A fibre laser sensor seabed array

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ABSTRACT

We have developed an 8-element fibre laser seabed array demonstrating state-of-theart performance characteristics for a fibre laser sensing system and highlighting the potential capability advantage this technology provides in the underwater sensing domain. The system employs sea-state-zero sensitivity hydrophones with a flat acoustic response over a bandwidth exceeding 5kHz and very low inertial sensitivity. Each hydrophone is pressure compensated to an ocean depth exceeding 80m. The system contains no outboard electronics and virtually no metal components making it extremely light, compact, and low complexity. The array may be deployed up to 4 km from a land or sea based platform. Power is delivered optically via a single 2mm diameter optical fibre lead weighing less than 5kg per km. The same optical fibre also serves as the telemetry link to relay full bandwidth data from all 8 sensors back to the platform.

INTRODUCTION

At the 2012 Australian Acoustical Society Conference in Fremantle we provided an overview of the general principles of interferometrically interrogated fibre laser sensors (FLS) and reported the status of an 8-channel FLS seabed array system under development by Defence Science and Technology Organisation (Foster et al. 2012a). The purpose of this development is to bring together a number of technological advances in the field – many of which have been reported elsewhere (Foster et al. 2005, 2006, 2011; Goodman et al. 2009) – into an ocean deployable system and to establish a set of performance benchmarks representing the broad start-of-the-art. In a related activity, DSTO is also engaged with Thales Australia under the Defence Capability Technology Demonstrator (CTD) program to transition FLS technology to industry and develop operationally focussed demonstration systems. Under this program Thales have developed a fibre optic towed array (FOTA) which is reported elsewhere in these proceedings (Souto 2013).

In the current paper we shall report on the performance of an 8-element seabed array system, focussing on the integration of the hydrophone elements into a robust array structure.

SYSTEM OVERVIEW

The basic architecture of our n-channel wavelength division multiplexed (WDM) fibre laser sensor system is shown in Figure 1. Optical power from a pump laser at 1480nm is launched via an optical fibre telemetry cable into an array of compact fibre lasers deployed to the environment (the “wet end” in Figure 1). Each fibre laser produces light at a unique wavelength λ_n that is extremely sensitive to changes in its local environment. The mechanical coupling of the laser to its environment will determine the sensor configuration (in the current context each sensor is coupled as a hydrophone). Light from each laser is relayed back to the “dry end” via the telemetry fibre and the information encoded on each laser wavelength is extracted using a technique called interferometric demodulation (Koo and Kersey 1995). For the purposes of demodulation it is useful to think in terms of monitoring laser frequency fluctuations rather than wavelength changes.

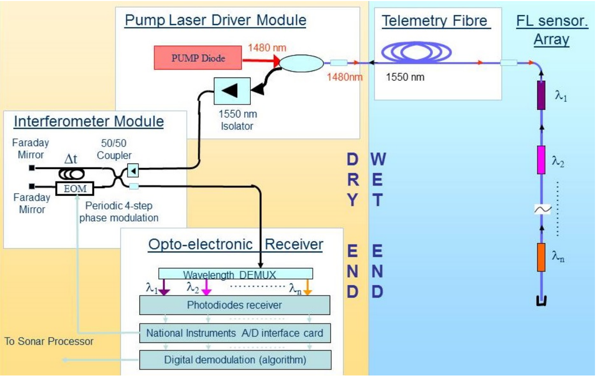

Figure 1. Multiplexed fibre laser array system.

We have previously described our dry end module and interferometric demodulation technique in considerable detail (Foster et al. 2012a, 2012b). The detection bandwidth is 5kHz and the frequency resolution has been verified as less than 5Hz/√Hz which is well below the intrinsic thermodynamic noise of the sensors themselves (Foster et al. 2009). All dry-end components have been integrated into a single $57\times47\times27\text{cm}^3$ transport case with the total weight being less than 30kg (Figure 2).

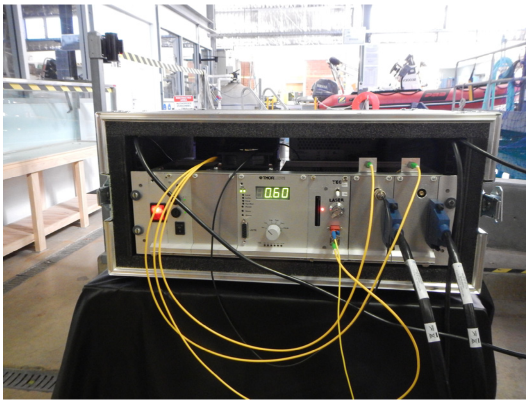

Figure 2. Dry-end components in transport case.

