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Paper 12

TURBULENCE MEASUREMENT WITH A CALIBRATED PITOT MOUNTED PRESSURE TRANSDUCER

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Abstract

A compressible one-dimensional analysis is presented to derive a relationship between the root mean square of the fluctuating total pressure and the streamwise velocity. A pitot mounted pressure transducer was calibrated against hot-wire anemometer and LDA measurements, and the results compared with the derived theory. The turbulence was grid generated and the maximum Mach number was 0.45, which is typical of rotor relative inlet Mach numbers. Hot-wire anemometer and pressure transducer frequency power spectra were also recorded and compared. A linear correlation was found to exist between the total pressure fluctuations and the product of density, mean velocity and fluctuating velocity. The frequency power spectra were found to differ in shape and this casts some doubt over the universality of the correlation; although, it is thought this is due to the nature of the way each sensor spatially integrates the fluctuating phenomena. However, the correlation presented is sufficiently accurate for use in assisting the development of turbulence models for turbine rotor flows.

Nomenclature

Symbols

F	Compressibility factor
M	Mach number
N	Rotor rotational speed
P	Pressure
R	Correlation coefficient
R_c	Hot-wire cold resistance
R_h	Hot-wire hot resistance
Re_c	Reynolds number based on true chord
T	Temperature
u, v	x- and y-direction velocity
γ	specific heat ratio
ρ	density
%Tu	turbulence intensity

Suffices

o	total condition
∞	freestream condition
-	mean value
~	fluctuating value

List of Abbreviations

LDA	laser Doppler anemometry
UL	University of Limerick
VKI	von Karmen Institute
rms	root mean square

$$\text{Hot-wire overheat ratio} = \frac{R_h - R_c}{R_c}$$

1. Introduction

There are numerous applications in which a pressure transducer is mounted in a pitot tube configuration to measure the time varying total pressure. This paper is particularly, though not exclusively, concerned with the use of such a pitot mounted pressure transducer at the stagnation point of a turbine rotor; at the nose of the rotor blade the pressure transducer will measure the variation in total pressure as the nozzle guide vane wakes and shocks are traversed by the rotor blades. Although the total pressure measurement is of interest in understanding the wake blade interaction it is more beneficial, in computational rotor blade predictions, to know the rotor relative freestream turbulence level; it is this parameter that is known to affect the development of the boundary-layer (Davies and Wallace, 1995). This paper is concerned with deriving an empirical correlation between the fluctuating total pressure and the streamwise percentage turbulence level.

An analysis of the Bernoulli equation for incompressible flow suggests that a linear correlation exists between total pressure fluctuations and the product of velocity fluctuations, mean velocity and fluid density. Turbulence levels and frequency power spectra measurements were recorded in two flow regimes; incompressible and compressible flow to a maximum Mach number of 0.45 which is representative of rotor relative inlet Mach numbers (Bicen and Jones, 1986; Moss and Oldfield, 1991). Turbulence in the flow was grid generated and hot-wire anemometry was extensively used as a reference measurement of turbulence, though limited use was made of a LDA system for the compressible flow measurements. Furthermore, unsteady total pressure measurements from the three-dimensional rotating gas turbine facility at VKI were sampled and converted into turbulence level readings using the compressible flow correlation derived for a pitot mounted pressure transducer.

2. Pressure Fluctuation Theory

The following analysis derives a one-dimensional theoretical relationship between the streamwise velocity and total pressure fluctuations in a turbulent flow as a function of the turbulence intensity and the freestream Mach number. Combining the isentropic relationship for compressible flow and the perfect gas law yields:

$$\frac{P_o}{P} = \left[1 + \left(\frac{\gamma - 1}{2}\right)M_\infty^2\right]^{\frac{\gamma}{\gamma - 1}} = \left[1 + \frac{\rho u^2}{7P}\right]^{\frac{7}{2}} \quad \text{for air where } \gamma = 1.4 \qquad (1)$$

Expanding equation (1) above using the Binomial series, then neglecting third and higher order terms and differentiating gives:

$$dP_o = AdP + Bdu + Cd\rho \qquad (2)$$

$$\text{where } A = \left[1 - \frac{5}{56}\left(\frac{\rho u^2}{P}\right)^2\right] \; ; \; B = \rho u\left[1 + \frac{5}{14}\frac{\rho u^2}{P}\right] \; ; \; C = \frac{u^2}{2}\left[1 + \frac{5}{14}\frac{\rho u^2}{P}\right]$$

Ignoring the variations in density, the root mean square values for n number of measurements are:

$$\sqrt{\sum_{i=1}^{n} \frac{1}{n} (dP_o)_i^2} = \sqrt{\sum_{i=1}^{n} \frac{1}{n} \left[A^2 (dP)_i^2 + AB (du)_i (dP)_i + B^2 (du)_i^2\right]} \tag{3}$$

Alternatively, in terms of mean square values, where the symbols - and ~ represent the mean and fluctuating values respectively, the relationship may be expressed as:

$$\tilde{P}_o^2 = \bar{A}^2 \tilde{P}^2 + \bar{A}\bar{B}\,\widetilde{Pu} + \bar{B}^2 \tilde{u}^2 \tag{4}$$

$$\text{where } A = \left[1 - 0.175 M_\infty^4\right] \; ; \; B = \bar{\rho}\,\bar{u}\left[1 + 0.5 M_\infty^2\right]$$

The static pressure fluctuation, $\tilde{P}$, describes the amount of energy being transferred into acoustic waves. Hinze (1975) obtained the following expression for isotropic turbulence:

$$\tilde{P}^2 = 0.49\,\bar{\rho}^2 \left(\tilde{u}^2\right)^2 \tag{5}$$

Substituting equation (5), which is also true for instantaneous values, into equation (4) and rewriting yields:

$$\tilde{P}_o^2 = \bar{B}^2 \tilde{u}^2 + 0.70\,\bar{\rho}\,\bar{A}\,\bar{B}\,\tilde{u}^3 + 0.49\,\bar{\rho}^2 \bar{A}^2 \tilde{u}^4 \tag{6}$$

Therefore, the theoretical relationship for root mean square values of velocity and total pressure fluctuations is:

$$\sqrt{\tilde{P}_o^2} = \bar{\rho}\,\bar{u}\sqrt{\tilde{u}^2}\;F \tag{7}$$

where the compressibility factor, F, is:

$$F = \sqrt{\left[1 + 0.5M_\infty^2\right]^2 + 0.70\left[1 - 0.175M_\infty^4\right]\left[1 + 0.5M_\infty^2\right]\left[\frac{\tilde{u}}{\bar{u}}\right] + 0.49\left[1 - 0.175M_\infty^4\right]^2\left[\frac{\tilde{u}}{\bar{u}}\right]^2}$$

Table 1 below lists the value of the compressibility factor, F, for different values of the turbulence intensity, %Tu, and the freestream Mach number, M_∞; a freestream Mach number of zero is equivalent to the incompressible flow case. A reasonable estimate of the compressibility factor can be made assuming it is only a function of the Mach number.

