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UNDERWATER SOUND DETECTION WITH A TAUT, VERTICALLY SUSPENDED FIBRE-OPTIC CABLE AND DISTRIBUTED ACOUSTIC SENSING

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ABSTRACT

The use of Distributed Acoustic/Vibration Sensing (DAS/DVS) for underwater sound detection with taut, vertical cables suspended in the water column is proposed. DAS is robust to extreme temperature/pressure conditions and inherently delivers concurrent, dynamic strain measurements at meter-resolutions with overlapping sensing elements over hundreds of meters. DAS also relies on dry-room interrogators and is generally known to have lower sensitivity than most hydrophones. Our approach consists of active sound generation in a fjord environment with a shallow, submerged source and detection with an adjacent, taut cable and a co-located, calibrated hydrophone. We present preliminary observations of the vertical propagation and attenuation of sound and estimates of Sound Pressure Level (SPL) detection thresholds in the 0.5-3.0 kHz range. We also observe a widespread occurrence of trapped waves along the cable below approx. 1 kHz. In comparison to rectilinear set-ups, we observe that cable coiling strategies can effectively add-up gains of nearly +20 dB to hydroacoustic signals, thus effectively decreasing the SPL detection threshold of DAS, extending its ambient noise detection range and reducing the minimum required source levels for active measurements.

Keywords: *Fibre optics, hydroacoustics, marine sensors*

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1. INTRODUCTION

Most marine sound measurements are based on sparse autonomous hydrophone nodes deployed in e.g. mooring lines or sea bottom installations. Node arrays can often be constrained by battery consumption at low temperatures, depth ratings, maintenance requirements, limited data storage or complex data transmission. Such drawbacks are avoided when using Distributed Acoustic/Vibration Sensing (DAS/DVS) [1, 2], a technique that effectively converts a fibre-optic (FO) cable into an array of dynamic strain sensors. DAS/DVS belongs to a broader group of photonics technologies known as Fibre Optic Sensing (FOS). These leverage the differential response of guided light along an optical fibre (e.g. for telecommunication) in response to external stimuli. DAS/DVS, for instance, is particularly sensitive to mechanical strain caused by e.g. impacts, pressure variations or impinging seismoacoustic waves. These techniques have gained notoriety in past decades due to their potential in wide variety of (on/offshore) applications, including environmental monitoring, energy production and surveillance [3].

While most underwater FOS studies implement quasi-horizontal, seafloor-coupled cables (e.g. buried on the seafloor), here we explore the underwater sound detection capacity of a taut FO cable vertically suspended in the water column. Specifically, the detected signals are described, and a minimum detectable SPL is estimated.

2. EXPERIMENT DESCRIPTION

A 50 m-long conventional, single-mode FO cable OFS 004f (simplex, loose fibres embedded in gel-filled plas-

