PRESSURE MEASUREMENTS AT A NOZZLE GUIDE VANE EDGE USING EMBEDDED FIBRE OPTIC SENSORS

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ABSTRACT

Small size, high bandwidth pressure sensors are required for instrumentation of probes and test models in aerodynamic studies of complex unsteady flows. Optical fibre pressure sensors promise potential advantages of small size and low cost in comparison with their electrical counterparts. We describe miniature Fabry-Perot cavity pressure sensors constructed by micromachining techniques in a turbine test application. The sensor bodies are 500 μm square, 300 μm deep with a ~2 μm thick copper diaphragm electroplated on one face. The sensor cavity is formed between the diaphragm and the cleaved end of a singlemode fibre sealed to the sensor by epoxy. Each sensor is addressed interferometrically in reflection by 3 wavelengths simultaneously, giving an unambiguous phase determination; a pressure sensitivity of 1.6 rad bar^{-1} was measured, with a typical range of vacuum to 600 kPa. Five sensors were embedded in the trailing edge of a nozzle guide vane installed upstream of a rotor in a full-scale turbine stage transient test facility. Pressure signals in the trailing edge flow show marked structure at the 8 kHz blade passing frequency. To our knowledge, this is the first report of sensors located at the trailing edge of a normal-sized turbine blade.

INTRODUCTION

Progress in understanding the complex time-varying flows in turbomachinery is central to improvements in gas turbine performance and efficiency. Experimental investigation of turbine aerodynamics places particular demands on instrumentation to measure rapidly fluctuating pressure and temperature in blade cascades and in test rigs in which rotor blade passing frequencies may be typically 10 kHz.

At present, the most widely developed instrumentation for unsteady pressure measurement is based on piezoresistive silicon sensors [1-2], comprising a silicon diaphragm containing an array of strain gauges on a silicon chip approximately 1mm square. These sensor elements can be commercially packaged in a supporting structure with temperature compensation circuits, or directly surface mounted onto blades. The sensor bandwidth is dependent on the natural vibration frequency of the diaphragm, typically in the range 150 to 400 kHz. It is generally necessary to protect the diaphragm against direct exposure to transonic flow by using a permeable screen or elastomer coating, reducing the bandwidth to 100 kHz or less.

MEMS-based sensors [3] offer a reduction in size to the range 1 mm to 1 μm and have found application in wall pressure measurement in turbulent flows, requiring high sensitivity but limited pressure range when compared with turbomachinery applications. Pressure-sensitive paint [4] enables two-dimensional pressure distributions over a test model surface to be determined by non-intrusive means. A luminescent component in the paint is excited optically and subject to pressure-dependent quenching by oxygen in the flow. The resulting luminescence is detected and processed using either intensity or decay time as the measure of pressure at the surface. This technique is complementary to the use of discrete sensors, which provide higher pressure resolution and bandwidth without the possibility of extensive or continuous spatial coverage.

Optical fibre pressure sensors have a number of potential advantages in comparison with their electrical counterparts. They are in the same size range as MEMS (micro-electromechanical systems) sensors; they are insensitive to electromagnetic interference, requiring no connecting leads in electrically noisy

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environments; and are potentially very low cost per sensor, a point of some importance for tests in which sensors may have a limited lifetime, or require instrumentation of a series of aerodynamic models.

We describe the design and fabrication of micromachined optical fibre pressure sensors sufficiently small to be embedded in the trailing edge of a nozzle guide vane (NGV), and present preliminary results from experiments in an engine-scale turbine test facility. To our knowledge, this is the first report of unsteady pressure measurements made at the trailing edge of a normal-sized guide vane.

I. OPTICAL FIBRE PRESSURE SENSORS

A wide range of optical fibre pressure sensors has been reported in the literature [5-11]. The most appropriate type for an aerodynamic probe or surface mounted application is a point sensor in a reflective configuration, i.e. a single optical fibre connects the sensor to the optical source and detection system. The sensor contains a compliant element such as a reflective diaphragm which results in the optical properties of the sensor changing with applied pressure. Micromachining techniques are well suited to the construction of optically-read sensors attached to fibres [5]. The sensors reported differ in their construction methods, sizes, mechanical properties and optical methods of interrogation.

Diaphragm displacement can be measured optically either by intensity based methods, which rely on the variation of reflective coupling efficiency to the addressing fibre, or by interferometry in combining the light reflected from the diaphragm with that reflected from a fixed element of the sensor, in principle forming a Fabry-Perot sensing cavity. An example of an intensity based sensor is described by Wang et al. [6] which uses an interference filter bonded to the fibre end face to generate a reference intensity reflection, separated in the wavelength domain from the reflection from the diaphragm.