Table 1 : Values of the Compressibility Factor, F, for Varying Values of the Freestream Mach Number, M_∞, and the Turbulence Intensity Level, %Tu

	%Tu = 5%	%Tu = 10%	%Tu = 20%	%Tu = 30%
		Compressibility Factor, F		
$M_\infty = 0$	*1.02*	*1.04*	*1.08*	*1.12*
$M_\infty = 0.2$	*1.04*	*1.06*	*1.10*	*1.14*
$M_\infty = 0.5$	*1.14*	*1.16*	*1.20*	*1.24*

3. Incompressible Flow Turbulence Measurements

A commercially available grid of interwoven round bars was used to generate turbulence in the UL mid-velocity range, atmospheric windtunnel test section (Davies and Casserly, 1992); the diameter of the grid bars was 0.49mm and the mesh spacing was 2.12mm giving a solidity of 0.41. The freestream velocity range in the windtunnel test section is 0-70m/s and the background turbulence intensity is less than 1%. True root mean square values of total pressure and velocity fluctuations and the mean velocity were recorded using a hot-wire anemometer, calibrated for two predetermined overheat values, and a pitot mounted pressure transducer; both sensors were laterally mounted at 10, 30 and 50 mesh-lengths downstream from the grid and approximately 40mm apart; caution was exercised to avoid any probe interaction errors.

The hot-wire sensor signal was processed using a sixteen channel A/D converter with a programmable scan rate of 50kHz, 12 bit resolution, and an input voltage range of 0-10V. Therefore, the maximum error of any one reading is ±1.22mV. The pitot mounted miniature pressure transducer used had a resonant frequency of 125kHz, range of 0.35bar and an outer diameter of 2.36mm. Figures 1 and 2 illustrate the measurements recorded and are plotted in order to verify the pressure fluctuation theory for measurements in grid generated turbulence.

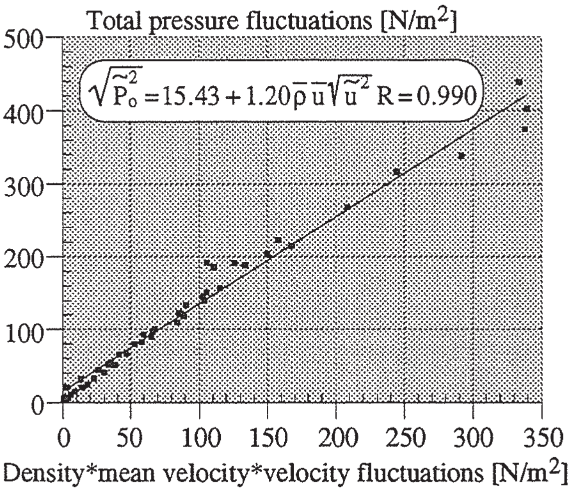

Figure 1 : *Incompressible flow data; hot-wire anemometer overheat ratio = 0.81*

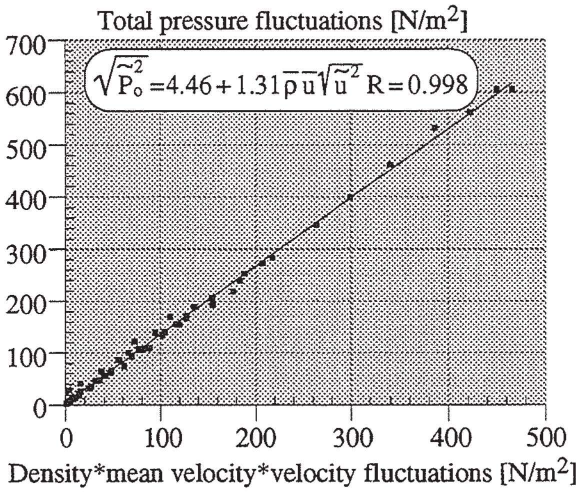

Figure 2 : *Incompressible flow data; hot-wire anemometer overheat ratio = 0.90*

The type of turbulence measured at the first measurement position differed considerably to that at the second and third positions; the first position was located approximately at the point of maximum turbulence intensity in a region of transition from flow establishment to axisymmetric turbulence decay, with the second and third positions located in the latter region (Roach, 1987). All measured values of velocity fluctuations decay in a similar manner and are in good agreement with values predicted by Baines and Peterson (1951) for turbulence decay downstream from a grid. Furthermore, there will be a higher voltage output from a hot-wire anemometer for a given velocity when it is set to a higher overheat ratio resulting in better probe sensitivity and has the effect of reducing data scatter as illustrated in figure 2 when compared to figure 1. However, the linear regression of the data shown in figures 1 and 2 do not intercept the origin for the different hot-wire anemometer overheat ratio values. This may be interpreted as an error in the recorded data from the pressure transducer where, especially at low pressures, the poor signal to noise ratio magnifies any combination of static pressure and temperature fluctuations, vibration, or sound.