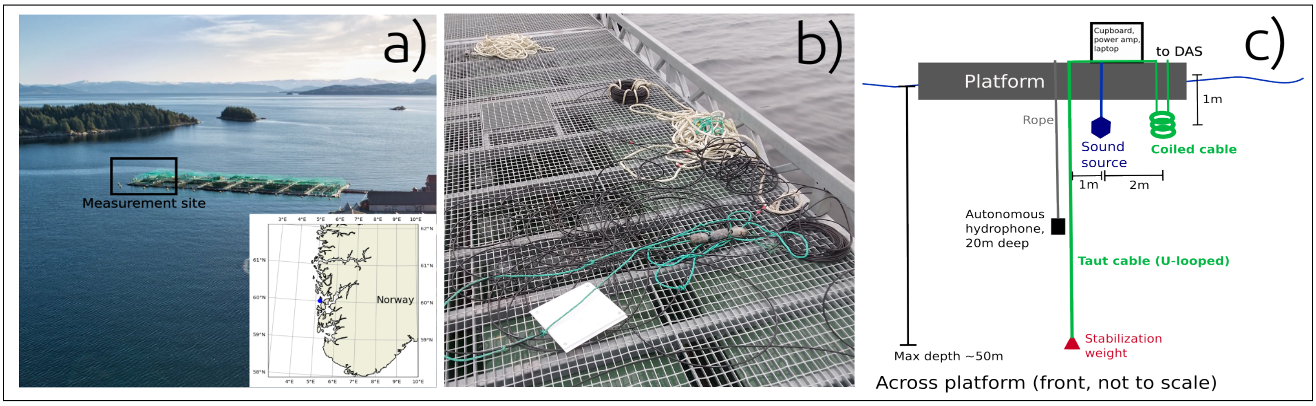

Figure 1. a) Site of the experiment in Austevoll, Western Norway (https://www.hi.no). b) cable used in the experiment (black). The white plates were used to protect the U-looped end of the fibres. Ropes were used to attach the stabilization weights. The coil can be seen in the background. c) sketch of the experiment geometry

tic buffer tube protected by a rubber jacket, 8 mm outer diameter) is suspended vertically from a floating aquaculture platform nearly down to the bottom of a fjord (Fig. 1). Two fibres running parallel inside the cable are spliced ("U-looped") at its submerged end so that both are interrogated in series. A rope with weights is attached to the submerged tip of the cable to keep it at fixed position and taut, and to prevent undesired cable oscillations prone to saturate the DAS signal when sufficiently strong. This implies that acoustic waves couple directly from the water into the cable, and are not in contact with, or embedded in a solid medium (e.g. sediments, soil), as in the vast majority of DAS/DVS studies [3].

The FOS interrogator is based on a $\Delta\phi$-OTDR (Optical Time Domain Reflectometry) scheme with a 3x3 imbalanced Mach-Zehnder interferometer [4]. A Differentiate and Cross-multiply algorithm is used to retrieve optical phase variations. This output is proportional to the axial fibre strain. The gauge length was fixed at 5 m, the pulse length at 4 m, and the pulse repetition rate at 20 kHz.

A Lubell LL916 underwater loudspeaker, which is nearly omnidirectional around 1-2 kHz, is submerged 1 m below sea surface, 1 m laterally from the cable axis. To estimate the acoustic pressure detection threshold along the span of the cable, 1 kHz-bandwidth linear chirp signals of 500 ms duration and center frequency increasing at 1 kHz steps are transmitted. A calibrated, MTE μAural hydrophone is located a few cm's from the cable at 20 m depth. For comparison, an additional segment of the same cable (80 m) was coiled (mean diameter of 40 cm), fastened and submerged at 1 m depth, as shown in Figs. 1b,c. During the experiment, the weather was calm, i.e. no rain, light breeze, and smooth sea surface.

3. RESULTS

Fig. 2 depicts the power spectral density (PSD) spectrograms of transmitted chirp signals and the respective hydrophone and DAS/DVS recordings on the taut and coiled segments of the cable. The ambient noise floor was close to 100 dB re 1 μPa. It can be seen that the hydrophone detects background noise signals from unrelated sources that are not present in the fibre (e.g. at 38 s). The taut cable manages to detect chirps up to nearly 3 kHz with max. signal-to-noise ratio (S/N) of 17 dB in the 1-2 kHz band. Remarkably, signals are recovered at 37 dB S/N with the coil in the same band, even when its separation from the source is nearly the same as that of the shallow segment of the taut cable. However, it is worth noting that the latter segment is affected by the broadside insensitivity of DAS due to rays arriving at steep-to-normal angles to the cable [2]. Higher frequencies (including higher-order harmonic overtones) are recovered by the coil up to 10 kHz, with an average S/N of 18 dB at 5 kHz.

