DESIGN CONSIDERATIONS FOR A DFB FIBRE LASER BASED HIGH SENSITIVITY BROADBAND HYDROPHONE

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1 INTRODUCTION

Over the last three decades extensive research has been carried out towards the design and development of fibre optic hydrophones. The inherent advantages of fibre optic sensing technology, like high sensitivity, immunity to electromagnetic interference, intrinsic safety to water leakage, remote measurement capability etc. makes it an ideal choice for underwater acoustic sensing[1, 2]. The initial designs focused on strain sensitivity enhancements through coatings and coiling long fibres on compliant mandrels [3-5]. With the advent of fibre brag gratings and fibre lasers with very high sensitivity to strain, the focus has shifted towards development of fibre laser based hydrophones for underwater water acoustic sensing[6]. In this paper, we present the major design considerations in the development of mechanical encapsulation for distributed feedback fibre laser (DFB-FL) based high sensitivity broadband hydrophone. DFB-FL is a laser cavity created on a rare-earth element doped fibre by introducing a π/2 shift in the Bragg grating written on the fibre[7]. When pumped with external laser source, DFB-FL generate very narrow band laser at a wavelength that depends on parameters like the grating pitch, refractive index of the fibre and emission bandwidth of the dopant. DFB-FL hydrophone works on the principle that any changes in the above parameters caused by the pressure changes due to an acoustic wave will result in corresponding change in wavelength of the DFB-FL. Thus the acoustic signals can be measured by monitoring the changes in the wavelength of the laser generated by the fibre laser.

2 DESIGN CONSIDERATIONS

The performance parameters of the of the DFB-FL hydrophone system like sensitivity, pressure resolution, dynamic range and harmonic distortion will depend on the pressure sensitivity of the active sensing region as well as on the parameters of the interrogation system used. Even though significant sensitivity improvements can be achieved by the use of interferometers, the intrinsic frequency noise from the fibre laser would still limit the achievable pressure resolution. Thus, the sensitivity improvements through interferometers often do not directly translate into corresponding improvements in measurement resolution. At the same time, a very high sensitivity value can also introduce harmonic distortion and reduce the effective dynamic range of the sensor. Hence, any improvements in the pressure resolution demands the improvement on the pressure sensitivity of the active sensing region, i.e. wavelength shift in DFB-FL output due to pressure changes in the acoustic wave. Under the assumption of constant operating temperature, the wavelength (λ_L) change of the fibre laser output can be written as in equation 1, where ε is the strain; n_e is the refractive index and p_{11}& p_{12} are the strain optic coefficients[8].

$$\frac{\partial\lambda_L}{\lambda_L} = \left(\varepsilon_z - \frac{n_e^2}{2}\left((p_{11}+p_{12})\varepsilon_r + p_{12}\varepsilon_z\right)\right) \quad (1)$$

For the cases where the sound pressure directly acts on the DFB-FL and the wavelengths of the acoustic waves are much larger than the dimensions of the DFB-FL, equation 1 can be rewritten as in equation 2 below, where, E and ν are the Young's modulus and Poisson's ratio of the fibre and P is the pressure amplitude of acoustic wave.

$$\frac{\partial\lambda_L}{\lambda_L} = \left(1 - \frac{n_e^2}{2}(p_{11} + 2p_{12})\right)\frac{2\nu - 1}{E}P \qquad 2$$

From equations 1 & 2, it can be observed that the wavelength shift of fibre laser output is directly proportional to the strain. Hence, for a bare fibre the wavelength shift produced by the sound pressure is very small (which is of the order of 8×10^{-16} for a *Sea-State 0* acoustic noise floor) owing to the very high modulus of the glass fibre. At the same time, the inherent noise floor of our DFB-FL expressed noise equivalent strain is 8×10^{-13} (which is one order of magnitude higher than experimental results reported in the literature [9]). This implies that for a successful operation of the DFB-FL based hydrophone down to a sea state 0 (ambient noise of 40dB ref 1μPa), the pressure sensitivity need to be improved by 2-3 orders of magnitude.

The requirement of high sensitivity over a broad operating frequency range imposes conflicting constraints on the design configuration. In order to achieve flat sensitivity response characteristics in the frequency range of interest, the sensor needs to operate reasonably below the first resonant mode of the system. For any mechanical system, the resonance frequency is directly proportional to the square root of the ratio of stiffness and mass corresponding to the resonant mode. Hence a broad operating frequency range demands the packaging or the active sensing region to have a high stiffness. At the same time, as cited before, high-pressure sensitivity requirement demands the sensor to be more pliant and hence of lower stiffness. Thus the design process involves achieving an optimum value of stiffness while minimizing the value of mass associated with the first natural mode.