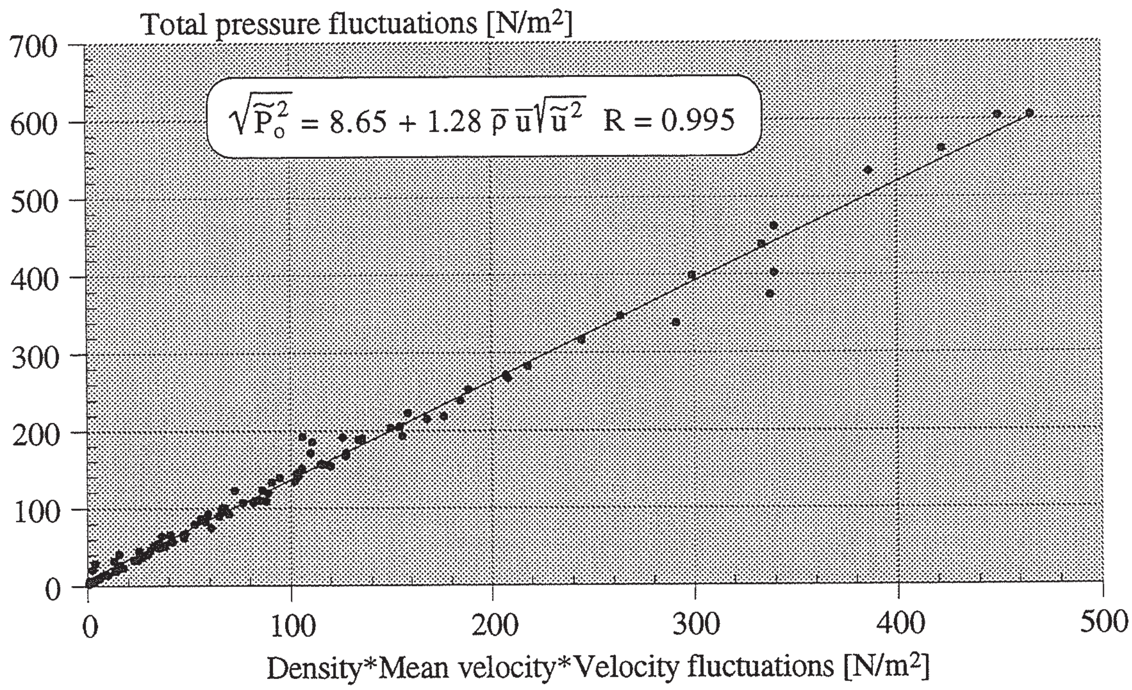

Figure 3 : *Combined incompressible flow data from figures 1 and 2*

For incompressible flow, a linear relationship exists between total pressure fluctuations and the product of density, mean velocity and velocity fluctuations as predicted by the pressure fluctuation theory. The data from both of the experiments were plotted together and are shown in figure 3. In isotropic turbulence, the lateral and longitudinal velocity fluctuations are the same and deviations from this relation are a measure of the anisotropy of the turbulence. However, measurements were recorded in grid generated turbulence which is axisymmetric as opposed to isotropic. Table 2 reviews the values of the ratio of the velocity fluctuations in the main flow to those perpendicular to it for turbulence generating grids.

Table 2 : Ratio of Longitudinal to Transverse Velocity Fluctuations (rms) for Grid Generated Turbulence $\left[\sqrt{\tilde{u}^2}\,/\sqrt{\tilde{v}^2}\right]$

Roach (1987)	1.25 ± 0.25
Laws and Livesey (1978)	≈ 1.15
Korneyev and Sedov (1976)	1.30 ± 0.20
Hinze (1975)	1.20 ± 0.15
Bradshaw (1971)	≈ 1.33

Roach (1987) reported a value of 1.25 for the ratio of turbulence energies for most grid types, though individual investigations specified this ratio anywhere from 1.0 to 1.5. This degree of uncertainty obtained with grids of nominally the same geometric and aerodynamic parameters would suggest that the ratio of the longitudinal to transverse velocity fluctuations might be strongly influenced by the experimental apparatus or instrumentation used rather than the grid. Regardless, caution must be taken when results of measurements in grid generated turbulence are compared with a theory derived for isotropic turbulent flow.

The theoretical slope evaluated using the compressibility factor in Table 1 differs markedly with that of 1.28 for the experimental correlation presented in figure 3. The slope of the experimental correlation is near to the degree of flow anisotropy for grid generated turbulence. The question arises, is the anisotropy of the flow and the relationship between pressure and velocity fluctuations related? Any velocity fluctuation may be separated into a streamwise or longitudinal velocity component and a traverse component. Additionally, a hot-wire anemometer is sensitive to velocity fluctuations in both the longitudinal and one traverse direction, however, a pressure transducer is only sensitive to longitudinal velocity fluctuations; the manner in which the flow is integrated is a fundamental difference between the hot-wire probe and the pressure transducer. Therefore, in isotropic flow both sensors will record the same streamwise velocity fluctuation value. However, in anisotropic flow the hot-wire probe, being also sensitive to the traverse component, will record a streamwise velocity fluctuation value lower than that of the pressure transducer.

Any investigation into the turbulence measuring capabilities of a pitot mounted pressure transducer compared with a hot-wire anemometer would not be complete without considering the frequency power spectra from both sensors. Tennekes and Lumley (1987) explain how a one-dimensional spectrum obtained in a three-dimensional field contains at a wavelength, w, contributions from components of all wave lengths larger than w; this phenomena is termed aliasing. The problem of aliasing is not serious at high wave numbers because smaller eddies tend to have the same size in all directions. However, care must be taken when discussing the physical significance of one dimensional spectra when used to characterise turbulent flows which are three dimensional in nature.

Figures 4 to 12 present plots of root mean square voltage in decibels against frequency for three different flow velocities at three different positions downstream from the grid. Each spectral curve represents 100 averages. The spectra from both signals indicate a broadband frequency content with no evidence of selective amplification of particular length scales and no indication of vortex shedding from either probe.

For each measurement position, the signal from the hot-wire anemometer has the same energy value near 0Hz irrespective of the freestream velocity, whereas the energy value of the pressure transducer near 0Hz gradually increases with increasing velocity. The spectra signals from both sensors at zero velocity do not change with position and the signal from the hot-wire anemometer is 4-5dB higher than the signal from the pressure transducer, due to the different amplifier gain settings in both instrumentation signal conditioning units. Another interesting feature of the spectra plots is that the intersection point of the signals from both sensors is the same regardless of the measuring position downstream from the grid: no intersection at u_∞ = 23m/s, 9kHz at u_∞ = 48m/s, and 16.5kHz at u_∞ = 70m/s.

