Fibre optic pressure sensing arrays for monitoring horizontal and vertical pressures generated by travelling water waves

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***Abstract*— Distributed pressure sensing arrays fabricated from fibre Bragg gratings have been demonstrated for real time monitoring of the dynamic sub surface pressures beneath water waves in a wave tank. Two sensing arrays were used to monitor horizontal and vertical pressures in the tank as periodic wave trains passed overhead. The horizontal and vertical arrays contained 90 and 35 sensing elements respectively spaced at 1 cm intervals allowing highly accurate spatial resolution to be achieved in both orientations. The wave tank paddle was programmed to generate wave-trains varying from ~5 cm to 30 cm peak-to-trough and the pressures measured using the fibre optic array were validated using commercial piezo electric pressure sensors and video image analysis. The length and sensor separation of fibre optic sensing array can be varied to suit the location under test, and the fibre optic elements make the devices inherently resistant to corrosion and electromagnetic interference.**

***Index Terms*— Wave tank instrumentation, fiber optic sensing, wave pressure, surf zone**

I. INTRODUCTION

Measurement and monitoring of sub-surface and sea/river-bed pressures provides an invaluable means of estimating a wide range of parameters associated with water surface dynamics including wave heights in the surf zone (required for sediment transport and storm surges analysis amongst others), tidal variations in estuaries, river elevations during floods and loads on coastal structures. To avoid issues with aliasing [1] [2] of the pseudo-periodic signals encountered during wave motion in these environments it is necessary to have multiple recording sites at separations less than or equal to half the typical surface wavelength and have a data acquisition speed that is at least an order of magnitude greater than the typical wave frequency. The sensors must be formed using a technology that is easy to deploy and recover, resistant to corrosion, and that does not require local power. Optical fibre sensors have now developed sufficiently to address all of these requirements and may provide a viable option for monitoring in regions including surf-zones, estuaries, groundwater aquifers and rivers. They also provide an opportunity to capture high spatial resolution data from laboratory experiments which traditionally rely on conventional piezoelectric pressure transducers or surface piercing capacitance probes which are both costly and relatively cumbersome in terms of having to run power and signal cables from each individual sensor.

In this paper we present a fibre optic pressure transducer design suitable for recording the relatively low pressure variations typical in sub-surface environments. We present results from a preliminary study of both horizontal and vertical pressure variations in a wave tank using arrays of these pressure transducers. A pair of fibre optic sensor arrays were used for the study; one consisting of 90 separate sensing elements located along the bottom of the tank and one consisting of 35 elements rising in a vertical column at the far end of the horizontal array. All sensors in the composite array were interrogated simultaneously using a solid state spectrograph set to an acquisition rate of 10Hz.

The sensor elements in both horizontal and vertical arrays were spaced 1 cm apart and were able to resolve variations in pressure of approximately 2 cmH_2O (note that this is not a fixed lower limit; it is determined by the 12-bit analogue to digital converter used in the data acquisition unit. Resolutions of <0.1 cmH_2O have been achieved using analogue data acquisition schemes). Since the technology is closely based on standard telecommunications fibre and equipment the optical feed into the array and/or the array itself could be extended in length, with total span lengths of >10 km being readily achievable. The total number of sensing regions is limited to 144 elements using the equipment currently available in our lab. This does not represent a hard upper limit to the sensor numbers however, and alternative off-the-shelf technologies are available that would allow the sensor numbers to be increased significantly [3].

II. THE OPTICAL FIBRE PRESSURE TRANSDUCERS

The pressure transducers used in our system were formed using Draw Tower Grating (DTG) arrays (FBGS, Geel, Belgium). These arrays contain a series of fibre Bragg gratings (FBGs) [4] written into the fibre during the fibre drawing process immediately prior to the application of a protective outer coating on the fibre. This results in significantly enhanced mechanical strength of the fibre compared to the more usual window stripping method of writing FBGs [5, 6]. FBGs have been described in great detail elsewhere [4] but, in brief, can be thought of as optical strain gauges that can be interrogated by observing the shift in wavelength reflected back from the element. Each FBG can be tuned to reflect a different wavelength of light; hence the entire array can be interrogated simultaneously by observing the optical spectrum covering the reflected peaks from every FBG in the array.

