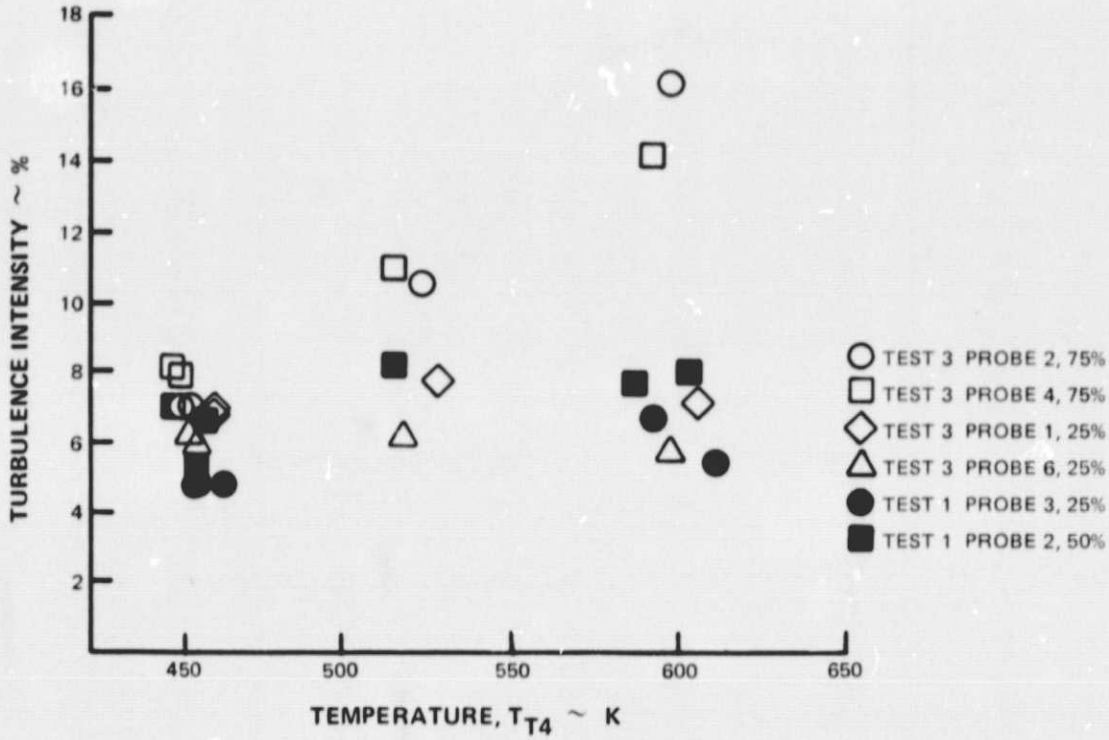

Figure 15 *Dependence of Turbulence on Engine Operation*

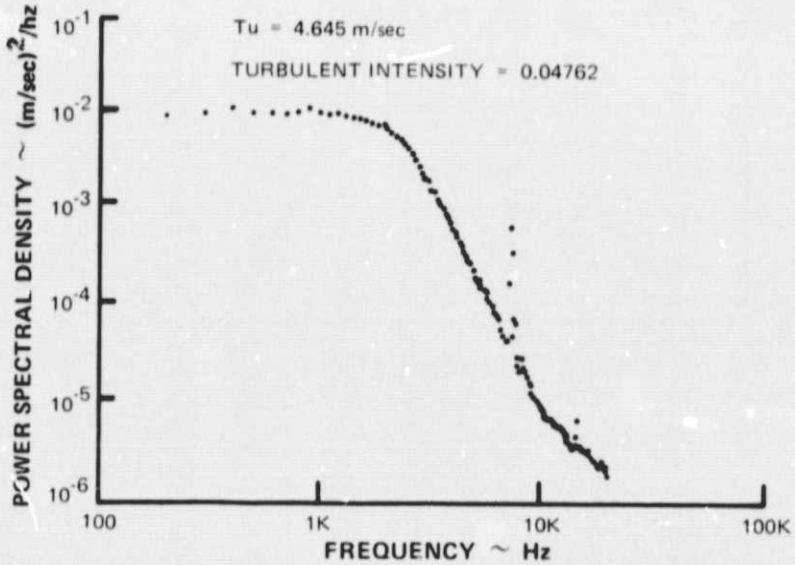

Figure 16 *Test 1, Probe 3 (Wedge Type) Power Spectral Density Function for Idle Condition at 25 Percent Span*