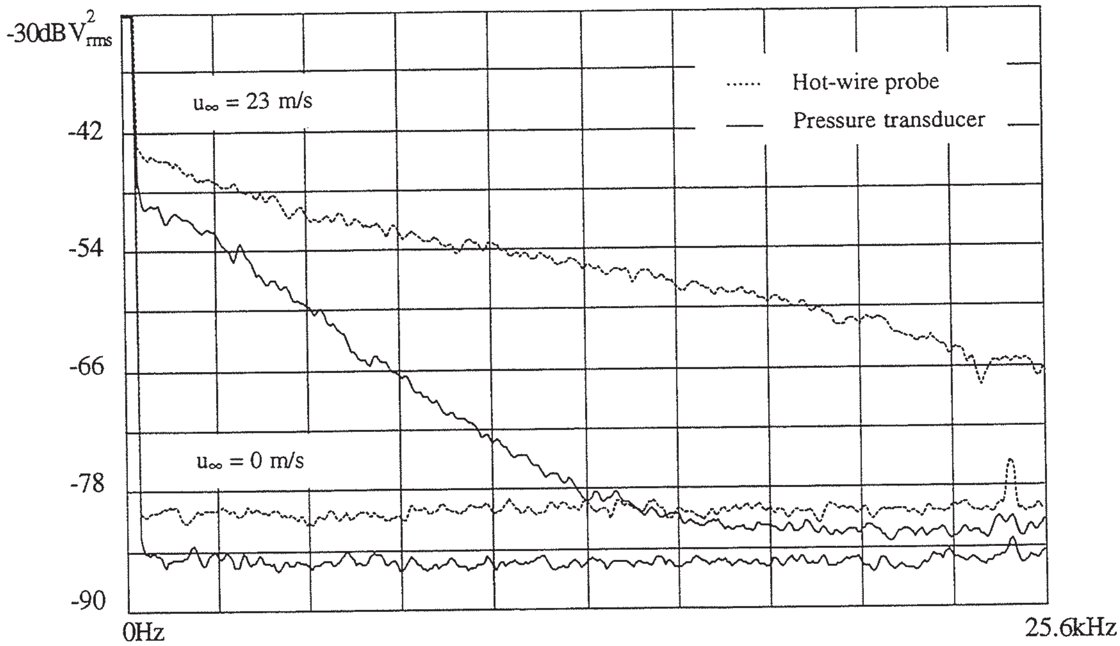

Figure 4 : *Frequency power spectra 21mm downstream of the grid: u_∞ = 23m/s*

As the freestream velocity is increased the spectra signals from the hot-wire anemometer and the pressure transducer extend to higher frequencies suggesting turbulence in the flow is spreading to higher frequencies as the energy transfer from the large eddies to the small eddies increases; the larger eddies will cause fluctuations at lower frequencies, whereas the smaller eddies will cause fluctuations of higher frequencies. As the turbulence decays, the energy transfer from the large eddies to the small eddies decreases so that the intensity of the small eddies decreases faster than that of the large eddies. This implies the dissipating eddies become larger and can be seen from the spectra plots figures 4 to 12 where at successive measurement positions downstream from the grid, the hot-wire anemometer and the pressure transducer signals maintain the same slope and drop parallel to the y-axis.

A fundamental difference between the hot-wire and the pressure transducer is that they are line and area integrators respectively and this may account for the obvious dissimilarity between the hot-wire anemometer and pressure transducer spectra, especially in the higher frequency range.

Isotropic turbulence can be defined as fluctuating velocities spread over all frequencies and wavelengths. It can be seen from figures 4 to 12 that the slope of the spectra from the hot-wire

