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Shock Wave Overpressure History Mapping Using High-Resolution Distributed Acoustic Sensing

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ABSTRACT

This study explored the use of high-resolution distributed acoustic sensing (HR-DAS) for measuring blast wave overpressures, addressing the limitations of conventional pressure transducers. Shock tube experiments were conducted to evaluate HR-DAS performance in capturing side-on blast overpressures, comparing its strain measurements with reference piezoelectric pressure transducers. The study examined the effects of sensing fibre orientation and mounting methods on sensor sensitivity. Results showed that HR-DAS strain histories aligned well with conventional pressure measurements. The findings demonstrate the feasibility of HR-DAS for blast wave sensing, highlighting its potential for further development and broader applications.

Keywords: High-resolution, DAS, Distributed acoustic Sensor, Shock wave, Blast wave.

1. INTRODUCTION

Explosive detonations produce blast waves characterised by rapid pressure rises and exponential decays, typically modelled using the Friedlander equation [1]. Accurately measuring these overpressures is critical for assessing blast impacts on structures, materials, and biological systems. Traditional piezoelectric sensors are widely used for such measurements but face limitations, including high costs, reliance on an individual acquisition channel for each sensing node, and limited sensor deployment due to size and installation constraints.

Optical fibre-based sensors offer significant advantages over electrical sensors, including immunity to electromagnetic interference, compact size, and fast response times. Among these, High-Resolution Distributed Acoustic Sensing (HR-DAS), based on Ultra-low Loss Enhanced Backreflecting (ULEB) fibre [2], is an emerging technology that enables accurate strain measurements at thousands of locations along a single optical fibre [3]. Unlike conventional DAS systems, which typically lack high spatial resolution, HR-DAS achieves sub-meter resolution by employing specially engineered optical fibres with periodic reflectors. These reflectors allow strain changes to be measured with nano-strain precision by analysing phase variations in the back-reflected light.

This study investigates HR-DAS, utilising Ultra-low Loss Enhanced Backreflecting (ULEB) fibre as a distributed pressure sensor for measuring blast wave parameters. While standard SMF-28 fibres have a low Poisson's ratio, the significant pressure levels generated by blast waves induce strain levels detectable by HR-DAS systems. The system's response to various blast wave scenarios was measured and compared to reference data obtained from piezoelectric (PZT) pressure sensors. The comparison highlights the potential of HR-DAS to overcome the limitations of conventional sensors, including scalability, cost-effectiveness, and deployment flexibility, while also addressing challenges in achieving precise and reliable pressure measurements in high-dynamic environments.

2. PRINCIPES

An idealised incident blast waveform is characterised by an instantaneous pressure rise (above ambient atmospheric pressure), reaching a peak incident, P_i at the time of blast wave arrival, t_A, followed by an exponential decay to ambient pressure, marking the end of the positive phase duration, t^+ (Fig. 1(a)) Subsequently, a period of under pressure exists before returning to ambient atmospheric conditions, over a relatively longer negative phase duration,

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t^-. A key objective in many blast research studies is determining the incident overpressure history i.e. P_i and t^+, caused by a blast wave propagating in the air.

