Paper 9

UNSTEADY TEMPERATURE MEASUREMENTS USING FIBRE OPTIC SENSORS IN TURBOMACHINERY

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Abstract

Fibre optic based sensors for unsteady temperature measurement are described for use in high speed turbomachinery. The sensors are based on optical interference in a thin zinc selenide coating deposited on the end face of a single mode optical fibre. These are incorporated in to probes for use in turbomachinery test facilities operating at engine realistic environments. The transduction mechanism is the temperature-induced change in the optical thickness of the film. The phase of the interference is detected by measuring the returned optical intensity from the sensor when it is illuminated with laser light of two distinct wavelengths. Results from tests in a compressor and turbine rig are presented, these have blade passing events in the order of 10 kHz. The sensors show measurements of gas temperature fluctuations up to 70kHz.

1.0 Introduction

Over the past few years, we have been developing a measurement tool needed to explore time-resolved gas total temperature flows within turbomachinery. The approach we have adopted is optical interferometry, the sensitivity of this technique is attractive when coupled with the technology of single mode fibres. Optical fibres allow these sensors to be interrogated remotely from the measurement point, they also permit construction of rugged sensors. Unsteady total temperature measurement has always been a difficult task, unlike unsteady pressure measurements for which sensors are now readily available. Conventional thermocouples loss frequency response at above 1 KHz., while aspirating probes have the highest bandwidths about 20 kHz, although their calibration can drift with ageing of the sensor wires (Ng et al. 1983). The sensors we have developed offer bandwidths of up to 70 kHz and have good spatial resolution.

Previously we described the use of fibre Fabry Perot interferometers for use as high bandwidth heat transfer gauges (Kidd et al. 1994) in the isentropic light piston facility (ILPF). We now describe the operation of unsteady temperature sensors based on thin film optical interferometry in full scale turbomachinery research facilities. The targeted specification for these sensors are summarised in table 1

gas temperature resolution	1 K
gas temperature range	500 K
gas velocity	200 ms^{-1}
bandwidth	> 60 kHz

Table 1 Specification required for gas temperature measurement in turbomachinery

For a fibre interferometer, a static temperature resolution of 1K would be very modest. However for gas temperature measurement at 60 kHz, the heat energy transferred from the gas to the sensor and the thermal penetration depth are both small, leading to a resolution requirement roughly equivalent to a static resolution of 1mK.

Two probes using ZnSe films as sensing elements have been constructed for full scale turbomachinery facilities at DRA Pyestock; a continuous running multi-stage core compressor rig the C147 (Cherrett et al. 1992) and a single stage transient turbine rig, the ILPF (Hilditch et al. 1994). Both the C147 and the ILPF are research facilities operated at engine realistic conditions. The probes were located a few mm downstream of the rotor trailing edge, in this location blade passing frequencies of the order 10 kHz were present

2.0 The fibre optic measurement technique

The fibre optic sensor is constructed by depositing a thin optical film on the end face of a single mode optical fibre (figure 1). Laser light of wavelength λ launched into the input end of the fibre is partially reflected by both sides of the film. The two reflected beams differ in phase by an amount ϕ proportional to the film's optical thickness.

$$\phi=\frac{4\pi nl}{\lambda}$$

Where n and l are the film's refractive index and thickness. Interference results in a reflected intensity periodic in ϕ, similar to the transfer function of a two beam interferometer. The optical thickness of a film is in general temperature sensitive, by the thermo-optic effect and by thermal expansion, resulting in a phase sensitivity to film temperature T given by

$$\frac{d\phi}{dT}=\frac{4\pi l}{\lambda}[\frac{dn}{dt}+\frac{n}{l}\frac{dl}{dt}]\Delta T_m$$

The reflective signal is a measure of the temperature averaged through the film. Thus when the sensing element is exposed to a gas flow, the reflective signal is a function of the gas temperature, including its unsteady component. Zinc selenide was suitable as a sensor material, having a thermo-optic coefficient dn/dt ~ 10^{-4} or about 8 times that of fused silica, with low optical absorption at operating wavelengths ~ 800nm (Buller et al. 1989). Films 2.4 µm thick were deposited on the cleaved ends of single mode fibres by vacuum evaporation, resulting in an estimated thermal sensitivity of ~5 x 10^{-3} rad K^{-1}.