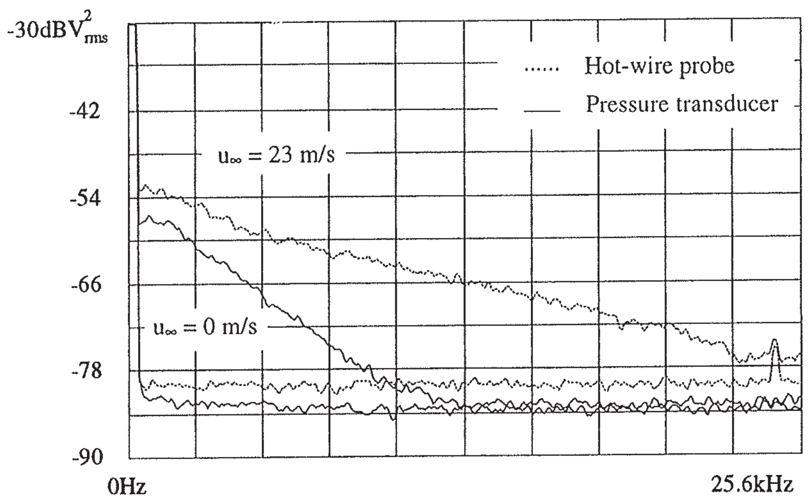

Figure 5 : *Frequency spectra at 64mm downstream: $u_\infty = 23m/s$*

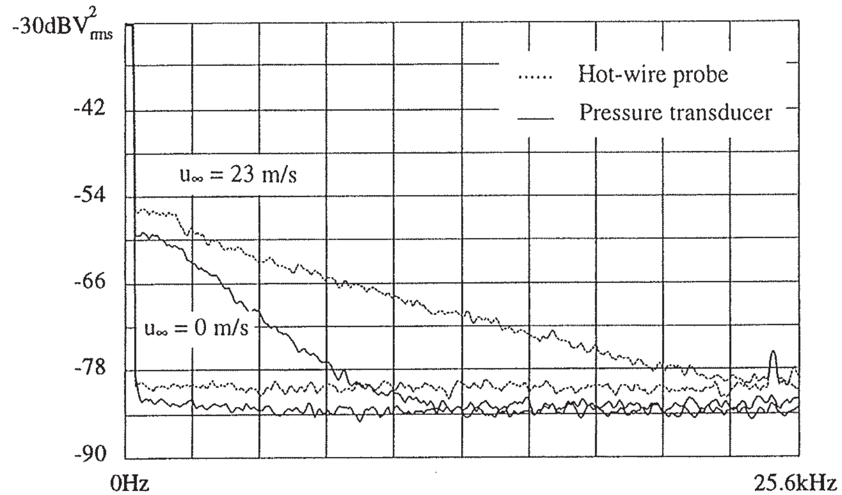

Figure 6 : *Frequency spectra at 106mm downstream: $u_\infty = 23m/s$*

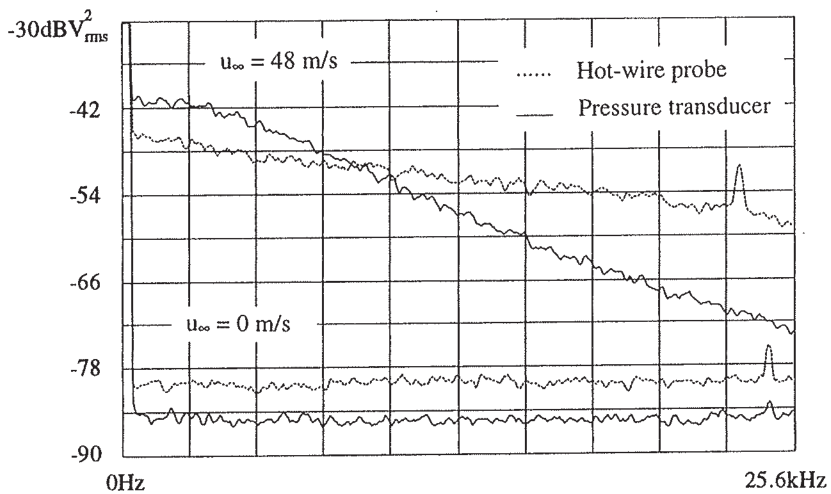

Figure 7 : *Frequency spectra at 21mm downstream: $u_\infty = 48m/s$*

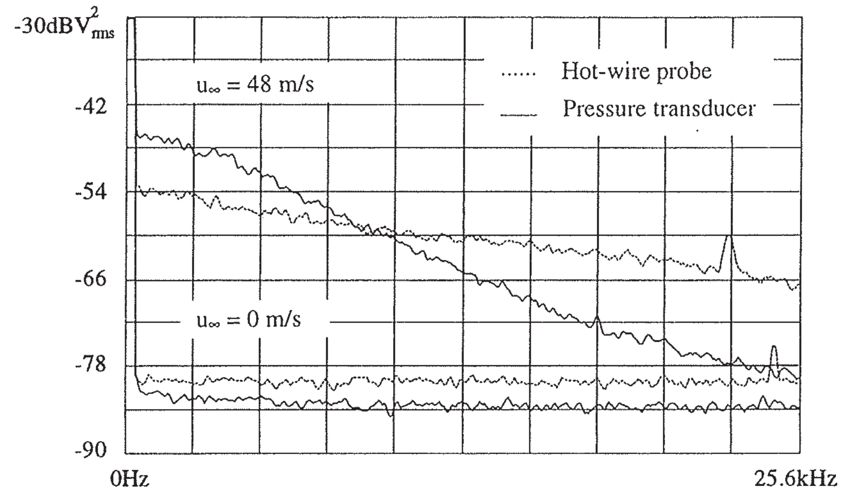

Figure 8 : *Frequency spectra at 64mm downstream: $u_\infty = 48m/s$*

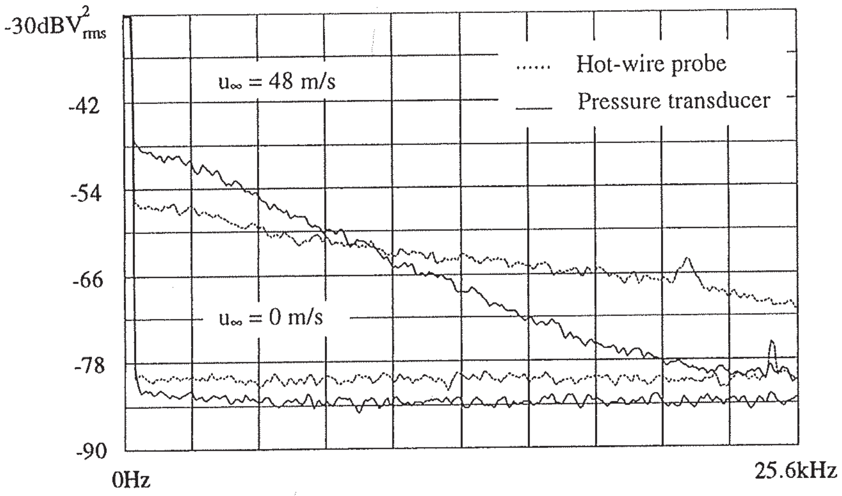

Figure 9 : *Frequency spectra at 106mm downstream: u_∞ = 48m/s*

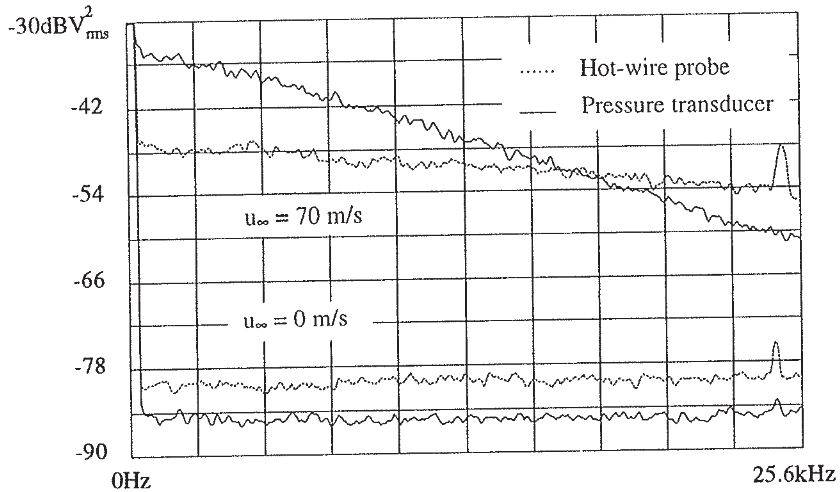

Figure 10 : *Frequency spectra at 21mm downstream: u_∞ = 70m/s*

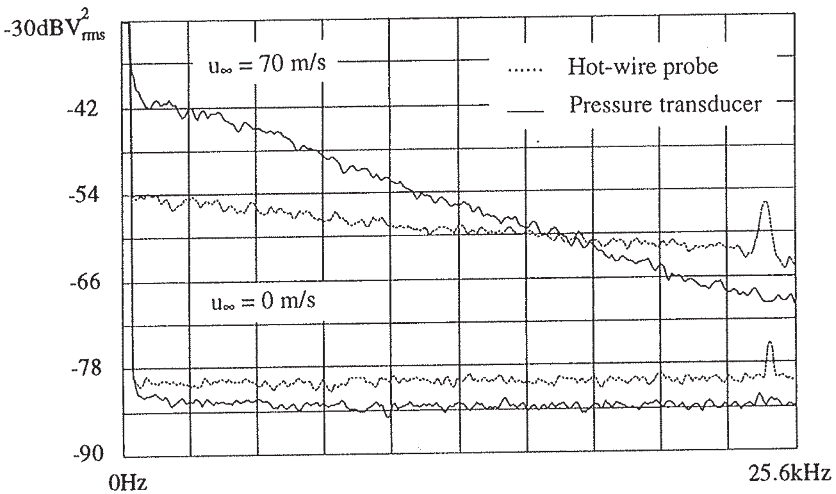

Figure 11 : *Frequency spectra at 64mm downstream: u_∞ = 70m/s*

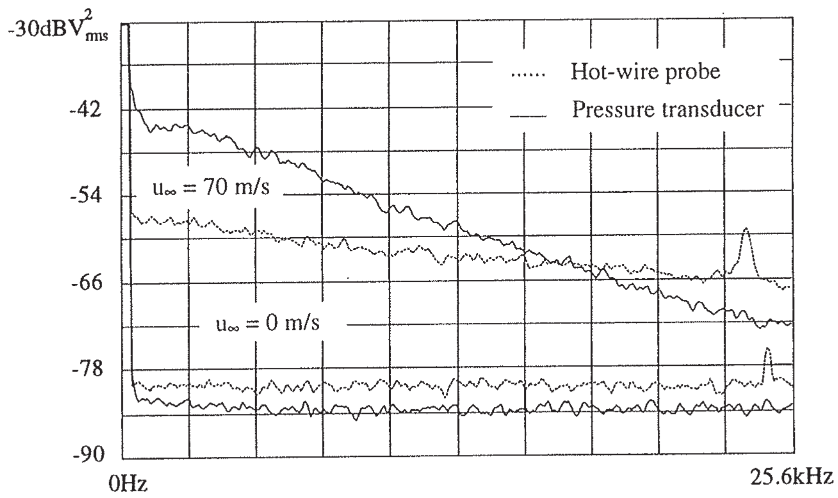

Figure 12 : *Frequency spectra at 106mm downstream: u_∞ = 70m/s*

anemometer increases with increasing flow velocity, irrespective of the position downstream of the grid, culminating in almost a flat spectra for a velocity of 70m/s. This suggests that the flow in the wake of the grid was anisotropic at low velocities with large vortices present in the flow and, at higher values of velocity, the flow behind the grid approached isotropic turbulence.

4. Compressible Flow Turbulence Measurements

The turbulence measurements presented earlier for incompressible flow provide some evidence to suggest a relationship exists between velocity fluctuations and total pressure fluctuations for grid generated turbulence. However, the limits in terms of Mach number, Reynolds number and percentage turbulence needs to be determined for the correlation between total pressure fluctuations and velocity fluctuations obtained from measurements in incompressible flow. Since a supersonic windtunnel is not yet available at the University of Limerick, one method of achieving representative gas turbine inlet Mach and Reynolds numbers was to deploy a flow of compressed air through a length of pipe, to extend the investigation into the compressible flow region. Existing and induced total pressure fluctuations could then be measured using the same instrumentation introduced earlier for the incompressible flow experimental investigations.