The pressure transducer design was based on that developed by some of the authors (JA & IU) for in-vivo measurement of peristalsis in the human gut [7, 8] and consists of a rigid metallic substrate into which one of the FBG elements of the DTG array was rigidly bonded. During the bonding process the fibre was constrained to form an arc, shown schematically in Figure 1, and was then covered with a tightly fitting pressure sensitive outer sleeve that induces a sideways deflection of the fibre towards the axis of the substrate (indicated by an arrow in the Figure) as the external pressure varies. The transducer design allows a second fibre to be positioned along the bottom edge of the substrate that can include an additional FBG element or to run a second array of FBG transducers from the end of the first array. In the first instance, the additional FBG can be used to overcome the inherent temperature sensitivity of the transducer, and in the second instance, the additional DTG array can be used to extend the overall length of the sensing array. The latter case was used for these experiments since the temperature of the wave tank was well controlled and variations in pressure over an extended length were of more interest for the study. In addition to this, the two voids running through the substrates can be used to route two more fibres along the transducer array to further increase the overall length of the sensing region.

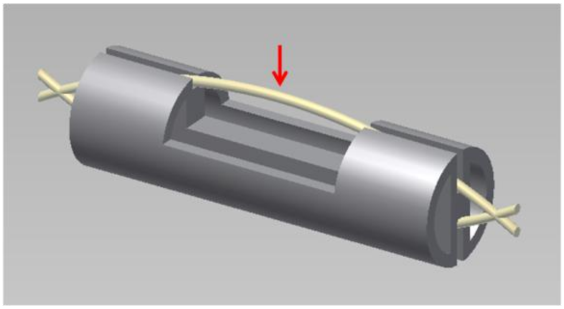
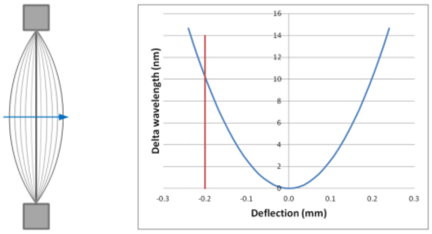


Fig. 1. Schematic of the fibre optic pressure transducer showing the arc-shaped pre-load applied to the fibre. Note the two voids running the length of the transducer on either sides of the fibres. These are used to carry additional fibres to increase the overall length of the sensor array.

The purpose of the arc shape put into the fibre is to increase the pressure sensitivity of the FBG strain gauge. This can be understood with reference to Figure 2 in which a fibre is shown held linearly between two fixed points and then distorted sideways in positive and negative directions. The plot shown in Figure 2b is the change in physical length of the fibre as a function of sideways displacement. Since the response of the FBG is related to the change in length of the fibre for a given displacement of the fibre, the sensitivity of a simply suspended FBG strain gauge has a quadratic dependence which goes through a minimum at zero displacement eg when the fibre is linearly disposed between the fixed points. To enhance the sensitivity of the FBG strain gauge, the operating point of the sensor can be shifted to a steeper part of the curve in either a positive or negative direction, indicated by the vertical line in Figure 2b.



(a) (b)

Fig. 2. Response of a linearly suspended fibre optic strain gauge to positive and negative sideways deflections. (a) shows the fixturing and deflection of the fibre; (b) shows the calculated change in arc length as a function of sideways displacement.