By assuming spherical spreading and disregarding sound absorption at the short distances considered, the active source level (SL) can be estimated to first order from the measured hydrophone SPL_r using the model:

$$\mathrm{SL} = \mathrm{SPL}_r + 20\log_{10}(r_{sr}) \tag{1}$$

where r_{sr} is the source-receiver distance. The same trans-

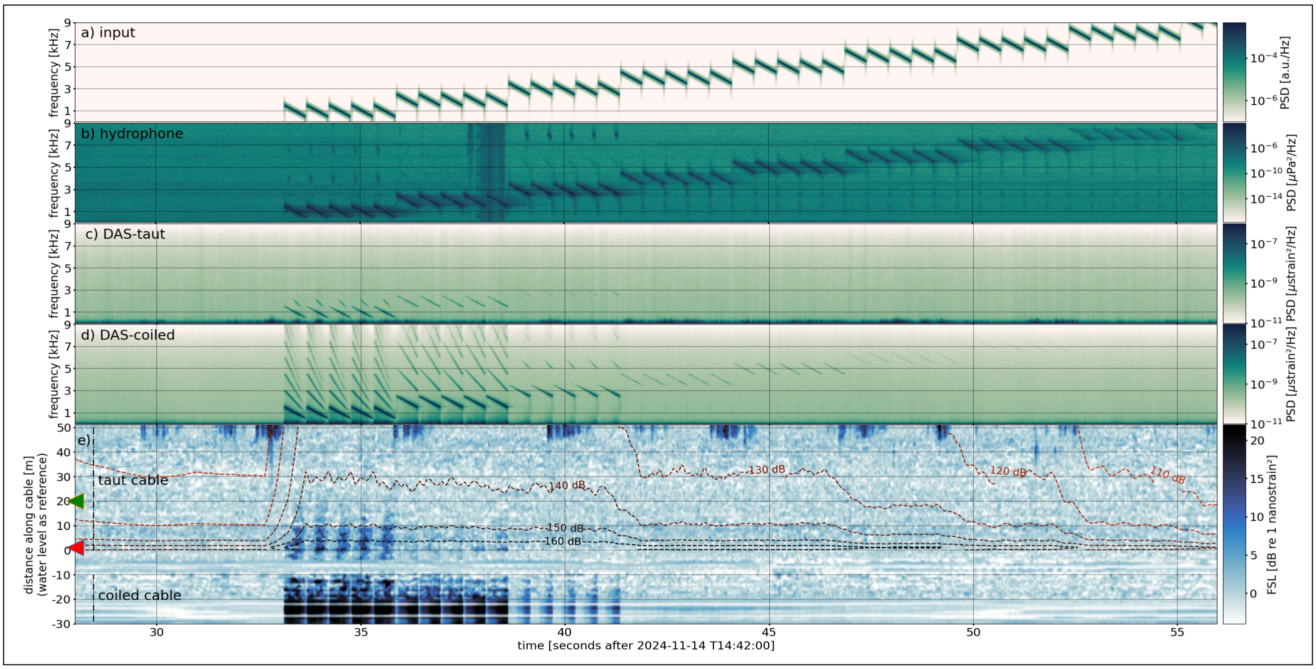

Figure 2. PSD of a) input signal, b) hydrophone recording, c) depth-averaged taut (first 10 m) and d) 60 m of coiled cable measurements. e) DAS time-range FSL of taut cable and a coil segment between 0.5-9.0 kHz. The contours represent the modeled SPL from the sound source (in dB re 1 μPa) assuming spherical transmission loss. The red and green markers pinpoint the DAS channels closest to source and hydrophone, respectively.

mission loss model allows us to estimate $\mathrm{SPL}(r)$ as a function of source-DAS channel separation, r by using the empirically estimated SL. The SPL detection threshold lies close to 140 dB for this DAS-cable set-up (Fig. 2e). This nearly corresponds to a 0 dB re 1 nanostrain *fibre strain level* (FSL), here defined as $10\log_{10}(s_{\mathrm{rms}}^2/s_0^2)$, where s_{rms} corresponds to the RMS value of the measured fibre strain signal and s_0 is a reference strain, here taken as 1 nanostrain, which is a typical sensitivity of commercial DAS systems. As the source is nearly aligned with the cable axis, it is expected that this detection threshold is directly related to the DAS-cable system sensitivity limit. Higher frequencies on the contrary, may be differentially affected by asymmetric source radiation patterns.