The small-signal temperature sensitivity of an interferometer depends on the operating point on the periodic transfer function. The output can be made independent of operating point by illuminating the sensing film with two wavelengths λ_1 and λ_2 chosen to give a phase shift of $\pi/2$ between the resulting transfer function, so that two signals in quadrature are recorded. Light from two separate laser diodes is combined by a fibre directional coupler before launch into a second directional coupler for input in to the addressing fibre. The forward coupler output is available as a reference signal to monitor laser power, while the reflected signal from the sensor is guided in the corresponding coupler arm.

Time division multiplexing was used in some of the experiments to separate the λ_1 and λ_2 outputs The system developed is shown in figure 2, in which each laser diode is alternately switched on by antiphase square waves applied to the laser injection current. Modulation frequencies of up to 100 kHz were used.

3.0 Fibre sensor probe construction

Two fibre sensor probes were constructed, one for use in the C147 compressor facility figure 3 and the second for the ILPF turbine facility figure 4. The primary requirement in both cases was to provide a rugged mounting for the optical sensor and protection for the fibre optic feedout.

3.1 Construction of compressor probe

The addressing fibre was protected within an aerodynamic probe constructed from stainless steel. The probe stem was inserted between the blade rows, with requirement for a right angle bend in the fibre near the probe tip. The bend section of the fibre was contained within a steel capillary tube closely toleranced to the outer diameter of the fibre buffer, which protruded very slightly from the probe body. A shielded thermocouple was also incorporated for low frequency comparison measurements.

3.2 Construction of turbine probe

A fibre coated with a 2.4 μm ZnSe film was installed in a standard ILPF probe stem, illustrated in figure 5. The fibre was supported internally by a small diameter steel capillary tube. The probe tip was a hemispherical ended brass insert, closely fitting the probe stem, with an axial hole to locate the capillary tube and fibre centrally at the probe tip. The addressing fibre was protected by metal capillary tubing which formed a semi-rigid bend between the probe and its support arm, and by the downlead from the optical system.

4.0 Experiments

4.1 Calibration

Investigation and calibration tests were performed on the turbine probe in an argon shock tube facility. The shock tube produced a well-characterised step increase in temperature in known flow conditions. Tests were made with approach Mach numbers varying form 0.28 and 0.72 and gas temperature rises at the shock between 71K and 460K. Gas flow over the probe tip remained constant for about 3ms, over which time the sensing film measured the rising temperature of the fibre in response to an approximately constant heat flux. An average heat flux was derived from the observed optical phase change converted to a fibre surface temperature. Average heat flux was also calculated from a heat transfer model based on stagnation flow around a hemispherical body at low Mach number (White 1991). The observed and calculated heat fluxes are given in figure 6; they agree within about 10% and are linearly proportional to independently measured values obtained from a second heat flux probe also located in the shock tube. We conclude that the thermo-optic calibration of the film and the stagnation flow heat transfer model are consistent over the range of flow conditions in this shock tube experiment.

4.2 Compressor tests

The fibre probe was operated downstream of the first stage rotor of the C147 core compressor rig. The probe could be moved to any radial position while the compressor operated at design peak efficiency. Data were acquired from the probe as it was inserted in the flow at 17 equally spaced radial positions, between hub and casing. At each point in the traverse, data were acquired in the free running mode and in the shaft synchronised mode. The return optical intensity from the probe was ensemble averaged over 128 rotor revolutions. A typical result for a mean flow of Mach 0.7 is shown in figure 7. Several data sets were taken until the probe signal deteriorated after a total exposure of about 1 hour to the compressor flow. On later examination the zinc selenide film was found to have been abraded from the fibre end face.

4.3 Turbine tests

The ILPF operates as a transient flow tunnel unlike the compressor rig. The tunnel is operated by spinning the rotor assembly in vacuum before releasing the isentropically heated air flow through the working section. A test experiment was run to check the absence of any significant optical signal at blade passing frequency with the rotor running at a constant speed in vacuum, for example from blade reflections or from vibration. The return intensity as a function of time was recorded with a free running transient recorder for the 500ms run time of the tunnel. Six runs were made with no apparent deterioration of the optical probe. A spectrum of the returned optical signal λ_1 is given in figure 8, showing an unsteady thermal signal at blade passing frequency and, at 19kHz its second harmonic.