One of the key features of fibre optic systems is the capacity for remote deployment without the need for any local instrumentation or power sources. Our system is designed to be deployable over a range of up to 4 km and is currently configured with a 4km telemetry cable. Operation of the system with up to 11km of lead-in cable has been verified in the laboratory. The lead-in cable has a diameter of 2mm and weighs approximately 5kg/km making the system extremely lightweight and compact. The total weight of all wet-end components, including the array, is around 20kg.

In the remainder we shall describe the acoustic array module in some detail.

HYDROPHONE

Our hydrophones are an evolved variant of the FLS sensor previsouly described in Foster et al. (2011). We fabricated the hydrophones from three silicon wafers of width 5mm and length 70mm, bonded together to form a 2mm×5mm×70mm structure. A 15mm long × 1mm wide × 0.5mm thick beam was fabricated in the upper wafer by means of a potassium hydroxide (KOH) wet etching process. A recess was etched in the middle wafer immediately below the beam which enables movement of the beam and forms the internal cavity. A small hole etched through the base of the middle wafer connects the internal air volume to the external environment via a 6mm × 25µm ϕ groove etched into the upper surface of the lower wafer which functions as a capillary.

To mount the FLS sensor a groove was cut on the upper side of the upper plate (the beam) into which a DFB fibre laser was uniformly bonded. A thin polymer sheet was bonded to the upper surface of the top plate providing a seal to the internal volume. The only way that air can flow in or out of the internal volume is via the capillary which acts as a low pass acoustic filter with a cutoff frequency of approximately 30Hz. In this way the hydrophone design permits pressure equalisation. Pressure variations at higher frequency may not be equalised by the capillary but cause the wall of the volume to flex, thereby moving the beam. The FLS is then sensitive to acoustic pressure above 30 Hz, but is insentitive to DC changes in external pressure due to the equilisation. This is critical for a functioning hydrophone due to the severe depth dependence of external pressure (Goodman 2009). The assembled structure is shown in Figure 3.

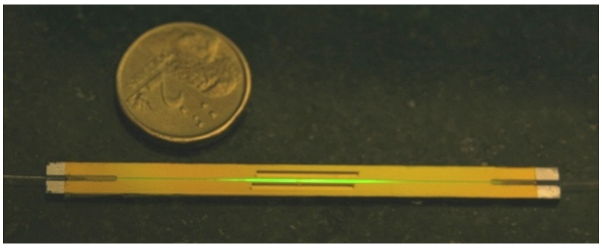

Figure 3. A “bare” fibre laser hydrophone showing green fluorescence from the laser sensor. A 2 dollar coin is shown for scale.

This structure differs from that previously reported in the slimmer profile, the addition of acoustic filtering and the FLS strain sensor being mounted to the external surface of the hydrophone. This latter change has two noteable implications. Firstly, the FLS no longer lies on the neutral axis of the overall hydrophone structure making it potentially more sensitive to mechanical flexure of the housing (this issue needed to be carefully managed in the integration of the sensor into the array structure). Secondly, the additional requirement that the optical fibre be flush with the upper surface of the silicon housing necessitated etching the groove deeper thereby reducing the displacement *d* of the fibre core from the neutral axis of the flexural beam by about 60µm. Because the responsivity of the sensor is directly proportional to *d* the effect was to reduce the hydrophone responsivity by about 1.4 dB from 107dB re Hz/√Hz (Foster et al. 2011) to a nominal 105.5dB re Hz/√Hz. As shown in Figure 4 the average measured responsivity across our 8 hydrophones was slightly lower than this figure for reasons that are not fully understood. Also note that our measurement is noisy above 1 kHz. The responsivity figure should be read from the low frequency region of the graphs in Figure 4. The upward trend above 5kHz is associated with the fundamental beam resonance at 15kHz

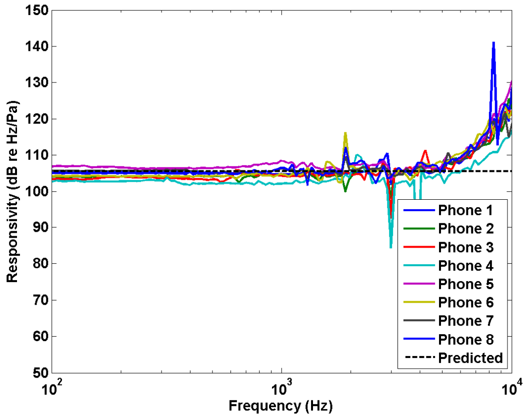

Figure 4. Responsivity of the 8 FOSA hydrophones. The dashed curve shows the theoretical expected responsivity.

Based on the responsivity measurements we inferred the noise-equivalent-pressure (NEP) based on the known frequency noise spectrum of the FLS (Foster et al. 2009). As shown in Figure 5, with the marginal exception of hydrophone 4, all sensors have noise floors below sea-state-zero (Cato 1997) for frequencies above 50Hz. Note that the two noise spikes at 50Hz and 500Hz respectively are artifacts of our noise measurements.

