Linear location of acoustic emission using a pair of novel fibre optic sensors

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Abstract. A novel fibre optic sensor system has been developed to enable the linear location of acoustic emission. The demonstration of linear location of acoustic emission was conducted using a pair of serial multiplexed fibre coupler-based acoustic emission (AE) sensors in conjunction with a single light source. The simulated AE source, via a pencil lead-break test, was located to within ±5mm.

1. Introduction
The detection of acoustic emission (AE) emanating from a material or structure as a consequence of specified degradation or fracture process is an established non-destructive evaluation (NDE) technique. In general, piezoelectric transducers are used as surface-mounted devices to detect the AE. Significant progress has also been made in recent years in the deployment of multiple transducers for identifying the source of the AE. This is computed by prior knowledge of the wave propagation constants for the material in question and the time taken for the AE signal to reach the various sensors. In the context of the current work, the motivation for developing the linear location of the AE is to enable the identification of damage initiation and propagation in fibre reinforced composites and the location of partial discharge in a transformer.

With reference to the deployment of optical fibre-based AE sensors, a number of interferometric systems have been reported previously [1][2][3][4]. The authors have recently reported on the design and the mode of operation of a novel ultrasound fibre optic sensor system. That sensor design was based on a custom-designed 2×2 fused tapered coupler configuration [5]. Given the intended use of this sensor for the detection of partial discharge in transformers, its immunity from electromagnetic interference is a unique advantage. Apart from the performance specification and reliability, the overall cost of the sensor system is major factor in their adoption by end-users.

In the current paper, we report on the use of the 2×2 fibre optic coupler-based AE sensor system for linear-location application. The low-cost manufacturing of this sensor was reported previously [5] and another unique feature of the system is that the output is fed directly to a commercially available, conventional piezoelectric transducer system. Furthermore, the current sensor system for linear location uses a single light source and photo-detector system.
2. Principle
Schematic illustrations of the fibre coupler-based AE sensor and its packaged counterpart are presented in Figures 1. The proposed mode of operation of the sensor was reported recently [5] and only a brief commentary is presented here. When an acoustic wave impinges on the packaged sensor, due to its mode of construction, the sensor is excited predominantly from one end; at the sensing or waist region the propagating wave causes a phase modulation between the fundamental and the secondary modes.

Considering a sinusoidal mode of acoustic excitation and a single port excitation, $E_1(0) = 1$ and $E_2(0) = 0$, the corresponding normalized two-output peak power from the fibre coupler-based AE sensor can be described by $P_i = |E_i|^2$ ($i = 1, 2$) [5]:

**Equation 1**

\[
\begin{align*}
P_1(t) &= \cos^2 \left[ \int_0^l C(z)dz + \int_0^l \varepsilon_0 C(z) \cos \left( \frac{2\pi}{\Lambda} z - \Omega t \right) dz \right] \\
P_2(t) &= \sin^2 \left[ \int_0^l C(z)dz + \int_0^l \varepsilon_0 C(z) \cos \left( \frac{2\pi}{\Lambda} z - \Omega t \right) dz \right]
\end{align*}
\]

where $P_1$ and $P_2$ are the output optical powers from the sensor. $C(z)$ is the coupling coefficient along the coupling region ($z$ axis) and $l$ is the length of the coupling region. $\Lambda$ and $\Omega$ correspond to the wavelength and frequency of the acoustic wave respectively. $\varepsilon_0$ is the effective strain amplitude and depends on the acoustic power, the diameter of the coupling region and material properties.

For a weak acoustic perturbation, equation (1) can be expanded in the form of a Taylor series in the vicinity of $\varepsilon_0 = 0$, and neglecting the high order terms, the output powers from the sensor can be written as (2):

**Equation 2**

\[
\begin{align*}
P_1(t) &= \cos^2 \left[ \int_0^l C(z)dz \right] - \frac{1}{2} \sin \left[ \int_0^l C(z)dz \right] \left[ \sin \left[ \int_0^l 2\varepsilon_0 C(z) \cos \left( \frac{2\pi}{\Lambda} z - \Omega t \right) dz \right] \right] \\
P_2(t) &= \sin^2 \left[ \int_0^l C(z)dz \right] + \frac{1}{2} \sin \left[ \int_0^l C(z)dz \right] \left[ \sin \left[ \int_0^l 2\varepsilon_0 C(z) \cos \left( \frac{2\pi}{\Lambda} z - \Omega t \right) dz \right] \right]
\end{align*}
\]

