Improved noise performance of a DFB fibre laser SONAR array using a frequency reference

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Abstract- **A reference frequency stabilised DFB fibre laser is used to reduce the interferometric detection system noise within optical fibre laser sensor (FLS) SONAR arrays by up to 20-30 dB.**

I. Introduction

Arrays of fibre laser sensors (FLSs) for SONAR applications have been presented in various configurations with a common property that the underwater acoustic waves modulate the frequency of the fibre laser [1-6]. Typically, the FLS lasing wavelength responds linearly to the acoustically induced FLS strain [7]. Although the optical fibre used to make the FLS itself will readily withstand strain of ~10mε the magnitude of the acoustic waves combined with the best hydrophone actuator designs dictate strain resolutions of ~10 p ε / √ Hz. To allow detection of such small strains and correspondingly small frequency variations, interferometers with a long optical path imbalance are used. The unbalanced interferometer converts the FLS's centre frequency modulation into a phase, and ultimately, intensity modulation. The sensitivity of this method can be enhanced by increasing the path imbalance. However, the imbalance cannot be made arbitrarily long as the interferometric detection system (IDS) is limited by signal-to-noise issues, largely arising from environmental noise. These issues have been addressed through active stabilization of the interferometer path imbalance using a frequency reference [8]. In this paper, we present a passive method where the path imbalance is allowed to drift with environmental perturbations and a frequency stabilized reference laser is used to characterise the path imbalance in real time. The output of the IDS for the reference laser is then simply subtracted from the response of all the FLSs in the SONAR array. A similar approach has been used by He et al. [9] in an array of passive fibre Bragg grating sensors.

II. Background

The IDS shown in Fig. 1 above provides the laser frequency to phase and intensity conversion mentioned in the introduction. A Michelson interferometer is configured with an optical fibre delay coil in one arm to provide the optical path imbalance. The Michelson includes a Faraday Rotator Mirror (FRM), on each arm, to minimize polarisation fringe fading. The acousto-optic modulators (AOMs) in each arm provide a small frequency shift to the light as it traverses through each AOM, providing a means of optical heterodyne detection. Since the light passes through each AOM twice, the light is frequency shifted by twice the drive frequency applied to each AOM. The output from each FLS in the array is interrogated using a single IDS. The separate FLSs are then de-multiplexed using a telecommunications wavelength division multiplexer/de-multiplexer (WDM). The acoustically induced laser frequency conversion is then seen at the audio output by mixing the IDS outputs from the WDM with a local oscillator at twice the difference in the drive frequencies of the two AOMs. The IDS phase for the i_{th} laser in the array can be described as

$$\phi_i = {4\pi \Delta L n f_i}/{C} \qquad (1)$$

Where ΔL is the fibre length difference, n is the fibre's effective refractive index, C is the speed of light in a vacuum, and f_i is the centre frequency of i_{th} laser in the array.

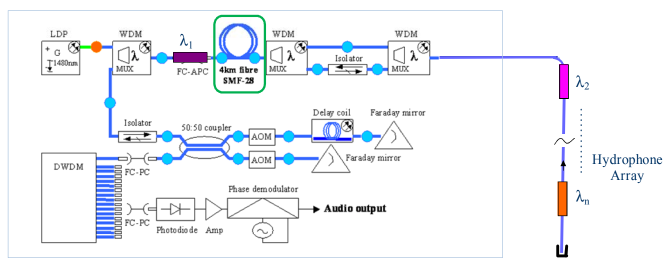

Figure 1: The FLS SONAR array system architecture

Ideally the variation in the output phase, ϕ_i, is due entirely to variations in the centre frequencies f_i . However the terms ΔL, and n are also subject to small changes or perturbations due to environmental factors such as temperature variations and acoustically induced vibrations. This can be thought of as a form of IDS induced noise and it can be remarkably sensitive. The unbalanced interferometer itself has been widely used as the basis of an optical fibre hydrophone [10]. However, an important observation here is that these perturbations are common to all FLSs in the array.

Using this insight in this experiment, one FLS was assigned as a frequency stabilized reference laser and it was mechanically isolated from external environmental perturbations. The IDS was then effectively characterised by looking at the reference laser response. The response of all the other FLSs in the array was then corrected for the IDS induced noise simply by subtracting the reference laser response from all the FLS sensors in the array. An additional advantage of this method is the reference laser response also includes any small instabilities, or noise, in the AOM drive frequencies. This results in a means of real time characterisation and correction for both electrical and optical noise in the IDS.

Effective implementation of this method requires a stabilized reference laser. Improving the frequency stabilization of spectrally narrow lasers has been studied extensively using various methods such as Pound-Drever-Hall [11, 12] – and these methods have already been applied to optical fibre lasers: for example, by Lam *et al.* [13]. In this demonstration, we mechanically isolate a free running FLS from external environmental perturbations and use this as the frequency reference with which response of the remaining FLSs are compensated. For demonstration, a SONAR array containing 8 FLSs was used with the first FLS assigned as the frequency reference and the remaining 7 FLSs assigned as acoustic sensors. The system architecture shown in figure 1 above represents the applied embodiment with the reference laser marked λ_1 and the FLSs marked λ_2- λ_n. In this demonstration, the reference laser remained in the array.

A. First demonstration

An acoustic perturbation was applied by periodically tapping the enclosure housing the IDS. The response of the reference laser is then scaled and subtracted from the response of all 7 FLSs. The system output was both played through a speaker and recorded as a .wav file. The reference subtraction was performed in real time using LABview and the .wav file was also processed to determine the signal-to-noise improvement.

