Investigation of shock waves in explosive blasts using fibre optic pressure sensors

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Abstract. We describe miniature all-optical pressure sensors, fabricated by wafer etching techniques, less than 1mm\textsuperscript{2} in overall cross-section with rise times in the µs regime and pressure ranges typically 600 kPa. Their performance is suitable for experimental studies of the pressure-time history for test models exposed to shocks initiated by an explosive charge. The small size and fast response of the sensors promises higher quality data than has been previously available from conventional electrical sensors, with potential improvements to numerical models of blast effects. Provisional results from blast tests will be presented in which up to 6 sensors were multiplexed, embedded within test models in a range of orientations relative to the shock front.

1. Introduction
The experimental measurement of air-blast pressures is a notoriously difficult problem. An ideal sensor for the task would have to be sufficiently robust to withstand a blast loading; small to reduce interaction with the flow; without significant inertia to record the pressure-time history accurately, and insensitive to various types of noise, both electromagnetic and mechanical, produced by the blast. While each of these requirements may be addressed separately with relative ease, no truly comprehensive solution has been presented so far. For example, commercially available specialised piezo-electric gauges are very robust with working pressures of hundreds of bar and rise times on the microsecond scale. Nevertheless, they are typically expensive, bulky (over 1 cm in diameter), and susceptible to acceleration, which makes accurate pressure measurements nearly impossible, especially for flows around relatively small structures.

Optical fibre pressure sensors have several potential advantages that are pertinent to this application. Their small size results in good spatial resolution and high packing density for mapping the pressure distribution over the surface of a test model. The low mass diaphragm is relatively insensitive to acceleration and, with resonant frequencies typically above 1 MHz, enables data capture over a bandwidth exceeding 100 kHz. The all-dielectric construction provides immunity to electromagnetic interference and pickup, and electrical connections are not required. The manufacture

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of sensor bodies by silicon wafer processing techniques is expected to lead to a low cost per sensor. We have already demonstrated the potential of earlier versions of these sensors in transient aerodynamic experiments [1], in which 5 sensors were embedded in the trailing edge of a nozzle guide vane in a turbine test rig to measure the unsteady pressure upstream of the rotor. Pressure fluctuations of 90 kPa (100 kPa = 1 bar) were measured at the 8 kHz rotor blade passing frequency with a resolution of 0.65 kPa, with harmonics of up to 180 kHz. The experiments reported here investigated the suitability of fibre pressure sensors in systematic studies of the interaction of blast waves with structures.

2. Operating principle
Reference [1] describes the sensors and the associated optical system, so we restrict the description here to an outline only. Fabry-Perot cavities were formed between a cleaved fibre end and a flexible diaphragm at the end of a micro-machined sensor cavity, typically 20-100 µm long and sealed at atmospheric pressure (figure 1). The low reflectivities of the fibre end and diaphragm resulted in an approximately sinusoidal response of the reflected optical signal versus external pressure and, for small deflections of the diaphragm, the optical phase was expected to vary linearly with pressure change. The fibres were single-mode at 1550nm and the sensors were interrogated with high stability 10 mW laser diode sources at 1532, 1547 and 1563 nm. The three resulting reflection signals follow three sinusoidal response functions as pressure changed, the phase separation of which was set by the source wavelengths. Phase was overdetermined by the three measurements and was thus insensitive to common mode intensity noise and changes in the visibility of the interference [2]. This interrogation method was chosen because the optical sources were unmodulated, unlike time-division multiplexed methods, allowing data capture over a high signal bandwidth, in principle limited only by the detector noise. The optical detection system (figure 1) was all-fibre in construction, using fibre Bragg gratings as signal filters [1]. The lasers were capable of addressing 6 sensors simultaneously through a fibre coupler tree.

3. Fabrication of sensors
The sensor bodies were fabricated on a 3 inch diameter, 380 µm thick silicon wafer. Deep etching by the Bosch process [3] was used to create the fibre holes to a depth of approximately 360 µm on the front side. On the back face, a similar pattern of smaller holes to define the pressure sensing apertures was aligned to the front array. The sensor holes of various diameters were deep etched through the remaining 20 µm depth to the large holes in the front side (figure 2). A 1 µm thick silicon dioxide (SiO₂) membrane was grown thermally on an auxiliary 3-inch silicon handle and transferred to the device wafer by a bonding technique.
To transfer the SiO₂ layer to the etched device wafer, the oxide film on the handle wafer was brought into contact with the array of pressure sensing holes on the other wafer so that the surfaces would adhere together by weak bonding forces. The wafers were then annealed to strengthen the bonds considerably. Finally, a rapid inductively-coupled plasma silicon dry etch process was used to remove the handle wafer, leaving the SiO₂ membrane intact and firmly bonded to the rear surface of the device wafer (figure 3).

**Figure 2.** SEM cross-section of a portion of the device wafer 380 µm thick, showing the fibre entry hole of diameter 128 µm above the 50 µm diameter sensing cavity.

**Figure 3.** SEM of the SiO₂ membrane covering one of the 50 µm diameter apertures, showing the internal silicon land surrounding the hole at the bottom of the fibre channel.

The wafers were diced and assembled into discrete devices. The diced parts, termed sensor bodies, typically had an area of approximately 1 mm². These were inspected under a microscope to ensure that there were no known imperfections before proceeding with assembly into a sensor. Their diaphragm surfaces, within the cavity, were then made reflective by coating with between 10 and 100 nm of aluminium. This was achieved by positioning them in a vacuum coating chamber with their fibre entry holes facing the thermal evaporation source.