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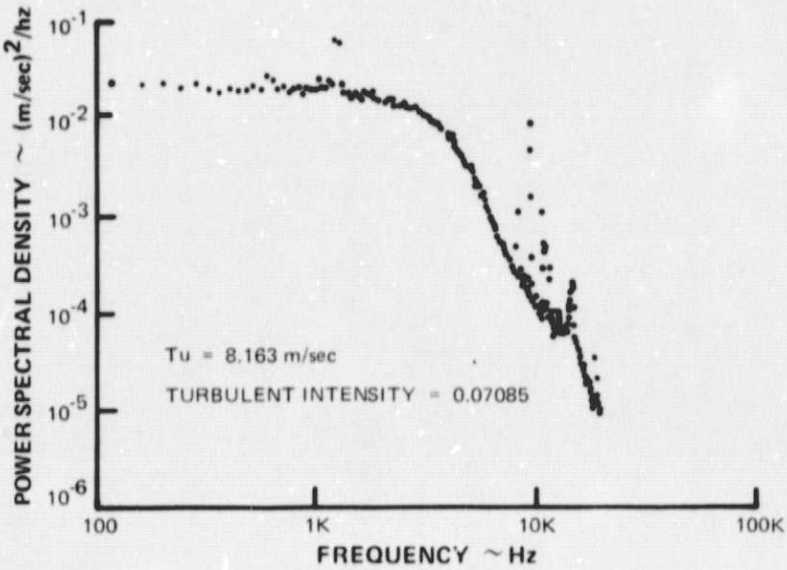

Figure 17 *Test 3, Probe 1 (Wedge Type) Power Spectral Density Function for Approach Power Condition at 25 Percent Span*

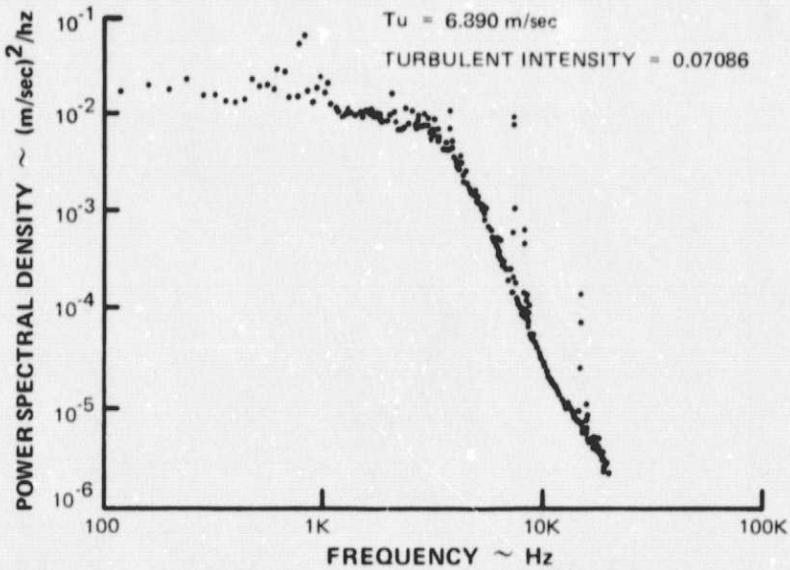

Figure 18 *Test 3, Probe 2 (Wedge Type) Power Spectral Density Function for Idle Condition at 75 Percent Span*