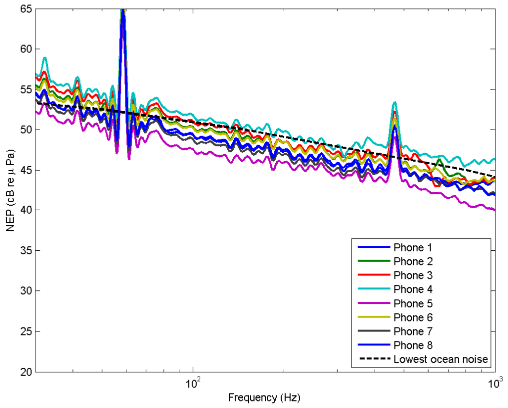

Figure 5. Noise floor of the FOSA hydrophones relative to lowest-ocean-noise (Cato 1997)

ACOUSTIC ARRAY MODULE

In order to be deployed into the ocean environment the hydrophones need to be integrated into a robust array structure. The dashed curve in Figure 6 shows the response of a bare hydrophone freely suspended in water. The peak at 9kHz is the fundamental resonance of the flexural beam (reduced from 15kHz in air due to additional fluid loading) which essentially determines the bandwidth of the sensor. The additional feature at 2kHz is the fundamental resonance of the silicon housing and represents a parasitic vibrational mode of excitation. To decouple this mode from external vibrations the sensor is suspended by rubber bands (acting as weak springs) within a rigid aluminium shell sealed with a soft polymer film (Figure 7). To damp residual vibrational excitations the housing is filled with a viscous fluid (castor oil) whose acoustic impedence is well matched to water. The response of the fully encapsulated hydrophone is shown as the blue curve in Figure 6. Note that the resonance at 2kHz has been almost completely suppressed. Indeed the "wobbles" in the curve are actually a residual artefact of the reverberent acoustic field in the tank, which our measurement technique only partially compensated. We believe the true response to be virtually flat from 30Hz to 7kHz.

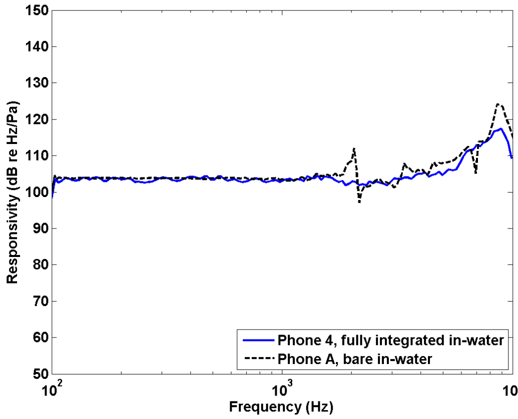

Figure 6. Responsivity of the fully integrated FOSA hydrophone showing a flat response over the full 5kHz design bandwidth.

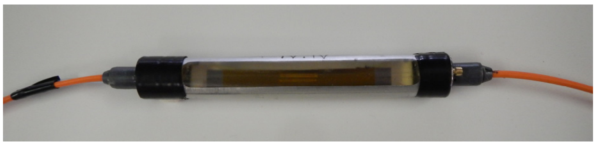

Figure 7. Fully assembled hydrophone.

To enable the internal pressure within the hydrophone to equalise to the external pressure, a free-flooding tube is attached to a pipe in the housing that connects with the aforementioned capillary structure of the bare hydrophone. The depth to which pressure compensation can be achieved is simply a function of the length of this tube. The system is currently pressure compensated to a depth of more than 80m.

To form the array, the 8 fluid filled hydrophone modules are connected via 3mm PVC jacketed fibre optic cable with Kevlar strength members terminated on the aluminium outer housing to provide strain relief. The separation between the sensors is 1.5 m resulting in an array cut-off frequency of 500Hz. Note however that the bandwidth of each individual hydrophone is limited by the 5kHz bandwidth of the in-board detection and demodulation system.

CONCLUSION

We have described an 8-hydrophone seabed array system that demonstrates the state-of-the-art performance characteristics of fibre laser sensing technology as applied to the problem of underwater acoustic detection. A key advantage of the technology is that the sensors are powered optically, thus eliminating the requirement for electronic components at the wet-end.

The array has sea-state-zero sensitivity, a flat response over a bandwidth exceeding 5kHz, and is pressure compensated to a depth exceeding 80m. It can be deployed and monitored remotely (up to 4km away) via an optical fibre link. The entire wet-end system (array plus fibre link) weighs approximately 20kg, providing a rapid deployment capability that is almost inconceivable with conventional piezo-electric sonar transducer technology. The first at-sea trial of the FOSA system is scheduled to take place on the 19th of September 2013 in the Gulf St. Vincent, South Australia.

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