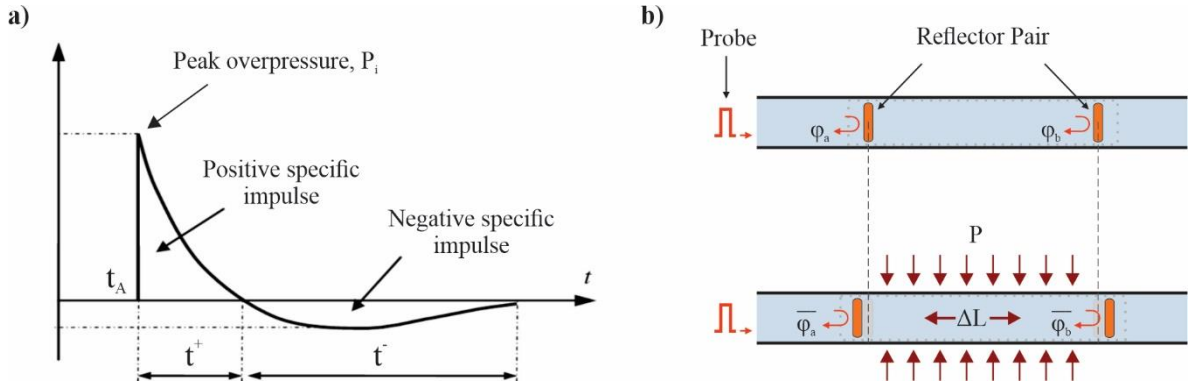

Figure 1. a) Friedlander curve illustrating the incident/side-on overpressure-time history for an idealised blast wave. b) The principle of pressure-induced strain measurement using ULEB fibre.

The overpressure history can be measured by measuring the pressure-induced strain between any given pair of reflectors on a ULEB fibre. For a pair of reflectors that are separated by L meters, the round-trip phase difference between the back-reflected lights is given by [3]:

$$\Delta\Phi = \frac{4\pi n\xi}{\lambda} L \tag{1}$$

where n is the effective refractive index of the fibre, ξ is the correction factor (for SMF-28 $\xi = 0.79$), and λ is the wavelength of the probe light. A hydrostatic pressure of P on the fibre changes the phase difference by $\Delta\varphi$ with the total phase change given by [4]:

$$\Delta\Phi = \frac{4\pi n\xi}{\lambda} L + \Delta\varphi = \frac{4\pi n\xi}{\lambda} L - PL\left[\frac{\beta(1-2\mu)}{E} - \frac{\beta n^2}{E}(1-2\mu)(2p_{12}+p_{11})\right] \tag{2}$$

where β is the propagation constant, μ is the Poisson's ratio, E is the Young's modulus, and p_{12} and p_{11} are strain-optic coefficients. By tracking the variation in phase difference $\Delta\Phi$, the variation in the hydrostatic pressure level on the fibre can be mapped with 200 Pa accuracy.

3. EXPERIMENT

3.1 Test Arrangement

Figure 2 illustrates the experimental setup used to assess the HR-DAS system's performance as a distributed pressure sensor. The optical interrogator comprised two main components: a pulse synthesizer arm and a receiver arm. In the pulse synthesizer arm, a narrow-linewidth seed source (λ = 1550 nm, $\Delta\nu$ = 2 kHz) was externally modulated by an electro-optic modulator (EOM) to generate 1 ns probe pulses. These pulses were launched into the sensing fibre and routed to the receiver arm through circulator C.

The sensing fibre, based on G.652 acrylate-coated fibre, was fabricated using an automated reel-to-reel fibre inscription setup [2]. It contained 10 reflector pairs inscribed in the fibre core, each with an average reflectance of −56 dB. The reflectors within each pair were separated by 15 cm, and the spacing between pairs was 20 cm. A 10 m section of standard G.652 fibre was used to connect the sensing fibre to the HR-DAS interrogator, which was housed in a separate room to isolate it from the test environment.

In the receiving arm of the HR-DAS interrogator, the backscattered signal was first amplified by an Erbium-doped optical amplifier (EDFA). Noise from the amplifier was minimized using an FBG filter (λ_B = 1550.1 nm, $\Delta\lambda$ = 0.2 nm, Reflectivity = 99%) The amplified back-reflected signal was then processed through a Mach-Zehnder Interferometer (MZI) with a 30 cm path imbalance, mixing the back-reflected signals from each reflector pair. The output of the interferometer was detected by three amplified photodetectors (BW = 500 MHz, TIA = 100 kΩ) and sampled at 1 GS/s using a PCIe digitizer with a 700 MHz bandwidth.