5.0 Data processing

Data processing requires the following three stages: i) converting the ZnSe return intensity to phase ii) converting the phase change to sensor temperature changes iii) calculating gas temperature change from sensor temperature change.
Intensity to phase change requires knowledge of the visibility V of the interferogram, found using the ZnSe film characteristics obtained by spectrophotometric analysis of a coating witness slide produced at the same time as the sensor coatings. Visibility of ~60% was found for the films. The return signal from the ZnSe film at the two interrogating wavelengths λ_i (i = 1,2) for the transfer function in quadrature are of the form

$$I_1 = I_{01}k(1+v\cos\phi)$$
$$I_1 = I_{02}k(1+v\cos\phi)$$

where I_{01} is the reference detector intensity and ϕ the optical phase difference introduced by the sensor film. These two equations can be solved for the phase ϕ independently of the transmission constant k, assuming it is non-dispersive over the range between the two interrogating wavelengths. The result is

$$\phi=\cos^{-1}\frac{c}{\sqrt{a^2+b^2}} - \tan^{-1}\frac{b}{a}$$

where $a=I_2/I_{02}$, $b=I_1/I_{01}$ and $c=(b-a)/v$. Conversion of ZnSe phase change to temperature change was simply calculated from the thermo-optic coefficient. However, the relationship between the ZnSe film temperature change and the gas temperature change can be modelled, or inferred from calibration experiments, in order to determine the heat transfer coefficient from the gas to sensor. Using our previously reported model (Kidd et al. 1994) , and applying the calibration found in previous lab based experiments on vortex shedding. The gas temperature amplitudes we infer from the data obtained in the compressor experiments (section 4.2) shown in figure 7 are 15K. Harmonic analysis of these data indicates that the frequency response of the sensor system exceeds 70 kHz. The noise in the ensemble averaged signal was equivalent to 1K in gas temperature.

6.0 Discussion

The shock tube and turbomachinery trials in section 4 were undertaken to investigate and demonstrate the feasibility of using an optical fibre sensor in realistic aerodynamic test facilities, rather than as a detailed investigation of the unsteady temperature field. The response of the thin film coated fibre to a step change has been tested and has shown that the ZnSe coating provides a sensitive surface temperature measurement of the fibre. The form of the output signals approximates to a $\sqrt{t}$ growth and numerical estimates of heat flux to the probe tip bear out this interpretation. For the compressor tests the sensor coating was damaged after 1 hour's exposure to the flow, however, the ZnSe coating in this trial sensor was unprotected. Technology exists to apply suitable protective coatings that are sufficiently thin to prevent an adverse effect on the high frequency thermal response. This new optical technique therefore has potential for application in high bandwidth unsteady temperature measurement in aerodynamic flows.

Fibre optic sensors based on interferometry have potential for other applications in aerodynamic test facilities. For example, we have shown previously that Fibre Perot interferometers are suitable for the measurement of heat flux in transient flow wind tunnels (Kidd et al, 1992, 1993).

7.0 Conclusions

The results presented in this paper represent the first such measurements of unsteady temperature data at 70 kHz, within full scale turbomachinery test facilities. We have demonstrated the high bandwidth capabilities of optical sensors and their application in the C147 and ILPF turbomachinery research rigs. The unsteady temperature sensors are less highly developed as the heat flux sensor, and further work is required to optimise them. Particular improvements are required to the durability of the optical coatings and in the calibration of the sensors. Attention also needs to be paid to define the probe characteristics more fully, with further development of the calibration and frequency response for the turbomachinery environment.