Normally, such a shift in the operating point would be limited by the elasticity of the fibre, but by constructing the FO transducer with a pre-loaded arc shape, this problem is overcome. We operate our transducers with a negative pre-load of ~0.2 mm, indicated by the vertical line in Figure 2b, so that increases in pressure cause a reduction in length of the fibre. Using a simplistic model in which the movement of the fibre is assumed to maintain a circular shape as it is distorted, and using a gauge length of 3.6 mm and a pre-load distortion of 0.2 mm to emulate our FO transducer design, we estimate the wavelength change for a 1 micron displacement of the fibre to be 0.1 nm. This is almost 400 times greater than the response of a similar 1 micron displacement from a linear position, and is the key to the enhanced sensitivity achieved using this design. Figure 3 shows a typical calibration curve for a fully assembled transducer; this device has a pressure sensitivity of -0.7pm/cmH_2O.

The sensor arrays are formed from a series of these transducers spaced at 1 cm intervals along the fibre and the pressure sensitive sleeve is applied to the whole array simultaneously; providing an easy means of manufacture for the sensing array. In operation, as the local ambient pressure is increased, for example as a wave passes over a given sensor in the array, the diaphragm is locally deformed and pushes the fibre towards axis of the array, causing longitudinal compression of the fibre, and hence a negative shift in wavelength that could be picked up via spectral interrogation using a solid state spectrometer (Fiber Scan 804, FBGS, Geel, Belgium). The spectrometer has 4 optical inputs and our DTG arrays can contain up to 36 discrete FBG elements, giving a maximum number of sensing elements of 144 using this configuration. Our composite 125 element sensor array contained 4 active fibres; 3 with 30 elements and 1 with 35 elements used for the vertical component of the array.

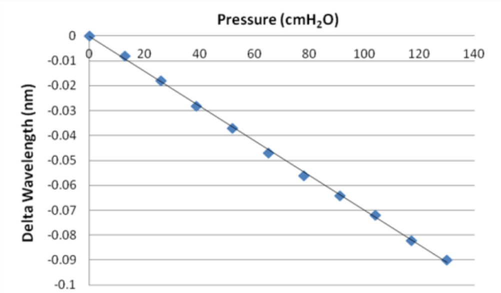


Fig. 3. Typical calibration curve for a fully assembled fibre optic pressure transducer; this device has a sensitivity of -0.7pm/cmH$_2$O.

III. EXPERIMENTS

Prior to use, the fibre optic sensor arrays were calibrated using a pneumatic pressure chamber. The two arrays were then placed in the wave tank as shown in Figure 4.

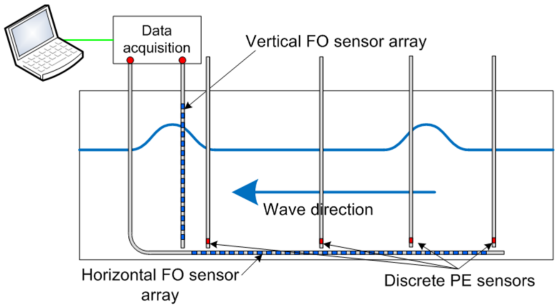


Fig. 4. Layout of wave tank and sensing arrays. Fibre optic (FO) arrays are shown in Blue, discrete electronic pressure sensors (PE) are shown in Red.

The horizontal array was fixed to a rectangular section steel bar using plastic cable ties in order to hold it in position on the bottom of the tank and the vertical array was fixed in a similar manner to a vertical steel rod located near the last sensor of the horizontal array. The wave tank paddle was programmed to generate regular periodic wave trains with heights varying from approximately 5cm to 25cm with a period of 2 seconds in a still water depth of 42cm. Each test condition was run for approximately 1 minute duration.

Each wave train was videoed to provide dynamic details of the height, shape, and length of each wave for subsequent comparison with the recorded data. Synchronization between the data and the video footage was achieved by simultaneously adding a marker pulse to the measured data and illuminating an LED that could be seen in the frame of the video camera. Figure 5 shows the profiles of each wave train once it had reached its steady state, derived by digitising the video images and recording the time-varying wave height at the location of the vertical sensor array.