Although the cable was kept taut, data from its bottom end indicates sporadic low-frequency noise (dominant below approx. 500 Hz). Figs. 2e and 3 confirm that this corresponds to trapped waves generated at the submerged end of the cable, bouncing down along its structure with phase speeds close to 2 km/s and likely induced by near-bottom currents strumming the mass loaded end. Note that the occurrence of these noisy signals is not synchronous with the transmitted sound.

4. DISCUSSION

Preliminary results suggest an upper sound detection frequency limit close to 3 kHz for the taut cable with our DAS configuration. The well-known broadside insensitivity of the fibre may explain the lack of detected noise signals. Altogether, these factors limit the capacity of conventional cables for ambient noise monitoring. Additionally, sound below 500 Hz may superpose in frequency with cable wave propagating along the cable. However, using heavy weights properly attached to the hanging cable tip greatly reduced this cable ”whipping” effect.

The coiled segments of cable effectively extended the sensitivity range up to at least 10 kHz due to the confinement of gauge lengths into a smaller volumes. It also improved the directional response, increased S/N through multiple channel stacking and is expected to allow detection of sound down to -20 dB below that of the taut ca-

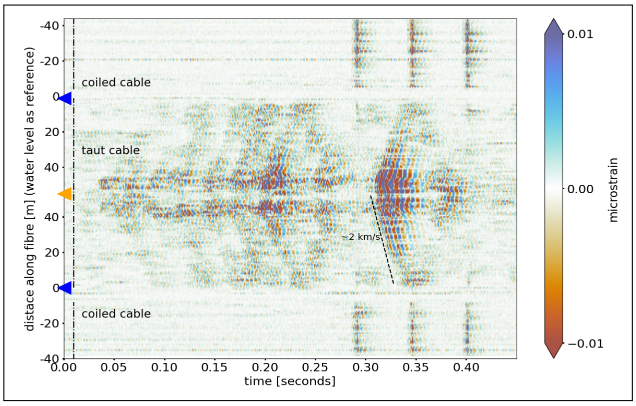

Figure 3. Trapped waves radiating from the deep end (orange marker) of the taut cable (filtered at 0.1-1.0 kHz). Blue markers indicate the shallow ends. The horizontal symmetry is due to the fibre U-loop

ble threshold. This approach is akin to that of FO hydrophones [5], where fibre is wrapped around a mandrel and used as point sensor. Here instead, no mandrel was implemented. FOS cable installations for ambient noise detection could rely on a number of coils at strategic positions in order to increase S/N and be used as matched filtering templates for detection of weak signals on the stretched cable. A recent study showed how a special, helically wound cable can be used as a seismic streamer while towed from a ship [6]. More generally, ensemble cross-correlation and stacking processing approaches (e.g. beamforming) are also known tools to improve S/N of array measurements, such as those provided by DAS/DVS.

The taut cable detection threshold of around 140 dB re 1 μPa for the highest S/N (at 1 kHz) is thought to be largely influenced by the optical noise floor of the interrogator system. However, the detection capacity of shorter wavelengths could be improved with shorter gauge lengths, whereby higher resolutions are achieved at the expense of lower S/N ratios. At the same time, FOS is a fast-developing field and performance improvements in the optical interrogation process are continuously emerging that could improve the detection capability [3].

5. CONCLUSIONS

We have presented preliminary results of underwater sound detection with a suspended FO cable and DAS/DVS. Our results highlight the capacity of a conventional FO cable to detect hydroacoustic waves when it is either taut and vertically suspended in the water, or coiled. The latter configuration has a notably higher detection capability compared to the former. As expected from the broadside insensitivity of straight fibres, the detected waves in the taut cable are those propagating quasi-vertically, i.e. nearly parallel to the fibre axis, while others arriving at high incidence angles (e.g guided sound waves from distant sources) are hardly detected, if at all. Compared to most hydrophones, our data suggests a relatively low underwater sound sensitivity for a conventional, taut FO cable, with minimum detection thresholds at approx. 140 dB re 1 μPa. However, we underline the possibility to improve the detection capacity through a number of strategies discussed in the previous section.

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