Acknowledgements

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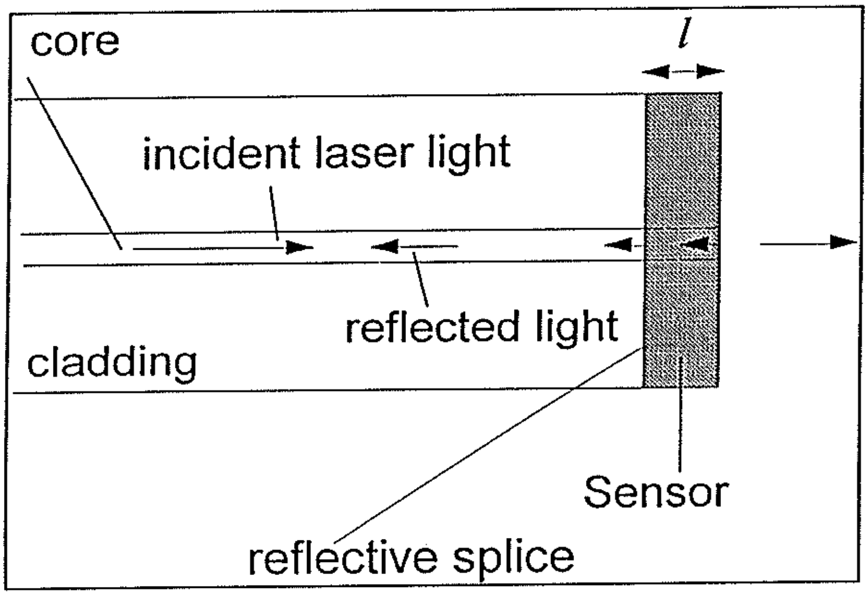