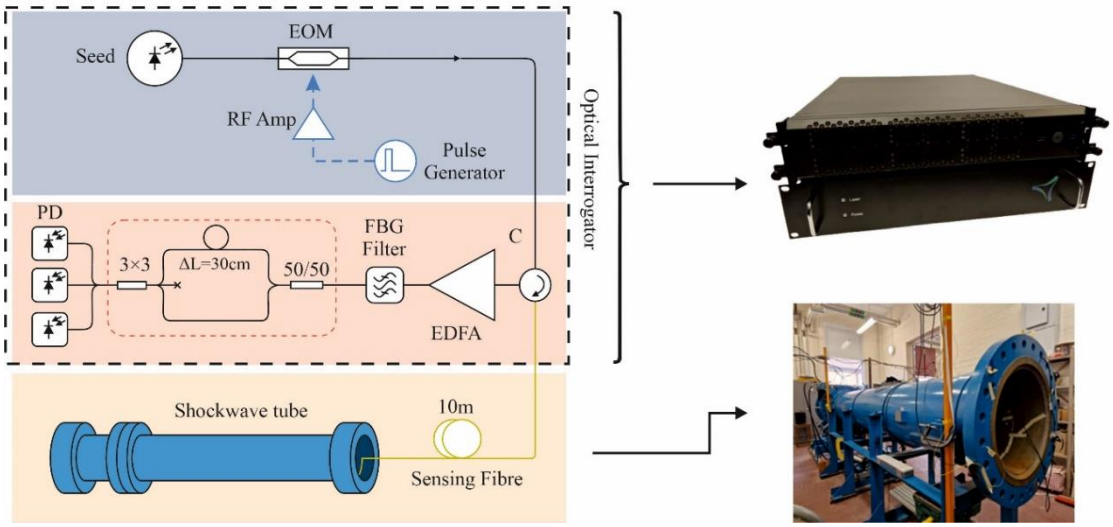

Figure 2. The block diagram of the test arrangement (left), a photo of the HR-DAS optical interrogator (top-right), and a photo of the shockwave tube (bottom-right).

A gas-driven shock tube [5] was employed to generate near-planar blast waves in the driven section following the rupture of a diaphragm separating the pressurized driver section from the driven section (Fig. 2 – bottom-right). The diaphragms were composed of Mylar sheet membranes secured by rubber gaskets. Blast overpressure histories were recorded at the inner wall surface of the shock tube by both the ULEB fibre and a piezoelectric sensor (Kistler 603B), flush-mounted within the inner wall of the shock tube, 200 mm from the tube exit. A Piezo Disc Buzzer Pressure Sensor Speaker was mounted adjacent to the piezo sensor to trigger and initiate data acquisition via the Imatek® C3008 General Purpose Data Acquisition System.

3.2 Test Arrangement

The HR-DAS system was used to interrogate the sensing fibre, which was mounted along the inner circumference of the shock tube wall, 0.2 m from the shock tube exit. The fibre was initially secured to the wall using double-sided Sellotape, with additional reinforcement provided by insulated/heavy-duty gaffer tape. The HR-DAS interrogator operated at a pulse repetition rate of 500 kHz, allowing each reflector pair to be sampled once every 2 µs. For a blast wave with a positive phase duration of approximately $t^+ = 2.8$ ms, this setup enabled the recording of 1400 data points per event.
Two Mylar membrane thicknesses, 125 µm and 250 µm, were utilized to create two distinct blast loading conditions in the driven section. Data was collected for a total of ten blast wave events under this experimental configuration.

4. RESULTS & DISCUSSION

Across these tests, good qualitative agreement is observed between the HR-DAS strain-time histories measured at two (out of ten) of the HR-DAS sensing nodes and the piezoelectric pressure profiles (Fig. 3 (left)).