The same pitot mounted pressure transducer used for the incompressible flow study was utilised for total pressure fluctuation measurements in compressible flow. Similarly, a hot-wire anemometer was calibrated for an overheat ratio of 0.90. LDA measurements were acquired for three freestream velocities. All the instrumentation was laterally mounted close to the centreline, without introducing probe interaction errors, in the flat portion of the velocity profile at the exit plane of a diffuser. The experimental results were plotted and are presented in figures 13a and 13b for different plotting axis, log-log and linear-linear respectively; the incompressible flow measurements are also plotted and shown in figure 13a.

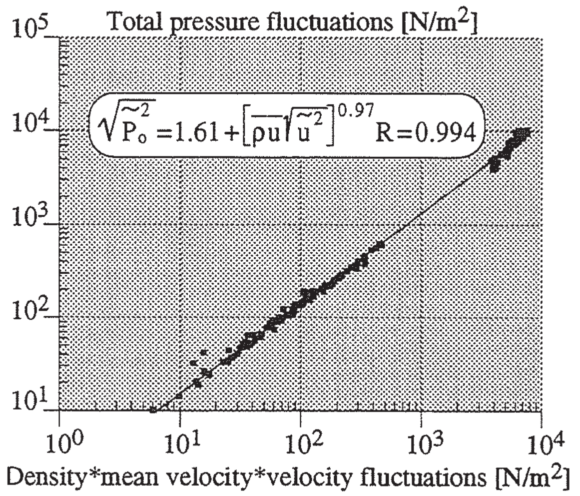

Figure 13a : *Combined compressible and incompressible flow measurements*

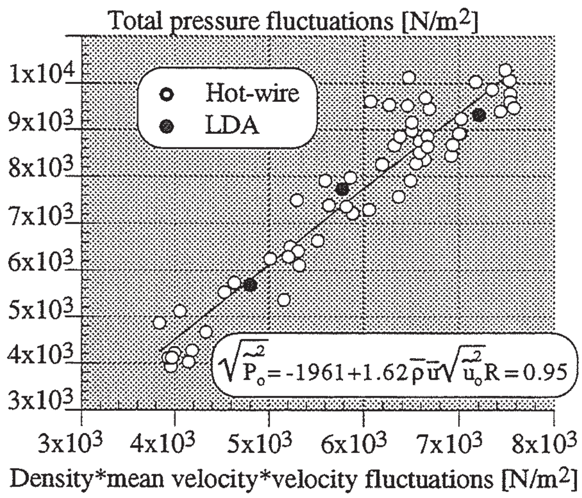

Figure 13b : *Hot-wire probe and LDA measurements in compressible flow*

A satisfactory correlation between the velocity measurement systems, the hot-wire anemometer and the LDA, and the pitot mounted pressure transducer was obtained in compressible flow. The range of Mach numbers studied correspond to typical inlet rotor relative values for an engine, nevertheless, the findings of this work from the compressible flow rig may only be applicable to the particular flow condition in question, the turbulence measured, or the situation where the flow is exhausted to the atmosphere. Therefore, further work is necessary to determine the universal nature, if any, of the correlation. The LDA measurements compared well with the measurements acquired from the hot-wire anemometer suggesting any errors or drift in the calibration of the hot-wire anemometer or loss in sensitivity in the compressible flow regime did not affect the validity of the mean and fluctuating velocity measurements. The slope of the correlation has increased by 27% and this may be due to a number of factors including, the higher level of turbulence intensity measured, compressibility effects, errors in the readings and a different turbulent anisotropic flow.