To simplify the calculation, it is assumed that the coupling coefficient $C(z) = \bar{C}$ is over the whole coupling region and the equation (2) is obtained after integrating:

**Equation 3**

\[
\begin{align*}
P_1(t) &= \cos^2 (\bar{C}l) - \sin (2\bar{C}l) \left[ \bar{C}\varepsilon_0 \frac{\sin (\pi l/\Lambda)}{(\pi l/\Lambda)} \cos \left( \frac{\pi l}{\Lambda} - \Omega t \right) \right] \\
P_2(t) &= \sin^2 (\bar{C}l) + \sin (2\bar{C}l) \left[ \bar{C}\varepsilon_0 \frac{\sin (\pi l/\Lambda)}{(\pi l/\Lambda)} \cos \left( \frac{\pi l}{\Lambda} - \Omega t \right) \right]
\end{align*}
\]

From equation (3) it can be seen that the output response to the acoustic perturbation from the sensor includes a DC and AC component. The DC component is determined by the geometry of the sensor including the packaging conditions and the coupling ratio. The AC element describes the consequences of the acoustic perturbation.
3. Experimental Details

The sensors were manufactured in-house by heating and drawing a pair of single mode optical fibres (Fibercore SM600) using hydrogen flame. The sensing or waist region was approximately 3 mm long and 10 µm in diameter. The insertion loss of the sensor was less than 0.5 dB and splitting ratio was 50%. The coupling waist-region was fixed in a silica V-groove (20 x 2.0 x 2.0 mm) by bonding its two ends (about 10 mm between the two bonded points) on the V-groove; this meant that the sensing region was suspended in air. One end of the coupler was bonded with UV cured epoxy and the other end was fixed using a silicone rubber adhesive.

A schematic illustration of the experimental setup for the AE linear location is presented in Figure 2. One output port of sensor 1 was spliced with an input port of sensor 2 to form a serial multiplexed sensor. A 633 nm light source with a 1 mW output power was launched into one input port of sensor 1. The optical outputs from the sensors were connected to three detectors (D1, D2 and D3: APD modules Hamamatsu Model C5460). The outputs from D1 and D2 were processed to yield $P_2 - P_1$ using a SRS low-noise amplifier (SRS Model SR560); this effectively removed the influence from sensor 1. The output data from the two sensors were acquired using a commercially available two channel AE signal processing system (PAL MI-TRA). Trigger mode was set at a threshold of 50 dB to synchronize the trigger for two channels. The test setup for the linear location is illustrated in Figure 3 and it involved the use of two fibre optic AE sensors that were surface-mounted on an aluminium plate (1.5 x 1.2 x 0.01 mm). The two sensors were located 30 cm apart and the simulated acoustic emission was generated using a pencil lead-break.

![Figure 1. Schematic illustration of the fibre coupler-based AE sensor.](a) Unpackaged Sensor (b) Packaged Sensor)

**Figure 2.** Schematic illustration of the experimental setup for the AE linear location involving a pair of sensors. D1-3 represent the three individual detectors, LD represents the light source and Mi-TRA represents the commercially available conventional interrogation unit for piezoelectric transducers.
4. Results

Figure 4 presents the results from the case where the simulated AE was generated at point A and the time delay between the two sensors was 100µs. This corresponds to an acoustic velocity of 3000m/s for the aluminium plate.

The above-mentioned experiment was repeated with the pencil lead-breaks being conducted at specified positions, in-line, between the two sensors. Using the time difference between the AE signals from the two sensors and the acoustic velocity, the precise location of the excitation source was calculated. The location of the acoustic source was achieved with repeat experiments to within ±5mm. Typical output from this experiment is presented in Figure 5.
5. Conclusions
We have demonstrated the deployment of a pair of novel fibre optic AE sensors for linear location on an aluminium plate. The sensor system for the AE linear-location involved the use of a single light source and serial multiplexed sensors. A number of repeat experiments were conducted and the position of the AE source was identified to within ±5mm. The sensor configuration can be extended to enable triangulation and the feasibility of multiplexing the AE sensor with strain and temperature sensors will be reported shortly.

6. Acknowledgements
The authors gratefully acknowledge the financial support from the DTI LINK (FOASMIE) Project.

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