Tohyama et al. [7] describe an interferometric sensor for biomedical applications in which a silicon structure supports a gold/chromium film diaphragm illuminated by a 1.31 μm wavelength LED delivered by a multimode fibre. This is amongst the smallest reported pressure sensors, with a sensing element only 270 × 270 × 150 μm in size.

For aerodynamic applications, Castracane et al. [8] and Zhou et al. [9] have developed interferometric sensors with silicon diaphragms. The authors in ref. [8] report a 32-sensor system for flush mounting in a hypersonic wind tunnel model. The diaphragms were 900 μm diameter with a resonant frequency of ~300 kHz. Two-wavelength laser illumination allowed the optical phase to be determined from a pair of quadrature signals from each sensor, at up to 50 kHz. The sensors in ref. [9] have silicon diaphragms 600 μm diameter supported on a glass substrate, with the cavity dimensions and diaphragm deflection designed to allow single-wavelength interrogation without ambiguity arising from the periodic interferometric transfer function. These sensors exhibited a bandwidth exceeding 200 kHz in shock tube experiments.

We have previously reported sensors with 125 μm diameter copper diaphragms supported by ceramic ferrules with single wavelength interrogation. The sensors were experimentally demonstrated in an aerodynamic total pressure probe in a turbine test rig [10] and in measurements of airborne blast waves in explosives trials [11]. The bandwidths of the pressure signals obtained exceeded 200 kHz, with a typical pressure resolution of ~ 500 Pa and a range from vacuum to 500 kPa. However, these sensors were hand assembled. In the present work we describe copper diaphragm sensors on silicon substrates made by micromachining methods, interrogated by a three-wavelength system resulting in more robust signal processing.

A. Principle of operation

The sensor comprises an air-spaced optical cavity formed between the copper diaphragm and the cleaved end of a singlemode fibre sealed to the sensor by epoxy. Assuming reflections from the fibre end face and diaphragm are low, typically less than 10%, the Fabry-Perot sensor can be approximated to a two-beam interferometer in reflection whose transfer function is a cosinusoidal function [12].

$$I = kI_0(1 + V\cos f) \qquad (1)$$

where I is the returned optical intensity, k the effective mean reflectivity, I_0 the incident intensity, V the visibility of the interferometer and f is the optical phase. If the cavity length changes by Δl due to a pressure change ΔP, the optical phase change is

$$\Delta f = \frac{4pn}{l}\Delta l \qquad (2)$$

where n is the refractive index within the cavity and l is the interrogation wavelength. The diaphragm deflection Δl is proportional to ΔP [10], within the pressure range corresponding to a linear diaphragm strain. Hence pressure change is measurable as an optical phase change.

B. Fabrication of micromachined sensors

The sensors are fabricated from a silicon wafer 100 mm (4 inches) in diameter and 300 µm thick. Prior to etching, an array of circular copper diaphragms (250 µm diameter) was electroplated onto the back surface of the wafer using a photolithographic pattern transfer technique: a layer of spun coated photoresist was exposed to UV light through a quartz/chromium mask. The areas of the resist exposed to the UV are then removed leaving an array of circular holes ready for electroplating. Once electroplated, another array of smaller diameter holes (50 to 100 µm) was generated in photoresist on the front surface of the wafer. This array was then etched to a depth of approximately 25 µm using Deep Reactive Ion Etching (DRIE). Finally a second larger diameter hole (125-140 µm) was etched on top of the first hole until the copper diaphragm was reached. The smaller hole is preserved due to the preferential etch direction of DRIE. To help maintain the feature resolution, the process employs repeated deposition of a protective polymer layer followed by etching. The polymer layer is deposited on *all* surfaces, but is removed from surfaces parallel to the plane of the wafer during the etch part of the cycle due to the directionality of DRIE. This leaves a protecting layer on surfaces perpendicular to the wafer, which acts to minimise unwanted etching in this direction. Repeatedly alternating between the two processes produces parallel side walls and maintains small features at the bottom of deep holes.