Figure 1 Fibre Optic Sensor Construction

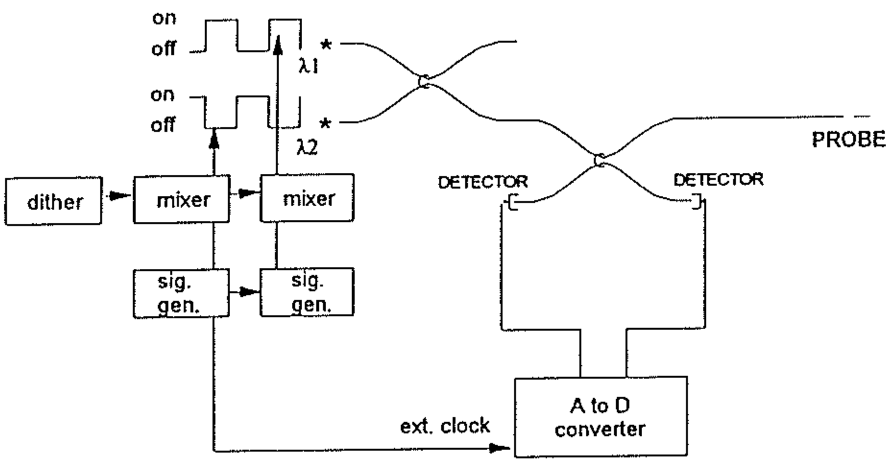

Figure 2 Time Division Multiplexing System

Probe cross section

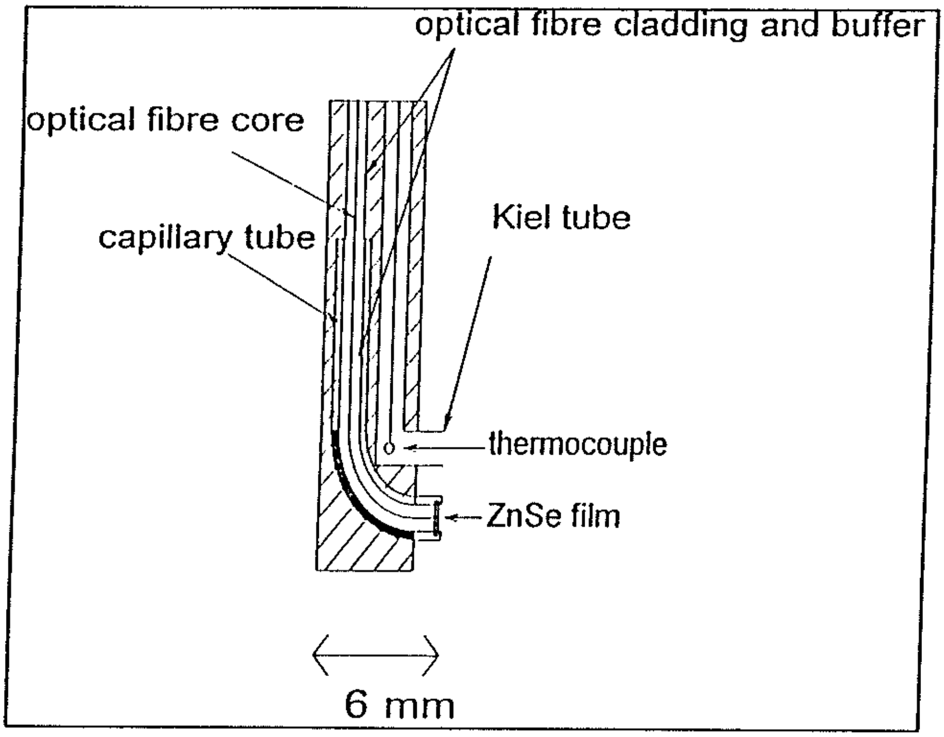

Figure 3 C147 Fibre Optic Temperature Probe

probe diameter 2mm