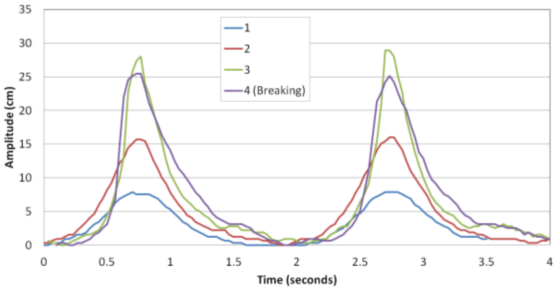


Figure 5: Wave shapes for increasing paddle amplitude. Note that the paddle amplitude for wave #4 was set to make the wave break as it passed over the sensing array.

To validate the fibre optic data against a known standard, 5 piezo electric pressure transducers were placed on the bottom of the wave tank close to sensor numbers 2, 21, 40, 59 and 85 of the horizontal fibre optic array. These sensors were calibrated prior to use using calibration factors supplied by the manufacturer and checked using a water column of known height.

IV. RESULTS

Figure 6 shows the responses from the horizontal fibre optic (FO) and piezoelectric (PE) transducers to an 11 cm wave train passing overhead in a mean water depth of 42 cm with peaks separated by 2 seconds. The inset in the figure shows a single frame from the video from this run.

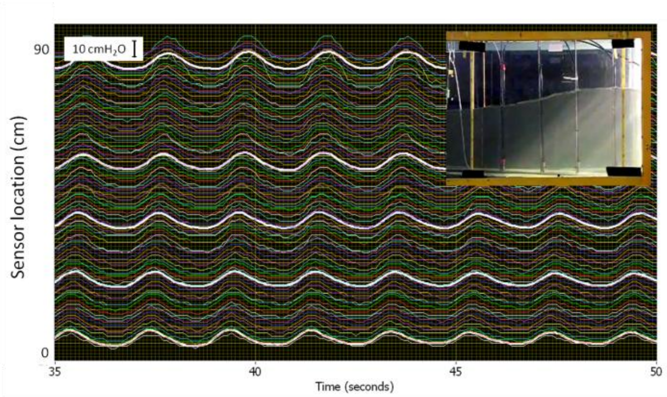


Fig. 6. Responses from the horizontal fibre optic (FO) and piezoelectric (PE) transducers to a 11 cm wave train passing overhead in a mean water depth of 42 cm with peaks separated by 2 seconds. The inset in the figure shows a frame from the video from this run.

Figure 7 shows similar responses from the horizontal fibre optic (FO) and piezoelectric (PE) transducers and a single video frame of a 24 cm wave train passing overhead in a mean water depth of 42 cm with peaks separated by 2 seconds. In this instance the wave parameters were chosen to cause the wave to break as the peaks passed over the sensor array and the asymmetric nature of the breaking wave is clearly seen on both FO and PE transducer plots.

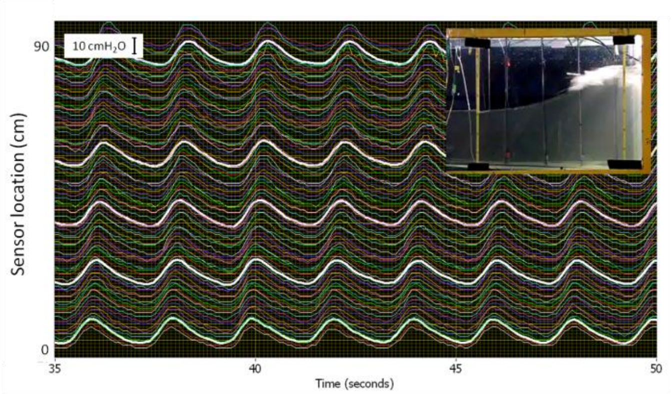


Fig. 7. Responses from the horizontal fibre optic (FO) and piezoelectric (PE) transducers to a 24 cm breaking wave train passing overhead in a mean water depth of 42 cm with peaks separated by 2 seconds. The inset in the figure shows a frame from the video from this run.