B. Second demonstration

An acoustic perturbation was created at a specific audio frequency using a sinusoidal function generator and an audio speaker. The speaker was place directly on top of the IDS enclosure. Three test frequencies were applied i.e. 40, 64 and 106Hz.

III. RESULTS & DISCUSSION

The system response obtained in the first demonstration is illustrated as a noise power spectrum. The results shown in Fig 2 (Upper) show a factor of 100 to 1000 (20 - 30dB) reduction in the noise floor up to about 1.5 kHz when the frequency reference is applied. The ratio of frequency components with and without the frequency reference correction is shown in red as a noise reduction ratio (Fig 2 Lower).

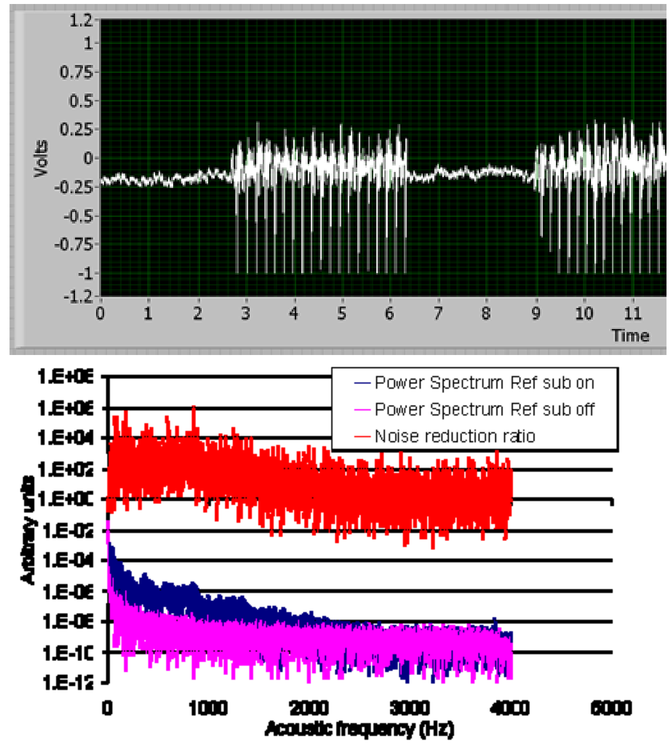

Figure 2: Upper: First demonstration system response with and without reference correction. Lower : System noise spectra

The system response chart shown in Fig 2 (Upper) clearly shows the capability to correct for the continuous tapping of the first demonstration. In the chart, the reference correction is initially switched on and then switched approximately every 3 seconds.

To further quantify the improvement the recorded data was processed to determine a noise spectrum. Fig 2 (lower) shows both the noise spectra with and without the reference correction and also the ratio of frequency components. A resulting improvement of 20-30dB up to approximately 1.5kHz can be seen with an apparent roll-off in improvement beyond 1.5 kHz. The roll-off is more likely to be due to an absence of any components to the acoustic perturbation in the higher frequencies ranges than any roll-off in the effectiveness of the method. More rigorous experiments over a broader frequency range are required to accurately identify the full potential of this method.

The system response in the second demonstration was recorded graphically and can be regarded as a qualitative demonstration of the effectiveness of the reference correction method at a specific frequency only.

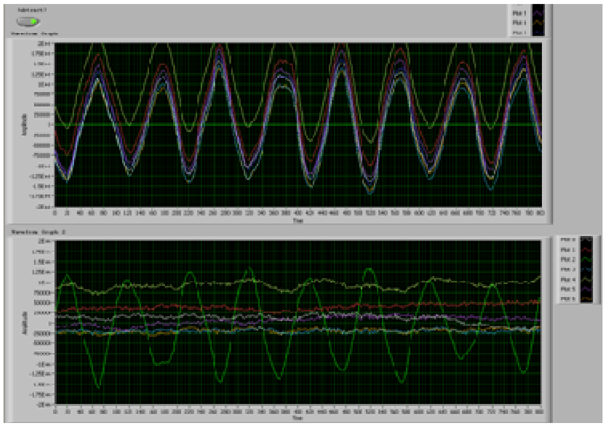

Figure 3: Second demonstration. Upper: Raw system response with a 64 Hz acoustic perturbation and without reference correction. Lower: System response with reference correction.

The system response, shown in Fig 3 (Upper), shows a clear response at 64Hz for all FLSs in the array except one. One demodulation electronic card was simply not working, resulting in a flat line response. The reference corrected response shown in Fig 3 (Lower) laser shows, graphically, effective correction for all functioning FLSs in the array. The FLS that shows a clear response at 64Hz (Fig 3 Lower) was the FLS with the faulty demodulation card and should be ignored.

IV. Conclusion

This reference correction method characterises in real time the common mode effects in the IDS. This includes not only environmentally induced changes in effective path imbalance, but also any instability in the RF and local oscillators used in the optical heterodyne detection (OHD) system. These factors greatly relax the design specifications for both packaging the unbalanced interferometer and its various components and also the electronic specifications for RF and local oscillators used in the OHD system. However, this method depends on a suitable highly stable frequency source. Since the FLS's used in the SONAR array have been designed for enhanced strain to frequency conversion, it seems that there is an opportunity to design and package a reference laser for reduced strain to frequency conversion. Laser thermal noise [14, 15] will likely be the limiting factor in the final frequency stability. If successful, the signal-to-noise performance improvements are sufficient to warrant rapid adoption of this technique since the added complexity by introducing a single frequency reference laser at the dry end of the detection system is insignificant.

Acknowledgements

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