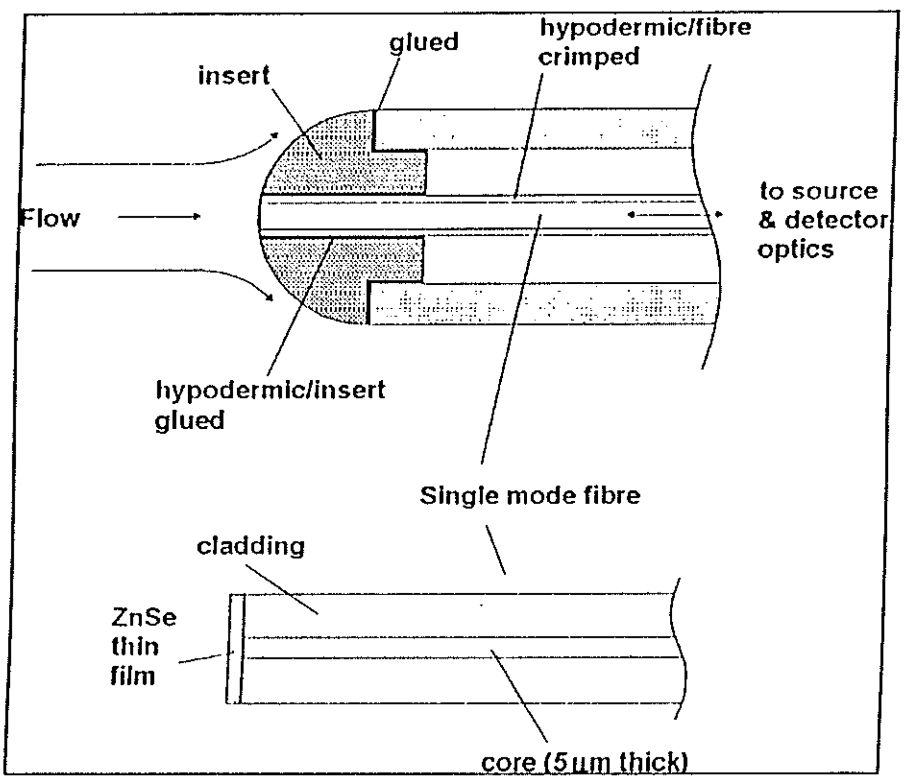

Figure 4 ILPF Fibre Optic Temperature Probe

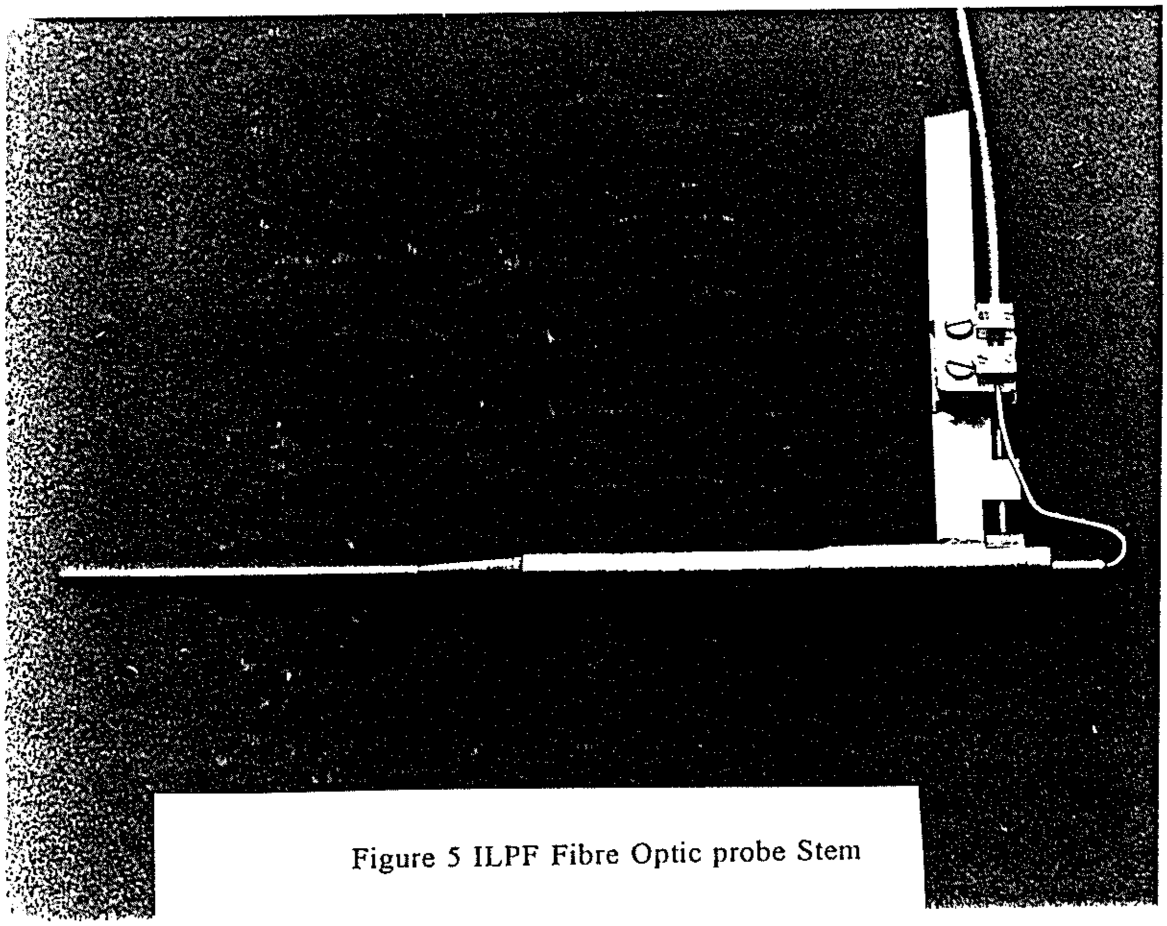

Figure 5 ILPF Fibre Optic probe Stem

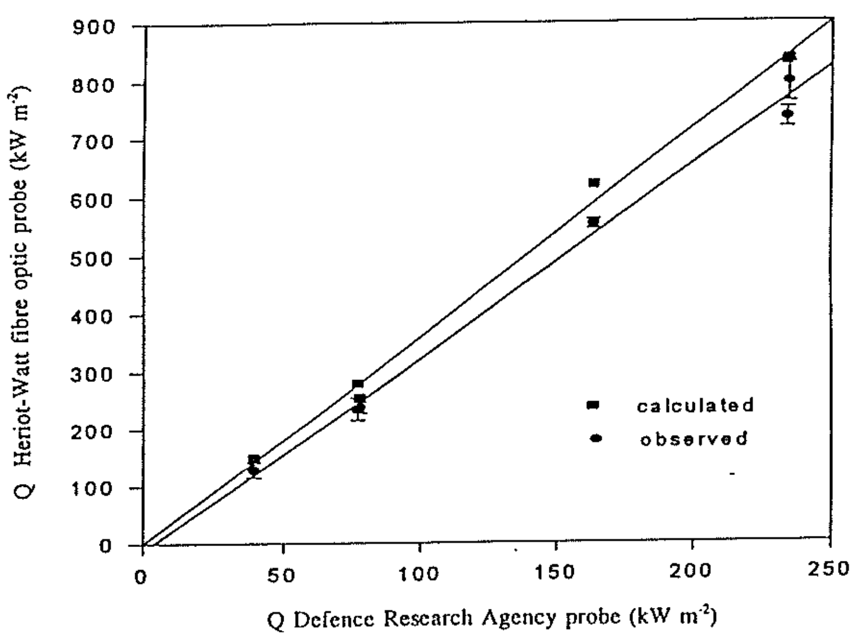

Figure 6 Calculated and Observed Heat Transfer Rate to Optical Probe in Shock Tube