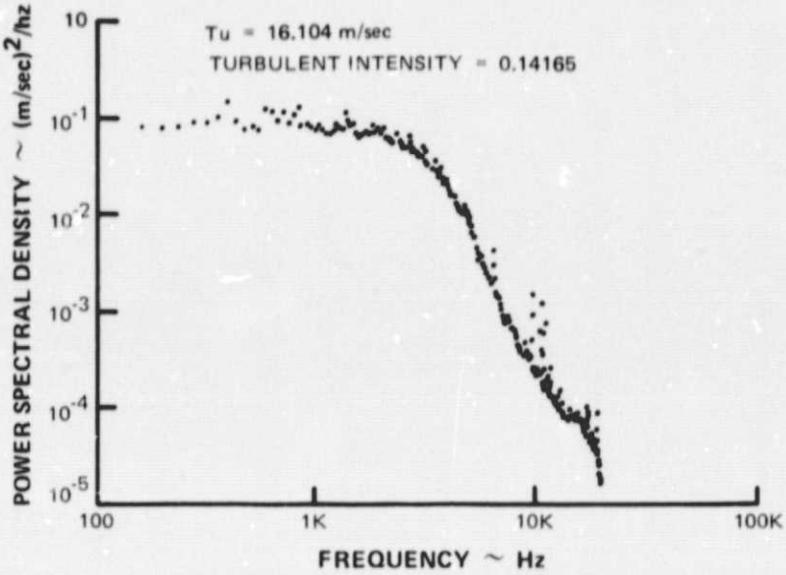

Figure 19 *Test 3, Probe 4 (Wedge Type) Power Spectral Density Function for Approach Power Condition at 75 Percent Span*