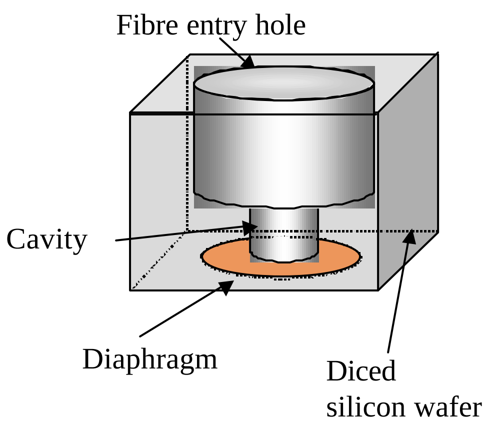

Fig. 1. Schematic of diced micromachined silicon pressure sensor

The structure provided two concentric holes: the first hole locates the fibre whilst the second narrower hole defines the cavity and diaphragm diameter. The wafer was then diced, defining the size of the sensors (500 x 500 x 300 µm). A schematic sensor is shown in Fig.1.

To complete the sensor a singlemode fibre was introduced into the larger hole and butted up against the step formed by the second smaller hole. As the fibre was inserted, fringes generated between the end face of the fibre and the diaphragm could be measured in real time using a broad band source and a spectrometer, to monitor alignment of the fibre and the cavity length. The fibre was fixed in the hole by epoxy, Fig. 2. The initial yield from the wafer was ~ 10 % of the possible 2200 sensors; this is expected to increase as the etching process is optimised.

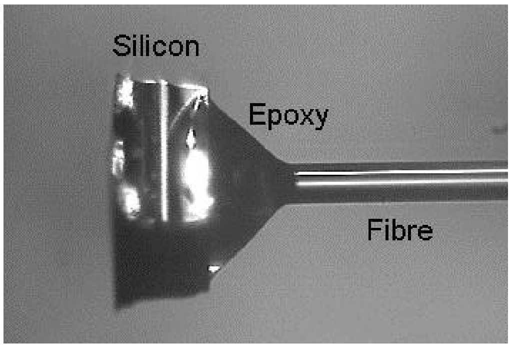

Fig. 2. Micromachined pressure sensor. Fibre diameter = 125 µm

C. Calibration

A shock tube, capable of both slow and fast pressure changes, was used to calibrate the sensors over their operational pressure range and also to investigate the transient response to a step increase in pressure. Using a low bandwidth electrical pressure gauge for calibration, the sensors were pressure cycled between vacuum and 500 kPa, a pressure far greater than that used in the intended application, giving an observed pressure sensitivity of ~ 1.6 radians per 10^5 Pa, which is consistent with the sensitivity calculated from the expected diaphragm displacement, Fig 3.

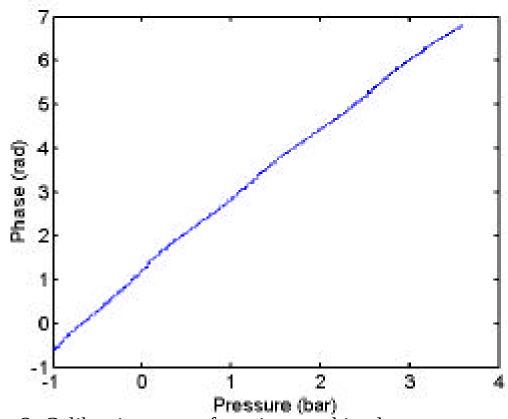

Fig. 3. Calibration curve for micromachined sensor

A high coupling efficiency from the diaphragm to the fibre causes the sensor's transfer function to deviate from the ideal cosinusoidal function given in equation 1. This produces the small ripple in the calibration curve. However as each sensor is calibrated, variation between sensors and deviation from linearity is taken into account.

When the chamber was held at a pressure of 300 kPa, no drift was seen in the sensor's return signal, demonstrating that the epoxy had formed a sealed cavity and that the diaphragm was attached securely to the silicon. The dynamic response was measured by exposing the sensor to the shock generated by a burst diaphragm, which propagated at approximately 300 ms^{-1} with a step rise in pressure of ~ 100 kPa. The response time of approximately 2-3 μs can be seen in Fig. 4. The subsequent pressure oscillations correspond to reflections of the shock front within the shock tube.

Thermally cycling the sensor over a 60^0C temperature range gave an apparent pressure change of ~ 3 kPa K^{-1}. Therefore any temperature change will give rise to an error in the mean pressure measured by the sensor but thermal fluctuations on the sub-millisecond timescale are too small to affect the high frequency pressure components in the sensor signal.