**Figure 4.** a) Illustration of sensor body. b) Photograph of assembled sensor. c) Interference fringes produced by illuminating a sensor with a broadband source.
Figure 4a illustrates a sensor body. The assembly of a sensor involved the operator guiding a 125 µm diameter cleaved fibre into the fibre entry hole, with the aid of a microscope and xyz translation stage. The other end of the fibre was coupled to both a broadband source and an optical spectrum analyser by a 50/50 fibre coupler. This enabled the operator to observe the appearance of fringes from the formation of the Fabry-Perot cavity as the fibre was inserted. When satisfactory fringes appeared and the fibre was butted against the step before the cavity, epoxy was applied between the fibre and the outside of the sensor body to fix the fibre in place and seal the cavity. Figures 4b and 4c show an assembled sensor and the fringe pattern of the sensor cavity. The free spectral range measured from the fringe pattern was used to calculate the length of the cavity. This provided the measure of the phase steps between the laser sources, with respect to the sensor transfer function, which were necessary for the algorithm used to calculate the interferometric phase.

4. Sensor calibration and mounting

Sensors were tested for their response to pressure changes by installing them in either a pressure chamber or a small shock tube. They were repeatedly cycled through pressure changes from atmospheric pressure to an absolute pressure of approximately 9 bar. This removed unwanted mechanical hysteresis from the sensor. Repeated cycling, of the type shown in figure 5, was also used to calibrate the optical sensors (middle) with respect to a low-bandwidth electrical sensor (top). A plot of phase against pressure (bottom) shows good linearity in response across the operating range. The final test for each sensor was to expose it to a face-on air shock of a few bar in the shock tube, to confirm its suitability for explosive blast experiments.

Figure 5. Pressure cycling and calibration. Figure 6. Mounted sensors.

For the explosives trials, the optical sensors were mounted in such a way that they were similar to commercially available electrical Kulite pressure sensors. Figure 6 shows an example of such an optical sensor, which was capable of being easily instrumented in experiments designed for Kulite HKM-375 sensors. The 1 mm × 1 mm sensor body can be seen at the centre of the mount. Smaller mounts were also used, similar in construction to the Kulite XCQ-080, with sensors glued into 25 mm long, 2 mm outside diameter, stainless steel tubes, with the sensor face flush with the tube end.

5. Experimental test arrangements

A particular test arrangement used for comparison tests between Kulite and optical sensors was designed to accurately reproduce conditions of a hemispherical blast. This arrangement was chosen because blasts from hemispherical charges on a semi-infinite plane have been widely studied analytically and experimentally, and a large volume of work on the properties of such blast waves at different scales has been published [4]. As shown in Figure 7, a set of hemispherical explosive charges between 40 g and 60 g were initiated at the centre of a 2 × 2 m plate made of 10 mm thick steel. In
order to prevent unavoidable plastic damage to the plate in the vicinity of a charge, a 15 cm diameter disk was removed from the centre of the plate, so that the charges could be placed on 15 cm diameter sacrificial anvils made of 20 mm thick mild steel. By mismatching the acoustic properties of the anvils and the rest of the structure, as well as using a thin layer of viscous decoupler, the amount of vibration transferred to the test models was significantly reduced. The main plate was welded onto a frame made of 80 mm box section and supported at four corners. The plate centre, where the highest loading occurred, was supported by a separate structure, as shown in Figure 7(c). The main anvil underlying the sacrificial anvil was made of 80 mm, thick 60 cm diameter steel disk, which was bolted to the main plate and supported by a piece of steel tube with an access hole for the centrally placed detonator.

Figure 7. A setup for producing hemispherical air blasts. (a) Top-up, (b) side views and (c) the structure of the central support.

Two identical test models, hollow rectangular steel boxes 26 × 27 × 10 cm, were prepared for the experiments. Both models were spot-welded along the plate diagonals at various distances from the charge. They were instrumented with Kulite HKM-375 and XCQ-080 sensors, and optical pressure sensors. The reflected pressures at the faces of test structures varied between approximately 3.1 and 5.0 bar.

6. Results
The optical sensors were shown to perform favourably when compared with the Kulite sensors, displaying rise times (10 to 90%) of less than 3 µs. Figure 9 compares typical responses of optical and Kulite HKM-375 sensors, normalised with respect to their peak. There is a small shift between the timebases of the two traces due to a difference in sensor distance with respect to the explosion, but it is negligible on the timescale shown here. Both traces show a rapid rise, although as the pressure decays the readings of the Kulite sensor exhibit considerable noise, which can be attributed to the high acceleration cross-sensitivity of this sensor. As a result, there appear to be more distinct features apparent in the optical traces, and information such as the impulse of the blast wave can more easily be determined, as compared with traces from the piezo-electrical sensors. Small Kulite sensors (XCQ-080) demonstrated considerably lower cross-sensitivity to acceleration at the expense of reduced measurement bandwidth.

Figure 8. An experimental setup with two rectangular test models.
Further experiments are in progress to study the effects of blasts in complex environments, by recording pressure-time data from the front, side and top faces of rectangular test models. The fine detail of the release waves from the boundaries at the front face of a structure or the arrival of separate shocks at the rear sensor are examples of the effects for which the fast response optical sensors are ideally suited. The optical sensors have survived repeated testing with peak pressures up to around 600 kPa, and have shown consistent results from similar tests, thus allowing the separation of random effects and noise from significant features in the signals.

7. Conclusions
Favourable performance of the optical sensors has been established against existing electrical sensors. The optical system used fibre connectors which eliminate the need for splicing equipment and facilitate setting up on site. We anticipate further development to improve repeatability and quality control in sensor fabrication, and plan to evaluate the thermal sensitivity of the optical sensors. Further experiments will be developed to exploit the optical sensors to investigate clearing effects at model edges and corners, and to provide data to test scaling laws against existing results from larger scale experiments.

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