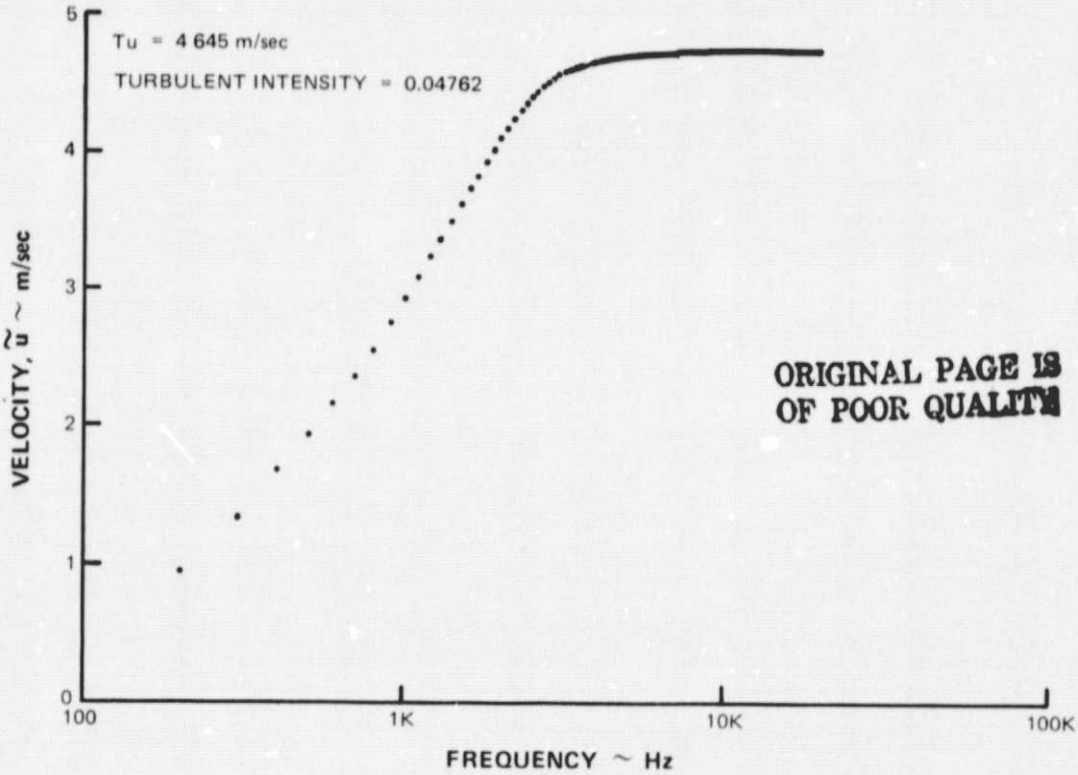

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Figure 20 *Test 1, Probe 3 (Wedge Type) Spectral Distribution for Idle Condition at 25 Percent Span*

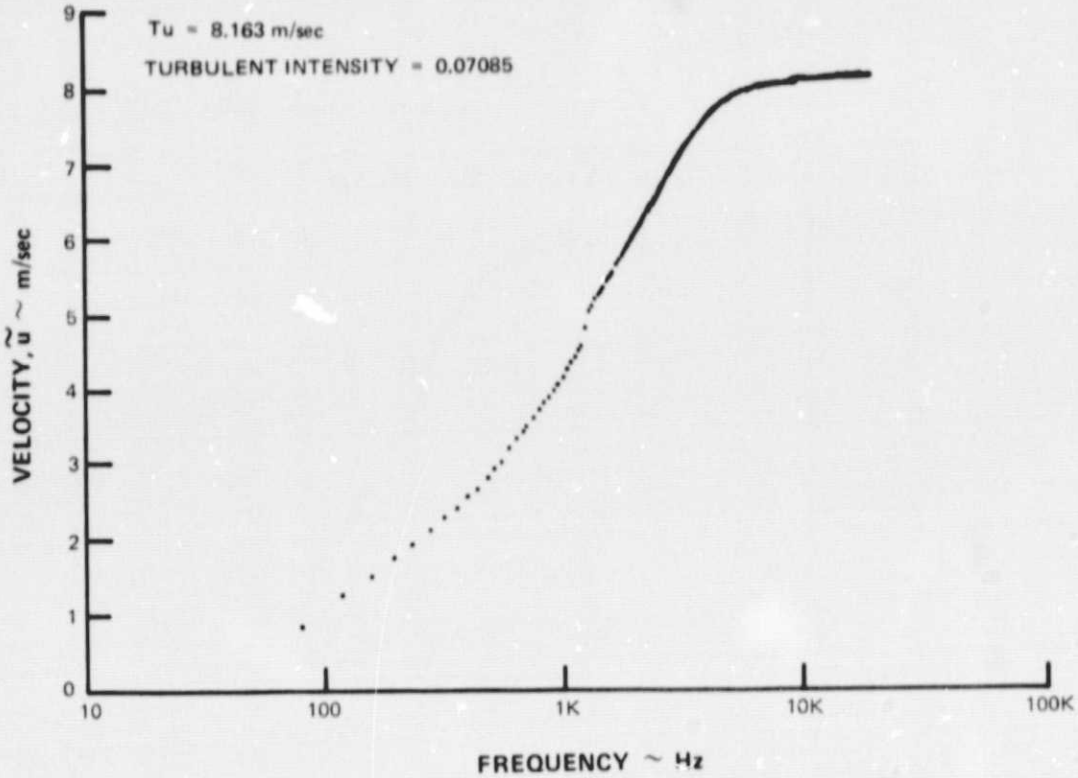

Figure 21 *Test 3, Probe 1 (Wedge Type) Spectral Distribution for Idle Condition at 25 Percent Span*