Figure 8 shows the correlation between a pair of co-located fibre optic and piezoelectric sensors during the passage of the 24 cm wave train. The average correlation is good, however the quantization of the 12-bit analogue to digital converter used in the data acquisition unit generates large error bars and the roll-off seen at high and low pressures. Figure 9 shows the peak-to-trough pressures recorded by all the sensors in the vertical array that remained below the surface during the passage of the wave trains. The data was averaged from 10 consecutive wave peaks recorded once the wave train had become established. The data shows a distinct reduction in pressure with increasing depth and the gradient becomes increasingly negative with increasing wave height. The dashed curves in Figure 9 are derived from non-linear wave theory [9] based on the wave shapes shown in Figure 5, and indicate a good fit to the measured values.

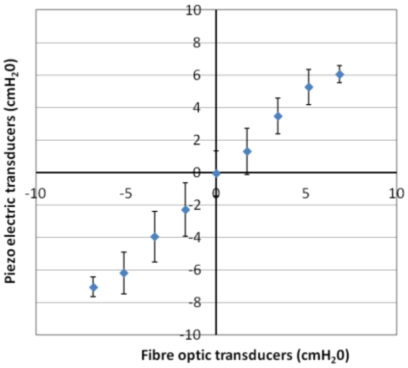


Fig. 8. Correlation between the fibre optic and piezoelectric transducers during a 24 cm breaking wave train.

The optical data acquisition system used during these experiments to interrogate the arrays was limited by an internal 12-bit analogue to digital converter which set the pressure resolution of the system to approximately 2 cmH$_2$O. This is not a fundamental limitation however, and to demonstrate this the data from a single sensor was monitored using a spectral detector that allowed dynamic monitoring of the optical spectrum rather than providing a digitised output of each reflected wavelengths from each transducer. Data was gathered while a sinusoidal pressure variation was applied to the transducer in a sealed pressure vessel. In this instance the resolution was better than 0.1 cmH$_2$O.

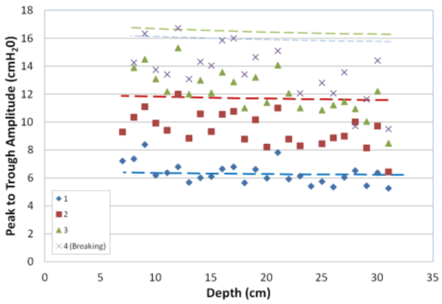


Fig. 9. Peak-to-trough pressures recorded by all the sensors in the vertical array that remained below the surface during the passage of the wave trains, for measured wave heights of 8, 16, 28, 25 cm (the 25 cm wave was breaking as it passed the sensor array). The data was averaged from 10 consecutive wave peaks recorded once the wave train had become established. The dashed curves show theoretical data calculated using nonlinear wave theory.

V. CONCLUSIONS

A pre-loaded fibre optic pressure transducer has been fabricated that is capable of recording the small variations in pressure typical of sub-surface wave induced pressure fluctuations. The transducer had a resolution of ~2 cmH$_2$O which was limited by the analogue to digital converter in the data acquisition unit used for the tests. A single transducer has been tested using an analogue detection scheme and resolutions of <0.1 cmH$_2$O have been demonstrated. The transducer is based on a fibre Bragg grating structure and can be readily formed into distributed sensing arrays containing >100 individual sensing elements. The technology has been proven by monitoring pressure variations in both horizontal and vertical orientations in a 10.5 m long wave tank and is suitable for scaling up to large sensing arrays for monitoring in real life situations such as surf-zones, estuaries, groundwater aquifers and rivers. The sensors also provide an opportunity to capture high spatial resolution data from laboratory experiments which traditionally rely on conventional piezoelectric pressure transducers or surface piercing capacitance probes.

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