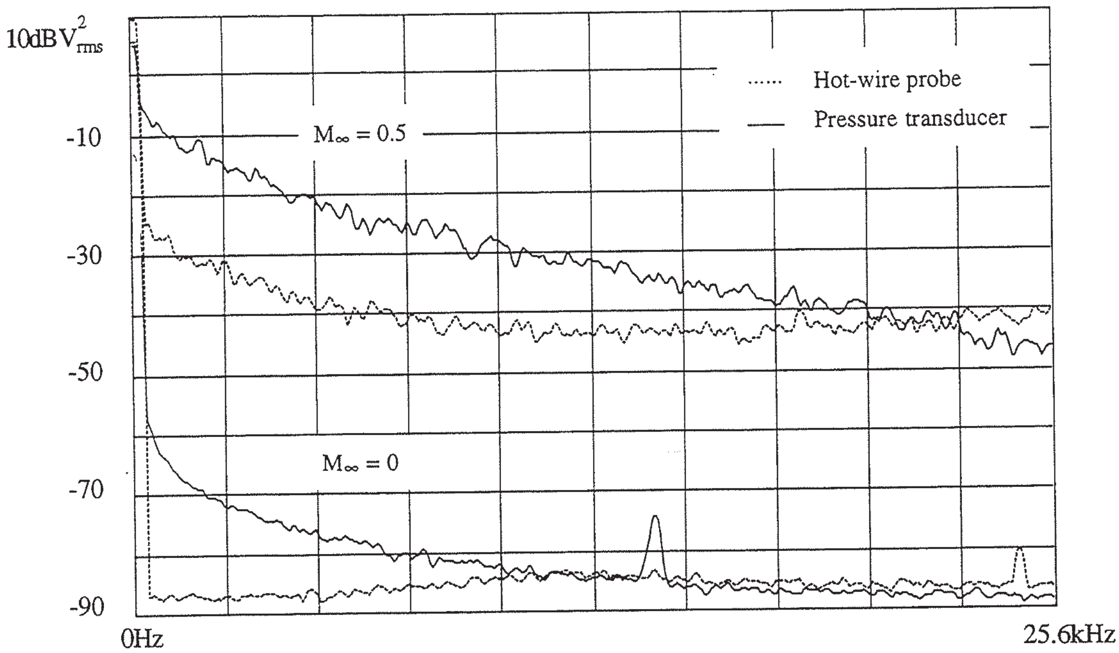

Figure 14 : *Frequency spectra at diffuser exit plane; $M_\infty = 0.5$*

A typical frequency spectra, computed for a freestream Mach number of 0.5, recorded at the exit plane of the diffuser and the zero velocity spectra are shown in figure 14 above. The frequency power spectra from both sensors, as was the case for incompressible flow are appreciably different. Nevertheless, a pattern emerges; the hot-wire signal is broadband whilst the pressure transducer signal is sloped downward, starting higher and intersects the hot-wire signal at a frequency of 21.4kHz. This frequency intersection point is consistent with its increasing trend with increasing freestream velocity. It is encouraging that the differences in the frequency spectra are consistent, and may be explained, as stated earlier, by the fundamental differences between the hot-wire anemometer and the pressure transducer and because they are line and area integrators respectively.

5. Rotor Blade Turbulence Measurement

A pressure transducer was mounted in the stagnation point of a turbine blade in the three-dimensional rotating gas turbine test facility at VKI; this rotor facility was redesigned as part of a Brite/Euram project (Santoriello *et al.*, 1993). Figure 15 below presents a sample of the instantaneous measurement of the stagnation point pressure fluctuations sampled at 200kHz. The data window as shown below relates to the experimental test run time of an experiment in the VKI isentropic light piston tube facility; ordinarily, the run time is of the order 0.7s and steady upstream flow conditions prevail in the time period 0.25-0.40s. The data shown is a random sample recorded from a test run of 150 blade passages and has not been ensemble averaged or otherwise.