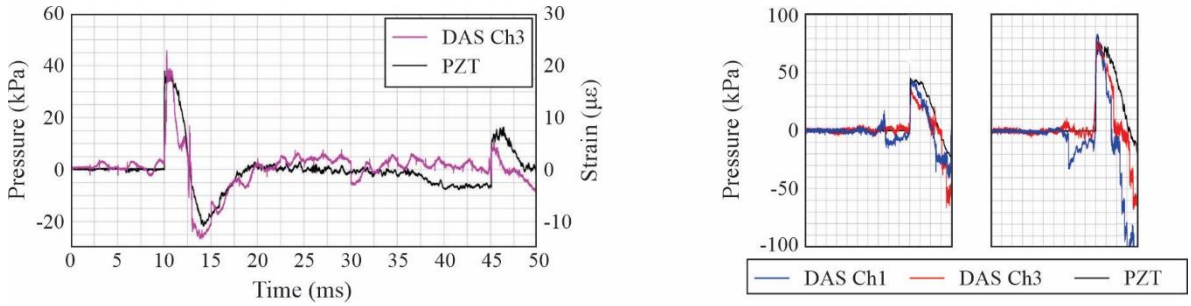

Figure 3. Overpressure and strain history measured by the PZT and HR-DAS with the fibre attached to the inner shock tube wall perpendicular to the direction of the blast wave propagation.

For the data collected from sensing channels mounted perpendicular to the direction of blast wave propagation (i.e., along the circumference of the shock tube), the blast wave arrival was marked by an instantaneous rise in strain for both HR-DAS channels, followed by a decay and a period of negative strain corresponding to the under-pressure phase. Peak positive strains ranged from 22.9 to 25.2 μ**ε** during repeated tests with the 125 μm Mylar membrane (P_i, average = 39.4 kPa). Tests conducted with the 250 μm Mylar membrane showed approximately double the peak strain values measured by the HR-DAS, aligning with the corresponding increase in overpressure recorded by the PZT (Fig. 3, right).

In contrast, results from DAS channels aligned parallel to the direction of blast wave propagation (i.e., along the length of the shock tube) showed little to no agreement with the PZT data (Fig. 4). This discrepancy can likely be attributed to the optic fibre's sensing length and its orientation relative to the shock wave direction. Blast wave propagation in the shock tube caused localised, incremental loading on the fibre, rather than the uniform loading conditions seen in the other configuration. This non-uniform loading is the probable cause of the spurious strain histories. These findings highlight the limitations of fibre sensing length and orientation under dynamic, spatially and temporally varying loading events, such as the passage of a shock wave, which can result in complex and unreliable data.

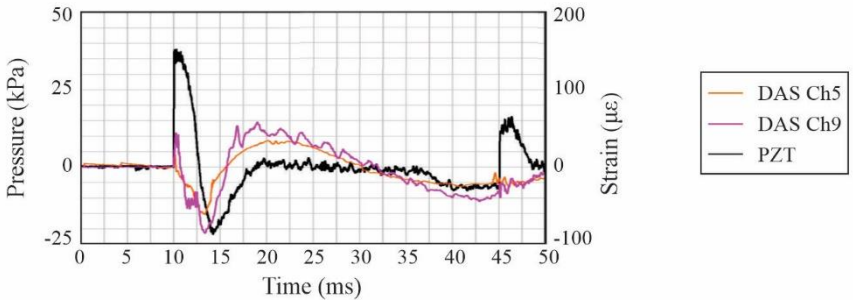

Figure 4. Overpressure and strain history measured by the PZT and HR-DAS with the fibre attached to the inner shock tube wall parallel to the direction of the blast wave propagation.

5. CONCLUSION

The HR-DAS system demonstrated the capability to measure overpressure histories and associated strain-time profiles with high accuracy during blast wave events. The results revealed a strong correlation between the HR-DAS and PZT measurements for sensors mounted perpendicular to the blast wave propagation, validating the system's efficacy under uniform loading conditions. However, discrepancies in data for sensors aligned parallel to the wave direction highlight the limitations of the fibre sensing length and orientation in dynamic, spatially varying loading scenarios. These findings emphasize the importance of sensor placement and configuration for distributed pressure analysis.

ACKNOWLEDGEMENTS

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