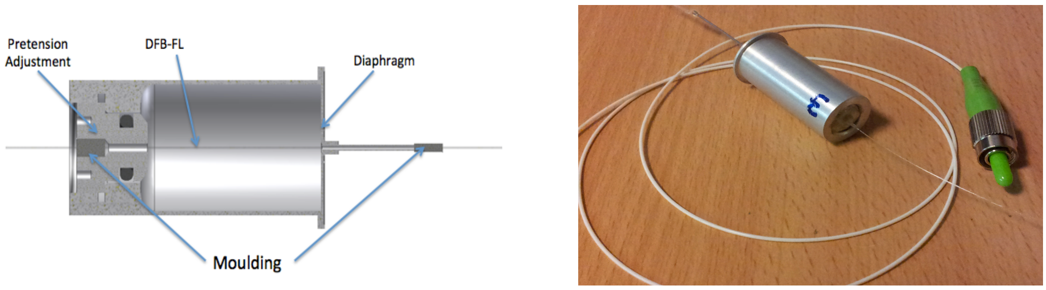

Figure 1 A prototype DFB-FL hydrophone design

3 DFB-FIBRE LASER HYDROPHONE DESIGN

One of the major design concepts gaining momentum in the recent years is diaphragm-based design of fibre laser hydrophones[10, 11]. Zang et al[12] presented a double diaphragm based hydrophone design and explored the effects of diaphragm material properties on hydrophone performance. In these designs, the focus was on increasing the pressure sensitivity and the high frequency performance is limited by the presence of mechanical resonances of the diaphragm. A diaphragm based design configuration to achieve the desired performance parameters in frequency range 0-5kHz is arrived at based on the guidelines from the previous section. Figure 1 shows the design configuration and a prototype sensor. The fibre is centrally placed inside the aluminium packaging with one end of the fibre glued to the diaphragm and the other end to a pre-tensioning arrangement. The diaphragm-based design amplifies the strain introduced onto the fibre by effectively increasing the active sensing area of the sensor. The deflection of the diaphragm due to the acoustic pressure variations will result in corresponding strain variations, which appears as a frequency modulation of DFB-FL output. Two major factors that determine the frequency response characteristics of the sensors are the fundamental natural frequency of the diaphragm and effective stiffness of the diaphragm. The added mass effect from the surrounding water will increase the total mass associated with the natural mode and hence reduces the natural frequency of active sensing region. Equations 3 and 4 gives respectively, the fundamental natural frequency [13]and effective stiffness [14] of an annular plate constrained at outer edge. In equations 3 and 4, C and C_y are constants, ρ is the density and h, a, b are the thickness, outer diameter and inner diameter of the diaphragm respectively. The basic dimensions of the diaphragm were selected based on above equations so that the first natural frequency of the diaphragm is much higher than the frequency band of interest and the stiffness of the diaphragm is of the same order as that of fibre stiffness. In order to optimize the stiffness and mass values associated with modes of vibration, aluminium was selected for fabrication of packaging owing to its low density and high modulus to density ratio. O-rings and end moulding provide adequate sealing required to maintain an air cavity inside the aluminium packaging.

$$F = \frac{C^2}{2\pi a^2}\left[\frac{Eh^2}{12\rho(1-\nu^2)}\right]^{\frac{1}{2}} \quad (3)$$

$$K_d = \frac{2\pi b}{C_y}\frac{E}{12(1-\nu^2)}\left(\frac{h}{a}\right)^3 \quad (4)$$

3.1 Finite Element Analysis

FEA analysis of the proposed design configuration was carried out using ABAQUS® software to optimize the design parameters. Fluid structure interaction effects between aluminium shell and fluids (air in side the cavity and surrounding water) were taken into account in the model to include the effects of fluid loading on the sensor performance. Steady state dynamic analysis was carried out over the frequency range of interest to predict the sensitivity and frequency response characteristics of the sensor. Plane wave excitations were applied on the sensor using acoustic propagation models available in ABAQUS. Non-reflecting impedance boundary condition was applied on the outer boundary of external fluid domain. Figure **2** and Figure **3** show the results from Axi-symmetric finite element model of the DFB FL based hydrophone. Figure **2** shows a typical scattered pressure distribution for plane wave excitation and Figure **3** shows variation of strain response of DFB-FL hydrophone with excitation frequency over a frequency band of 0-10kHz.