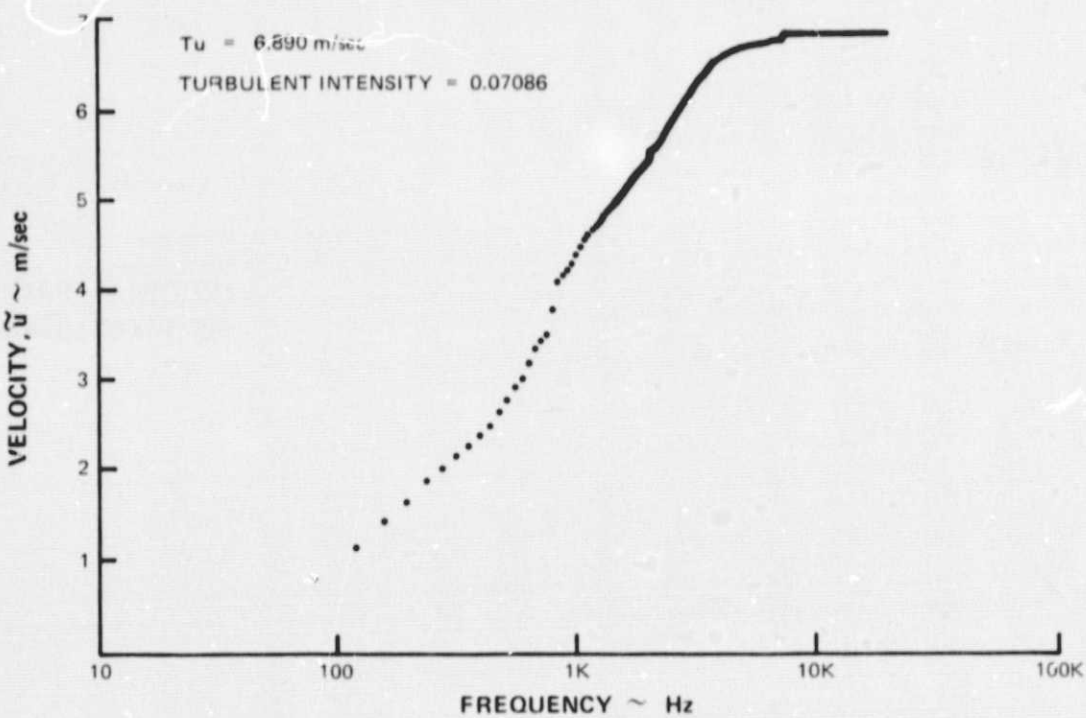

Figure 22 *Test 3, Probe 2 (Wedge Type) Spectral Distribution for Idle Condition at 75 Percent Span*