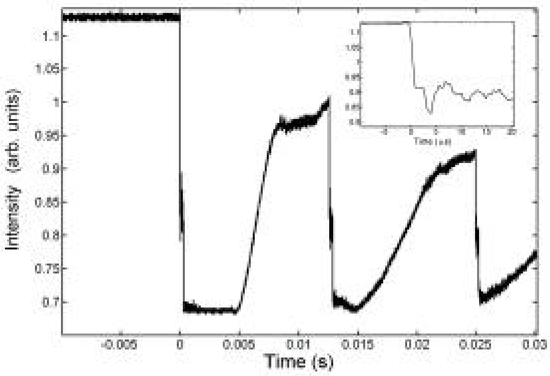

Fig. 4. Shock test experimental results

D. Embedding sensors in the test vane

The small size of the sensors was exploited to measure the unsteady flow between a nozzle guide vane (NGV) and the rotor stage in a gas turbine test rig. A ring of NGVs comprise the stator section immediately upstream of the rotor. The pressure sensors were embedded flush with the trailing edge of the NGV.

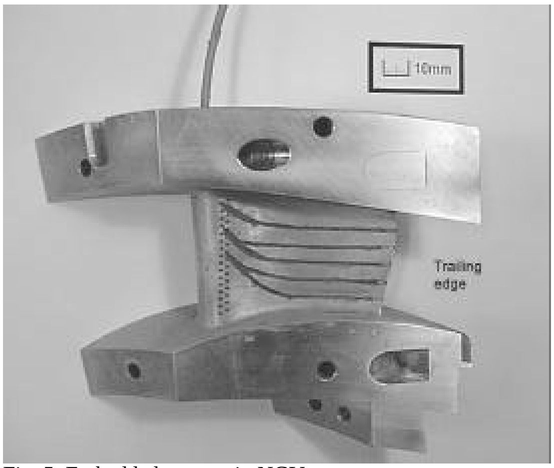

Fig. 5. Embedded sensors in NGV

Previously, constraints due to the relatively large size of available pressure sensors have required the use of vanes scaled up in size from those used in engines [13]. The small size of our sensor enabled us to embed 5 sensors directly into a normal sized NGV, 7 cm by 4 cm with a 1 mm thick trailing edge. Each sensor lay in a machined channel in the side of the NGV and was embedded using metal loaded filler providing support for the sensor whilst keeping the original shape of the NGV surface. The fibres were fed through the centre of the blade to the outside of the test facility in a ruggedised cable.

II. INTERROGATION SYSTEM

If the cavity were interrogated with a single wavelength the phase modulation would be restricted to no more than π radians thus limiting the sensors pressure range. Also, such intensity based measurements are sensitive to bend losses in the downleads, coupling losses and laser intensity noise. By introducing additional wavelengths the cavity can be observed simultaneously at more than one point on the transfer function which can eliminate phase ambiguities and common mode effects such as downlead losses and noise [14].

The interrogation scheme used with the optical pressure sensors is shown in Fig. 6. Three 10 mW DFB laser sources, each a different wavelength, are combined using a 3x3-fibre coupler and passed through a circulator to the sensor. The three output ports of the coupler allow three sensors to be interrogated simultaneously. The reflections from the sensors are then wavelength division de-multiplexed using a combination of Bragg gratings and fibre couplers. Following de-multiplexing each wavelength is monitored using high bandwidth connectorised InGaAs photodiodes, and the voltage outputs captured using a data acquisition A/D system sampling up to 1 MHz.

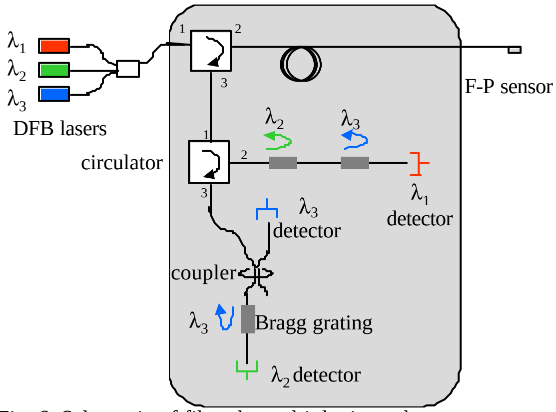

Fig. 6. Schematic of fibre de-multiplexing scheme

The all-fibre components used in the interrogation scheme removed the need for bulk optics and the consequent alignment problems, resulting in a rugged portable system capable of interrogating 3 sensors. The wavelengths were chosen to produce, for each sensor, 3 reflection transfer functions approximately evenly separated in phase over the range 0 to 2π, in order to make efficient use of the 3-wavelength algorithm to construct the sensor phase signal *f*. Commercially available lasers were used with wavelengths of 1532, 1546 and 1562 nm. The interrogation system cost per sensor is competitive with the cost of special order surface mounted miniature electrical pressure sensors, with the advantage that the cost resides mainly in the optical system; the replacement cost of sensors is low. Further development to improve the yield of the micromachining process will open up the possibility of disposable sensors.

