CHARACTERISATION OF INTELLIGENT DISTRIBUTED ACOUSTIC SENSOR IN COMPARISON WITH VIBROACOUSTIC SENSORS

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1 INTRODUCTION

Distributed acoustic sensor technology offers a new way to monitor oil and gas resources. The operating principal for this technology is based on interference effects in optical fiber that are associated with the optical time domain reflectometry. The backscattered centres form low contrast Fabry-Perot interferometers, which are illuminated by optical pulses travelling along the fibre. A major limitation of many disturbance sensors based on this approach is that they are incapable of determining the full acoustic field – namely the amplitude, frequency and phase of the incident signal. The new measurement technique – intelligent Distributed Acoustic Sensor (iDAS™) was developed and successfully tested by Silixa Limited to remove this limitation for determination of the amplitude, frequency and the distance of an acoustic event. The iDAS technique has been applied for downhole measurements of flow, sound and seismic vibration. In this paper we will compare the iDAS performance with standard laboratory measurement tools such as tri-axial accelerometers and hydrophones.

The operating principle for the iDAS is illustrated in Figure 1; a pulse of light travels down an optical fibre, a small amount of the light is naturally scattered in the fibre and returns to the sensor unit. The iDAS utilises a novel optoelectronics architecture that uniquely measures the modulation of the backscattered light. The acoustic field around the fibre exerts tiny pressure/strain changes onto the fibre. The iDAS measures these pressure changes at a rate of up to several kilohertz and so can be used to measure the acoustic field.

![Distributed Acoustic Sensor (DAS)](image)

Figure 1 - The Intelligent Distributed Acoustic Sensor (iDAS™) provides digital acoustic measurements along the entire length of single mode fibre.

This paper offers physical characterisation of the iDAS signals. Firstly, the amplitude and phase linearity of the iDAS system will be tested by means of laboratory experiments. Using the same
experimental setup, the IDAS signal is then compared with that of conventional acoustic sensors. Some acoustic modelling of the experimental setup was also designed in order to better understand the nature of the IDAS signals.

2 METHODS

2.1 Amplitude linearity study

In this test, an 8 cm PVC tube measuring 1.5 meters in height was wrapped with several tens of meters of fibre optic cable, mounted vertically, and filled with water, as shown in Figure 2. A compact underwater speaker (MA001, Aqua Symphony) was submerged at the top of the pipe and was used to transmit 35 second waveforms of linearly increasing amplitude and constant frequency. Four frequencies (100Hz, 200Hz, 1kHz and 2kHz) were tested within the bandwidth of the speaker. A hydrophone (CS-3, supplied by GST, UK) was positioned in the centre of the tube, and acted as a reference receiver.

The sound waves were acquired simultaneously by the IDAS and the hydrophone, and the signals were post-processed with Matlab (The MathWorks Inc., Natick, MA). The IDAS was setup to acquire at a sampling rate of 50kHz and a measurement length of 256m.

The post-processing was performed over a section of fibre positioned around the location of the hydrophone. For each tested frequency, the amplitude was plotted as a function of time.

![Experimental setup for the acquisition of sound waves.](image)

2.2 Phase linearity

The phase linearity of the IDAS was tested using a fibre stretcher (PZ1, Optiphase, CA). An arbitrary waveform generator (AWG, Agilent Technologies, CA) was used to transmit to the stretcher a linear sweep of frequencies ranging from 10Hz to 40kHz over a duration of 30 seconds and amplitude of 1Vpp. The IDAS was setup to acquire at a sampling rate of 150kHz over a distance of 256m. The waveform recorded by the IDAS was post-processed with Matlab and the change of frequency content was calculated as a function of time.

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2.3 Comparison of iDAS with accelerometer signals

A tri-axial accelerometer (4524-B, Brüel & Kjær, Denmark) was attached to the exterior of the plastic pipe, at the same height as the hydrophone. Each transmitted waveform consisted of a few seconds of continuous wave, followed by 4 short bursts at the same frequency. The frequencies tested were 100Hz, 250Hz, 500Hz, 1kHz and 2kHz. The waveforms were recorded simultaneously by the iDAS (sampling rate 50kHz, recording duration 15 seconds, measurement length 256m), the hydrophone and the accelerometer. The results from the 1kHz transmission only, will be described in the results section.

The radial component of the accelerometer was used to measure the radial acceleration experienced by the pipe during the acoustic transmission, and was converted into radial displacement. The radial displacement of a thin-walled pipe was also estimated following equation (1), using the pressure measured by the hydrophone and knowing the composite properties of the pipe.

\[
\frac{dR}{R \cdot dP} = -\frac{\xi R}{Y_t (1 - \nu)} (1 - \frac{\nu}{2})
\]  

(1)

where \( R \) is the pipe radius, \( dR \) its radial displacement, \( Y \) the Young’s modulus of the pipe material, \( t \) its wall thickness, \( \nu \) its Poisson’s ratio and \( dP \) the pressure differential. \( \xi \) is the strain optic coefficient which is assumed to be 0.71.