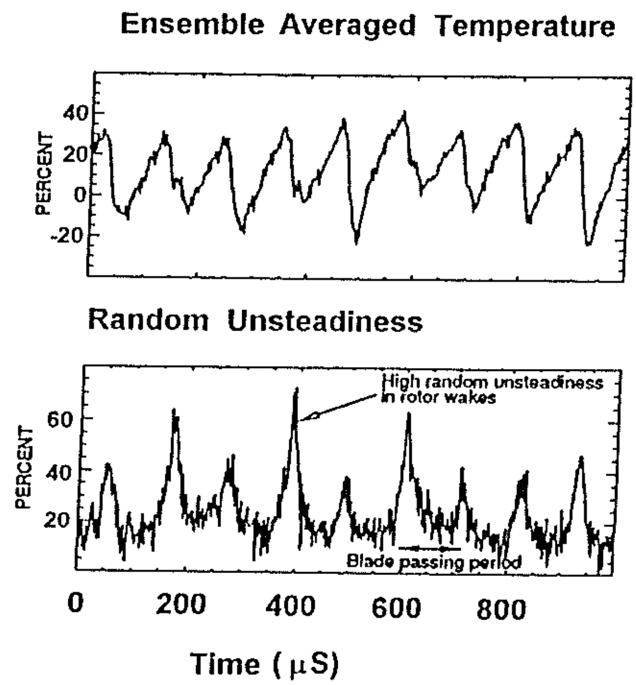

Figure 7 Time-Resolved Compressor Data

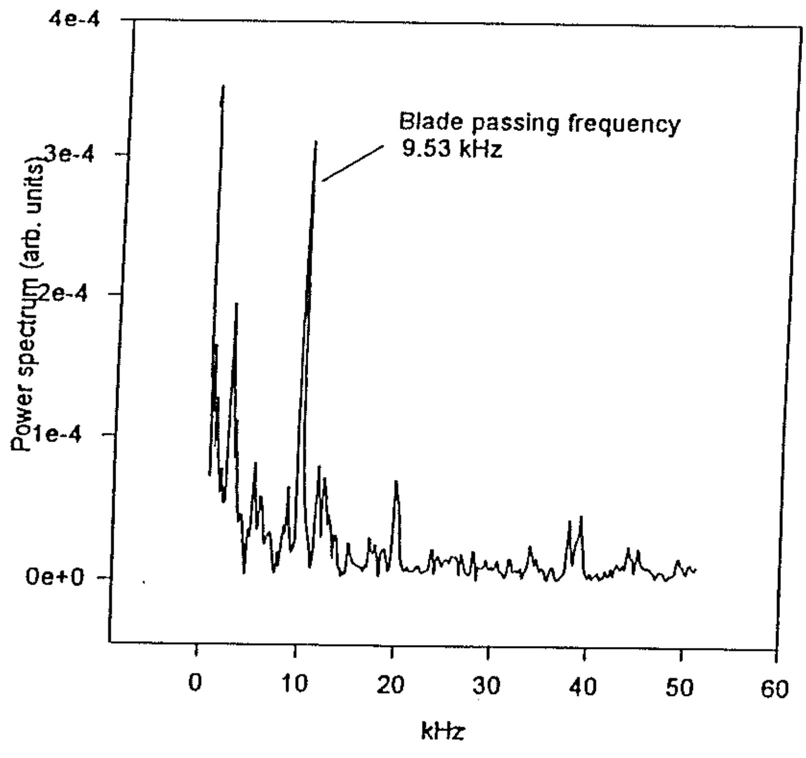

Figure 8 Power Spectrum of ILPF Data