III. TURBINE TEST FACILITY

The isentropic light piston facility (ILPF) at QinetiQ, Pyestock, UK, is a transient flow facility used for gas turbine engine research and development. It comprises a full-scale stator and rotor, simulating a high pressure turbine stage [15]. The rotor contains 60 blades and is spun up to design speed before a transient hot air flow is released through the stage. The resulting transonic flow has a mean pressure of 150 to 200 kPa, with pressure oscillations due to individual blade passing events at a frequency of ~8 kHz. The flow duration is ~500 to 1000 ms, depending on operating conditions.

IV. EXPERIMENTAL RESULTS

In total, 13 runs were performed in the test rig with data captured from three sensors in each run. Recording data before the flow started, but as the rotor was spun, gave a measure of the system noise, from which a sensor resolution of ~ 12 mrad (0.65 kPa) was obtained. These pre-run data were also found to contain no apparent pressure fluctuations above the noise, indicating that the sensors were not vibrationally sensitive. Calibrated data are shown in Fig. 7 as pressure *vs* angular rotation from a single sensor during the flow. The data have been averaged over one rotor revolution. The high frequency structure of oscillations about 50 mbar (5 kPa) in amplitude is clearly evident, and is expected to depend on rotor blade passing and vortex shedding interactions.

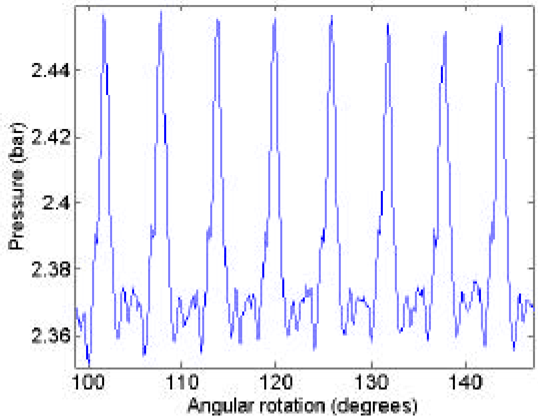

Fig. 7. Rotor averaged blade passing events

The frequency spectrum of the pressure was found by Fourier analysis of the rotor averaged data, fig. 8.

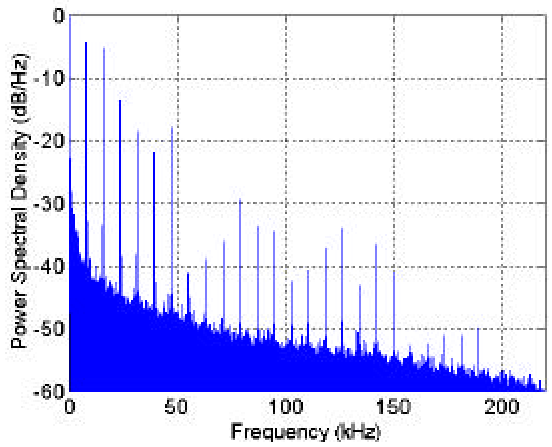

Fig. 8. Fourier transform of rotor averaged data

A strong frequency response can be seen at the blade passing frequency 8 kHz, with further harmonics measured up to 180 kHz.

V. DISCUSSION

We have successfully demonstrated a robust, micromachined optical fibre pressure sensor capable of measurements in aerodynamic applications. The sensor dimensions of 500 x 500 x 300 µm were suitable for embedding in a 1mm thick trailing edge of a nozzle guide vane in an engine-scale turbine test facility. Data shown in Fig. 6 demonstrate a clear blade passing signal of about 4.4 kPa with noise equivalent to 0.65 kPa. The pressure resolution, set by laser and detector noise, was measured to be 0.9 Pa Hz $^{-0.5}$, to be compared with a noise floor of ~ 0.3 Pa Hz $^{-0.5}$ for the nearest equivalent piezoresistive pressure sensors.

Further data analysis, such as examination of the signal varaition across the span of the trailing edge, is in progress.

Temperature cross-sensitivity in this type of sensor may arise through expansion of the copper diaphragm, expansion of the sensor body and thermally-induced pressure rise within the sensor cavity [10]. The data presented here have not been corrected for temperature effects, although the temperature rise in the transient experiments is expected to be small. Further work will investigate other diaphragm materials such as silicon nitride.

We have described the construction of all-optical miniature pressure sensors and their application to transient aerodynamic experiments. Their small size and simplicity of single-fibre connection has enabled them to be embedded at the thin trailing edge of a turbine guide vane, allowing pressure measurements to be made which were previously unobtainable with conventional sensors.

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