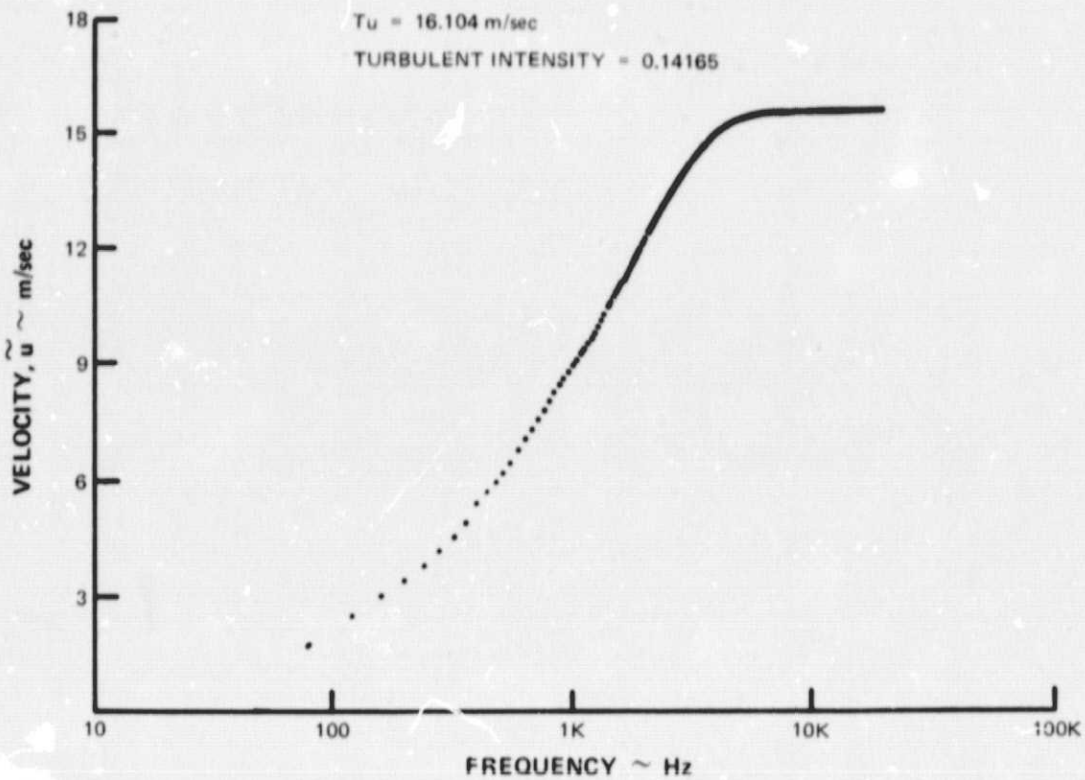

Figure 23 *Test 3, Probe 4 (Wedge Type) Spectral Distribution for Approach Power Condition at 75 Percent Span*

Macroscale and microscale computed as described in Chapter II are listed in Table VI. The values lie between 0.5 cm and 3.3 cm.

A 3 kHz component corresponds to an axial scale of 3.53 cm. Since 90 percent of the energy in the wave is contained in the 0.1 to 5 kHz bandwidth, the axial length of the fourier components of the velocity wave vary from 0.021 to 1.05 m. The turbulence measured in the diffuser is of quite a large scale. Although the turbulence levels at the 75 percent span were unusually large, there were no qualitative changes between the PSD functions measured at the 25 percent and 50 percent span locations and the 75 percent span.

A distinct peak in the PSD function is observed at blade-passing frequency (about 10kHz) and at higher multiples of blade-passing frequency in some cases. This would be expected in the turbulent flow at any compressor exit for a distance of at least 20 chord lengths behind the rotor.

At idle, evidence of a weak 800 to 900 Hz peak was observed consistently at the 75 percent span location (Figures 22, 24, 25 and 26) and periodically at the 25 percent span location (Figure 21). This peak is unexplained since it lies well above N_2 (80 Hz) or N_1 (50 Hz) and well below blade-passing frequency (7200 Hz) at this condition.

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TABLE VI

TURBULENCE CHARACTERISTICS OF COMPRESSOR DISCHARGE FLOWS

Hot Film Probe						
Number	Percent Span	Angular Location	Tu (meters/sec)	Turbulent Intensity Tu/$\bar{u}$	Λ (Macro-scale In Meters)	λ (Micro-scale In Meters)
2	50	358° 22′	6.782	0.06998	0.0079	0.0051
			8.556	0.08160	0.0116	0.0097
			8.620	0.07644	0.0083	0.0104
			6.471	0.06593	0.0094	0.0078
			9.145	0.07958	0.0124	0.0093
			5.103	0.05216	0.0169	0.0079
3	25	17° 52′	4.645	0.04762	0.0153	0.0094
			7.560	0.06650	0.0109	0.0076
			4.723	0.04782	0.0111	0.0082
			6.273	0.05416	0.0107	0.0090
			4.710	0.04814	0.0121	0.0089
1	25	323° 05′	6.725	0.06831	0.0212	0.0087
			8.209	0.07695	0.0099	0.0089
			8.163	0.07085	0.0086	0.0076
			6.774	0.06880	0.0181	0.0077
2	75	358° 22′	6.890	0.07086	0.0082	0.0079
			11.166	0.10557	0.0063	0.0085
			18.482	0.16169	0.0100	0.0058
			6.834	0.07050	[illegible]161	0.0071
4	75	143° 04′	7.683	0.07927	0.[illegible]323	0.0064
			11.561	0.11026	0.016[illegible]	0.0064
			16.104	0.14165	0.0104	0.0090
			7.807	0.08080	0.0333	0.0086
6	25	217° 25′	5.747	0.05873	0.0104	0.0081
			6.453	0.06136	0.0095	0.0083
			6.489	0.05677	0.0088	0.0077
			6.007	0.06178	0.0290	0.0072