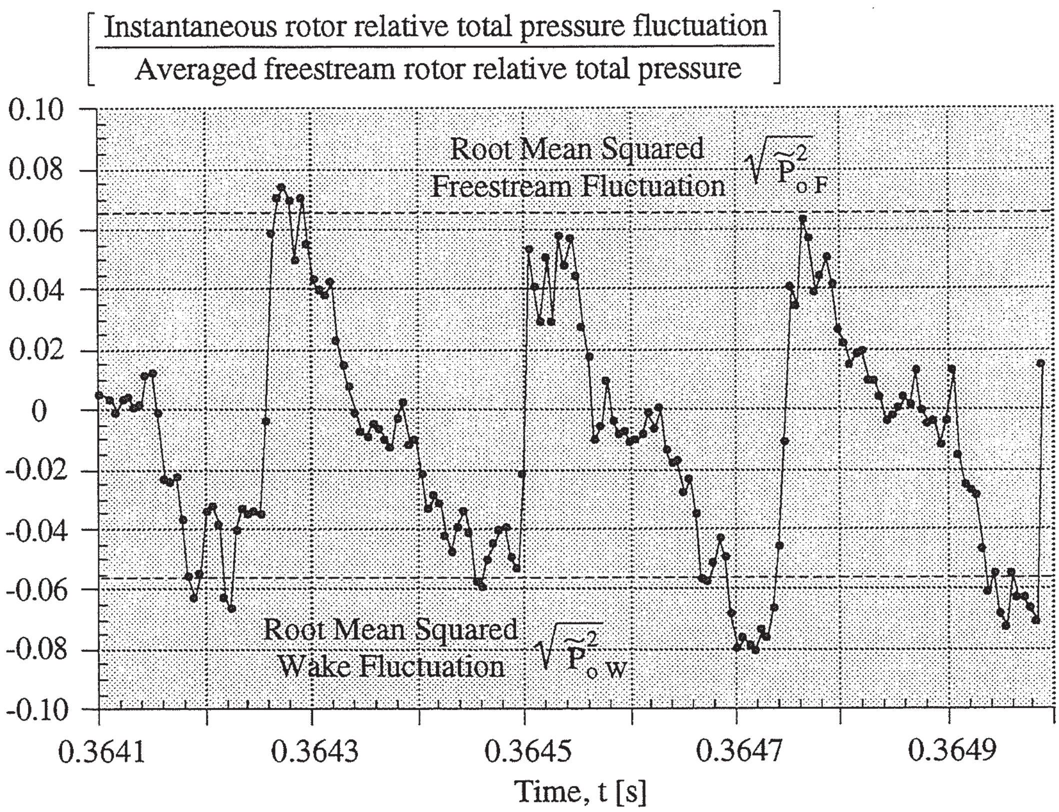

Figure 15 : *VKI rotor blade stagnation point instantaneous pressure fluctuation signal: rotor relative parameters are* $M_\infty = 0.448$, $T_o = 377K$, $Re_c = 5 \times 10^5$, $P_o = 92.7 kN/m^2$ *and* $N = 6467rpm$

One contribution to unsteady flow in gas turbines is wake passing; the unsteady process where the rotor blade row continuously traverses the wakes shed by the trailing edges of the stator blade row. For transonic airfoils like those in the VKI Brite/Euram facility, there is the additional unsteadiness due to the periodic normal and oblique shock wave passing. This unsteadiness and wake passing is evident in figure 15 which presents the instantaneous pressure fluctuations measured in three blade passages. If these blade passages were ensembled averaged, a regular and periodic distribution of the rotor relative pressure fluctuation would emerge.

The theoretical analysis and compressible flow turbulence correlation presented earlier was a relationship determined for root mean square values of fluctuations and is not an instantaneous value relationship; turbulence intensity levels are time averaged quantities and are not defined instantaneously. Therefore, to estimate a rotor relative turbulence level for the wake and freestream, the instantaneous pressure fluctuation data must be time averaged at two positions over a number of blade passages, assuming all passage flows are identical and the acceleration of the turbine rotor is minimal; this will define two turbulence levels - a wake turbulence level and a freestream turbulence level.

The rotor relative pressure fluctuation was root mean squared averaged at two points for 25 blade passages to determine the two different mean rotor relative total pressure fluctuation levels.

$$\sqrt{\tilde{P}^2_{oF}} = +0.0650\bar{P}_o \equiv 19.2\%Tu$$

$$\sqrt{\tilde{P}^2_{oW}} = -0.0557\bar{P}_o \equiv 16.4\%Tu$$

The turbulence compressible flow correlation presented in figure 13b was used to convert the mean rotor relative total pressure fluctuation data in the wake and freestream, into two different turbulence intensity levels; the fluid density was determined using the reference temperature of Eckert (1955). The fluctuations due to turbulence in the wake are of the same order of magnitude as the freestream. However, this may be due to the lack of periodicity between consecutive nozzle guide vane passages which the rotor sees as turbulence.

6. Conclusions

A new probe for turbulence measurement was proposed that responds to total pressure fluctuations and was calibrated against hot-wire and laser Doppler anemometry measurements.

- Theoretical analysis and experimental measurements in an incompressible grid generated turbulent flow and in compressible pipe flow determined a relationship between root mean square values of the fluctuating total pressure and the product of the fluid density, mean freestream velocity and the root mean square value of the velocity fluctuations.

- The true root mean square total pressure and velocity fluctuation measurements correlate very well, but not so in the frequency domain; this may possibly be due to the different manner both probes integrate the fluctuations in the flow or else, new correlations must be derived for different turbulent flows.

- An accurate knowledge of the flow anisotropy, the ratio between the streamwise and lateral velocity fluctuations, may help to predict the slope of the correlation between the fluctuating components of total pressure and velocity for a given flow.

Acknowledgements

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References

Baines, W.D. and Peterson, E.G., 1951, "An Investigation of Flow Through Screens," *Transactions of the ASME*, July, pp. 467-480, Paper No. 50-A-23

Bicen, A.F. and Jones, W.P., 1986, "Velocity Characteristics and Isothermal and Combusting Flows in a Model Combustor," *Combust. Sci. and Tech.*, Vol. 49, pp. 1-15

Bradshaw, P., 1971, "An Introduction to Turbulence and its Measurement," 1st Edition, Pergamon Press, Oxford

Davies, M.R.D. and Casserly, N., 1992, "UL Low Speed Windtunnel Design Report," Mechanical and Aeronautical Engineering Department, University of Limerick, Ireland

Davies, M.R.D. and Wallace, J.D., 1995, "Gas Turbine Model Scaling," ASME *40th International Gas Turbine and Aeroengine Congress and Exposition*, Houston, Texas, Paper No. 95-GT-205

Eckert, E.R.G., 1995, "Engineering Relations for Friction and Heat Transfer to Surfaces in High Velocity Flow," *Journal of the Aeronautical Sciences*, Vol. 22, pp. 585-587

Hinze, O.J., 1975, "Turbulence," 2nd Edition, McGraw-Hill, London

Korneyev, A.I. and Sedov, L.I., 1976, "Theory of Isotropic Turbulence and its Comparison with Experimental Data," *Fluid Mechanics - Soviet Research*, Vol. 5, No. 5, pp. 37-48

Laws, E.M. and Livesey, J.L., 1978, "Flow Through Screens," *Annual Review of Fluid Mechanics*, Vol. 10, pp. 247-266

Moss, R.W. and Oldfield, M.L.G., 1991, "Measurements of Hot Combustor Turbulence Spectra," ASME *36th International Gas Turbine and Aeroengine Congress and Exposition*, Orlando, Florida, Paper No. 91-GT-351

Roach, P.E., 1987, "The Generation of the Nearly Isotropic Turbulence by Means of Grids," *International Journal of Heat and Fluid Flow*, Vol. 8, No. 2, pp. 82-92

Santoriello, G., Colella, A. and Colantuoni, S., 1993, "Rotor Blade Aerodynamic Design," Brite/Euram Technical Report, IMT Area 3 Aeronautics Contract AER2-CT92-0044, *Investigations of the Aerodynamics and Cooling of Advanced Engine Turbine Components Package A: Wake Blade Interference in Transonic HP Turbines*

Tennekes, H. and Lumley, J.L., 1987, "A First Course in Turbulence," 1st Edition, MIT Press, London