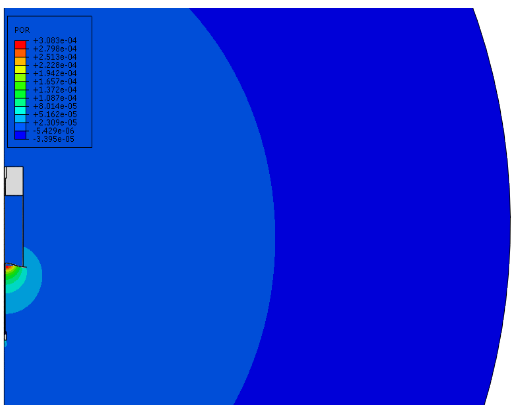

Figure 2 Scattered Pressure Distribution from Axis-symmetric analysis

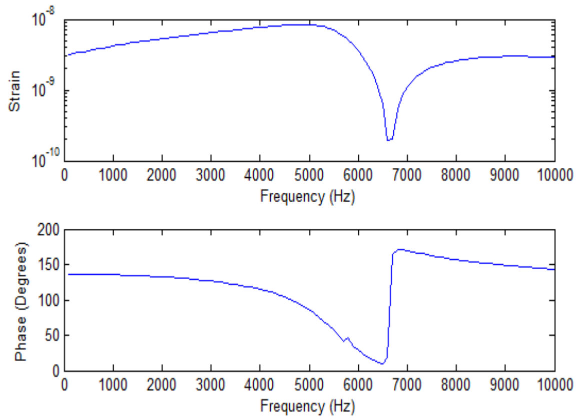

Figure 3 Strain Response for a 120dB acoustic excitation

3.2 Experimental Setup

The experimental set up used to evaluate the acoustic characteristic of the DFB-FL hydrophone is shown in figure. A Phase Generated Carrier (PGC) demodulation technique as detailed in [15] is used in the measurement. The performance of the FOH was compared against a standard hydrophone B&K 8104 for the acoustic pulses transmitted using B&K 8105 projector.

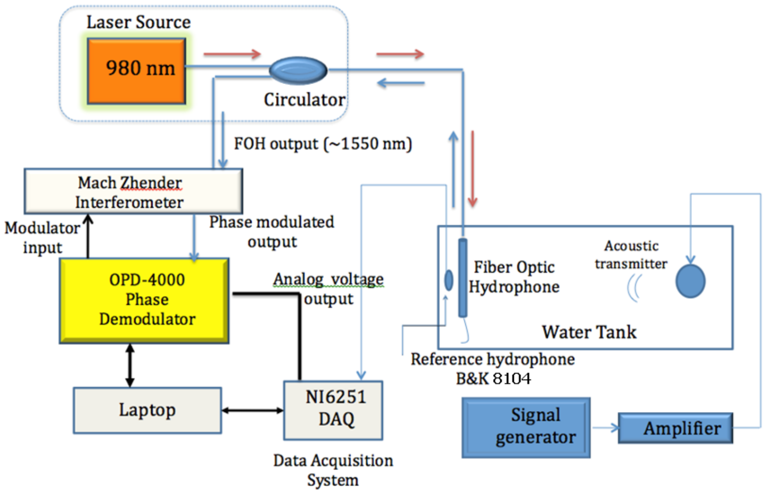

Figure 4 Experimental Setup

4 RESULTS

Figure 5 shows the comparison between the experimental results with the simulation results obtained from FEA. The results from the proposed design are also compared with a bare DBF-FL coated with 60micrometer thick UV curable resin coating. Even though the FEA simulation predicts a sensitivity improvement of the order of 30 dB over the Frequency range of interest, sensitivity values measured from the prototypes are off by approximately 10dB. This could be due to the imperfect modelling of the moulding of the fibre to the diaphragm and to the pre-tensioning arrangements. The low modulus value of EVA (Ethylene-vinyl acetate) based glue, used in the design, may affect the strain coupling between the fibre and the diaphragm, and may result in reduced sensitivity. Even with this limitation, the prototype showed a sensitivity improvement of the order of 15-20dB over DFB-FL with a thin protective resin coating.

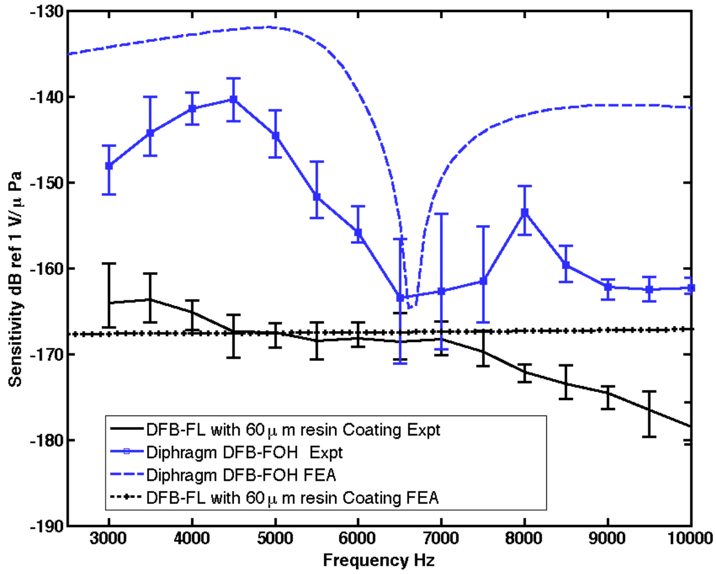

Figure 5 Comparison of Experimental results with FEA results

5 CONCLUSION

We have presented the key design considerations in the development of a DFB-FL based broadband high sensitivity hydrophone. A diaphragm based DFB-FL hydrophone is developed and tested. The proposed design showed a sensitivity improvement of the order of 15-20 dB over the frequency band of interest. Even though the FEA simulation results showed similar frequency response pattern as the experiment, the response values were 10 dB off from the experimental results. This deviation could be due to the imperfect modelling of the moulding of fibre on to the diaphragm. We are currently working on the cause of this deviation and modification of the moulding techniques to improve up on the sensitivity values.

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