While the origin of the large values of the turbulence cannot be described by the present experimental data, it can be pointed out that the turbulence level at the 75 percent span is large enough to affect airflow from the diffuser to the front end of the burner. For example, if the local ratio of the static pressure across the burner liner, ΔP, and the dynamic pressure of the diffuser flow, q, is 2.5, a ±30 percent (± 2 tu) change in the local velocity will cause the $\Delta P/q$ value to vary from 1.48 to 5.1. The discharge coefficient of the burner liner holes will vary markedly over this range of $\Delta P/q$ values. The scale of turbulence is sufficiently large that significant areas of the burner will be affected simultaneously by the flow perturbations.

Finally, it can be pointed out that the increased turbulence at the O.D. diffuser wall may be useful in improving the performance of the diffuser. Independent measurements show that increasing the turbulence near a diffuser wall can reduce separation of the flow through the additional local mixing caused by the turbulence. A more aggressive diffusion of the gases near the O.D. wall may be possible due to the high level of turbulence in this area.

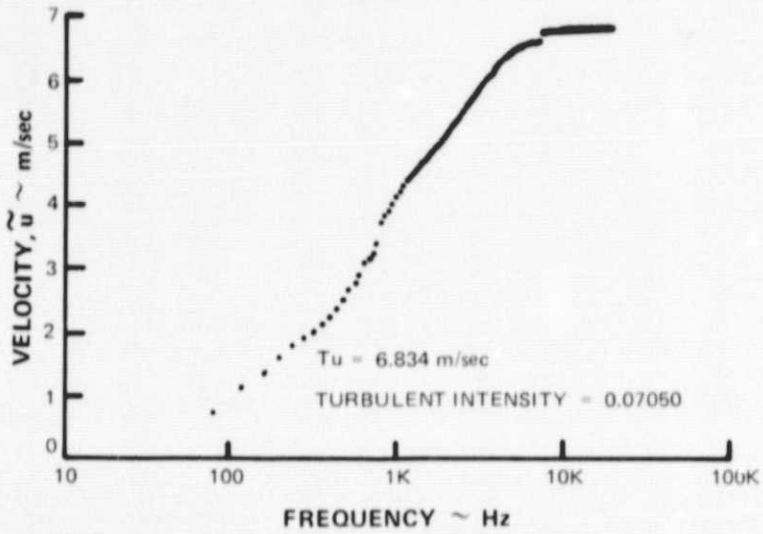

Figure 24 *Test 3, Probe 2 (Wedge Type) Spectral Distribution for Idle Condition at 75 Percent Span*

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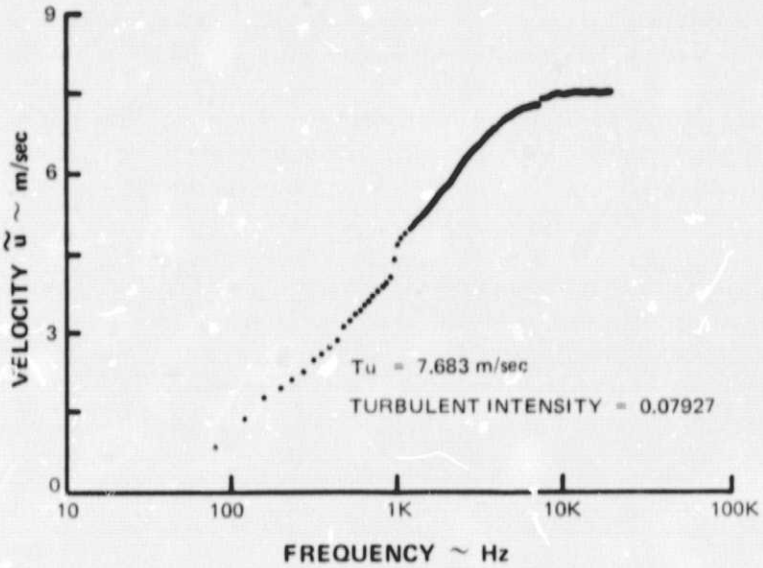