2.4 COMSOL Modelling

The Acoustic-Structure interaction Module of the multiphysics modelling package COMSOL V4.3a was used as a complementary study to 2.3, to model the radial acceleration of the pipe subject to a pressure wave. A 2D-axisymmetric approach was used (Figure 3), where only half of the longitudinal cross-section was solved, with the following initial conditions: applied acoustic plane wave radiation of pressure 50Pa, the base of the pipe was constrained as fixed, all other walls were set as free. The maximum radial acceleration was calculated for a point sensor located half way up the pipe and for a frequency range of 10Hz to 2kHz with a step of 10Hz.

![Figure 3 - Modelling setup of the PVC pipe used in the experiments.](image)

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2.5 Dynamic Range

The dynamic range of the iDAS was tested, as shown in Figure 4, by elongating the fibre via a pulley system, at a rate of 1kHz. The acquired signals were compared with the z component of a tri-axial accelerometer.

![Dynamic range test setup](image)

Figure 4 – Dynamic range test setup

3 RESULTS

3.1 Amplitude linearity

The following five figures (Figure 5 to Figure 8) show the response in amplitude to the transmitted ramps of the iDAS signal and compares it to the recorded hydrophone reference signals.

Both Figure 5 and Figure 6 show that the change in iDAS amplitudes at 100Hz and 200Hz respectively, follow the hydrophone reference signal very closely. At 200Hz, the pressure level could be increased up to 200Pa, and the iDAS signal amplitude shows strong linearity in that higher amplitude range.

![Amplitude linearity at 100Hz](image)

Figure 5 - Amplitude linearity at 100Hz
At 1kHz, as shown by Figure 7, the iDAS signal closely follows the hydrophone signal, but also starts to exhibit limited excursions from the reference amplitudes.

These excursions are also visible at 2kHz. As shown in Figure 8 the iDAS exhibits stronger amplitude variations around the hydrophone reference signal at 2kHz than at 1 kHz.

### 3.2 Phase linearity

Figure 9 shows the calculated frequency content over time of the iDAS signal, recorded at the fibre stretcher, subject to a linear sweep. The graph displays strong phase linearity between 10Hz and 2kHz.
15kHz as well as between 22kHz and 40kHz. The spikes appearing between 15kHz and 22kHz correspond to the resonance region of the stretcher and make the phase linearity interpretation difficult at these frequencies.

Figure 9 - Linearity in phase of the iDAS signal, shown by the linear increase in frequency over the duration of the sweep.

3.3 Comparison of iDAS signal with reference sensors

The following three graphs in Figure 10 to Figure 12 show the transmitted 1kHz waveform, recorded simultaneously by the hydrophone, the radial accelerometer and the iDAS.

Figure 10 - Hydrophone signal measured inside the pipe, at 1kHz.

Figure 11 - Radial acceleration measured on the outside of the pipe, at 1kHz.
Figure 12 - IDAS signal measured on the corresponding fibre section, at 1kHz.

The hydrophone measured a pressure of 50Pa (Figure 10) in the middle of the pipe. Using equation (1) leads to an estimated radial displacement of the pipe of 4nm.

The radial acceleration was measured to be of 0.5m/s\(^2\) (Figure 11). After integrating it twice, at 1kHz, this leads to an estimated radial displacement of 12.6nm.

The modelling results show that a standing wave is formed in the water between the speaker and the bottom of the pipe. This has an influence on the stresses and strains observed by the walls of the pipe, i.e. both stresses and strains also oscillate in a standing wave form, closely mimicking that of the acoustic wave inside the pipe.

At 1kHz, as shown in Figure 13, the model predicts a maximum radial acceleration of 0.05m/s\(^2\), which leads to a radial displacement of 1.2nm, which is 3 times less than what was measured by the accelerometer.

Figure 13 - Maximum radial acceleration predicted by the model for a point sensor placed half way up the pipe across a wide frequency range.

A fair comparison between modelling results and observed accelerometer readings presents challenges, particularly with respect to spatial bias. In these tests, an accelerometer was placed on the outer wall of the pipe half-way down the pipe. It has been shown in the modelling that the spatial response of the system is however non-uniform as a result of standing waves. The distributed signal recorded on the fibre represents a global average over a limited region of interest, whereas the point sensor is clearly only representative of the acceleration at the exact point of contact between the sensor and the structure. As a result, it is difficult in a simple test to ensure that the physical dynamics driving the IDAS response are identically matched to those driving the accelerometer. It is presumable that greater accuracy in the comparison can be obtained by
referencing the iDAS output to a multi-element array of point sensors arranged over the entire optically-sensed region.

3.4 Dynamic Range

The results of fibre elongation measurements are presented in Figure 14, where the iDAS signals are compared with the z-axis acceleration measurements at 1kHz. Elongations ranging between 10nm to 10mm were detected by the IDAS, corresponding to a dynamic range of 120 dB.

![Image](image)

Figure 14 – Fibre elongation tests demonstrate a 120 dB dynamic range.

4 CONCLUSION

This paper shows that the iDAS exhibits a linear response in both phase and amplitude, over a wide range of frequencies. A dynamic range 120 dB was demonstrated. The frequencies tested were limited to the bandwidth of the loudspeaker and the sampling rate of the iDAS. Future work will demonstrate such capabilities over an even wider range of frequencies.

5 REFERENCES