Figure 25 *Test 3, Probe 4 (Wedge Type) Spectral Distribution for Idle Condition at 75 Percent Span*

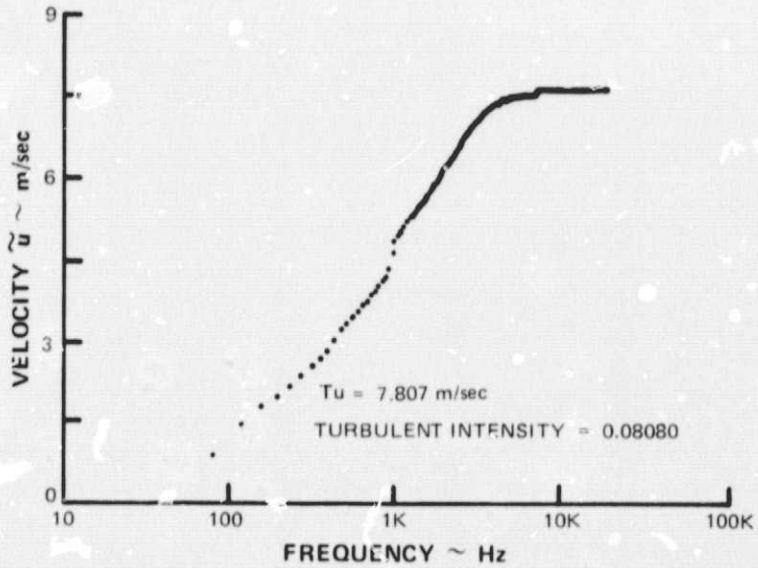

Figure 26 *Test 3, Probe 4 (Wedge Type) Spectral Distribution for Idle Condition at 75 Percent Span*

CHAPTER IV

CONCLUSIONS

The turbulence in the diffuser duct of a large gas turbine has been measured from idle to approach engine conditions. Several features of the turbulence have been documented:

1. The turbulent intensity at the I.D. (25 percent span) and midspan locations increases gradually from 6 ±1 percent at idle to 7 ±1 percent at approach; the turbulent intensity at the O.D. (75 percent span) location increases from 7.5 ±0.5 percent at idle to 15 ±0.5 percent at approach.

2. The energy in the velocity waves is uniformly distributed over a 0.1 to 5 kHz bandwidth. The axial length of the fourier component within this bandwidth varies from 0.021 to 1.05 m.

3. The cut-off frequency of the turbulence (−3 db) is approximately 3 kHz and is not a function of the engine operation. Above the cut-off frequency, the fourier components of the wave decrease at a rate proportional to $f^{-2.5 \pm 0.1}$. Ninety percent of the energy of the waves is contained within a 0.1 to 5 kHz bandwidth.

4. Determination of the origin of the high level of turbulence at the diffuser O.D. requires further information on the development of the turbulence along the diffuser.

5. The turbulence at the diffuser O.D. is of sufficient amplitude and scale to affect the flow to the front end sections of the burner.

6. Velocity fluctuations at blade passing frequency were identified at all span-wise positions. These fluctuations are probably of not sufficient amplitude and scale to affect the flow inside the combustor.

7. Measurements at higher engine power levels are lacking due to sensor probe durability limitations. Data is still needed at higher power levels to determine whether shifts in either the amplitude or scale occur. Use of L.D.V. (Laser Doppler Velocimeter) optical instrumentation should be considered for studies at high power.

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