FBG Hydrophone: Theory and Experiment

Wen-Tao Zhang, Fang Li, and Yu-Liang Liu

Abstract—A fiber Bragg grating (FBG) hydrophone with enhanced sensitivity is demonstrated. A novel piston-like diaphragm with a hard core fixed at the center is used as the sensing element. Theoretical analysis shows that the Young’s modulus of the diaphragm and the radius of the hard core have significant effect on the pressure sensitivity. Experiments are carried out to test this effect and the performance of the hydrophone. The static measurement result is in good agreement with the theoretical result and an acoustic sensitivity of 7 nm/MPa has been achieved.

Index Terms—Diaphragm, fiber Bragg grating, hydrophone.

1. Introduction

Fiber optic hydrophones have been one of the most promising acoustic detection devices in future operational sonar systems due to their high sensitivity, wide dynamic range, immunity to EMI, and feasibility in multiplexing[1]. Many conventional fiber hydrophones are based on Mach-Zehnder or Michelson interferometers, which include a sensing leg and a reference leg. The fiber is usually wound on a plastic cylinder. However, the multiplexing of the interferometric fiber hydrophones is complex[2], and the dimensions of this type of hydrophone cannot be very small[3]. So, fiber Bragg grating (FBG) hydrophones become popular for use in under water acoustic detection[4]-[6]. In the past several years many configurations for FBG hydrophones and pressure sensors have been demonstrated. These include bare FBG[4], [5], polymer coating on bare FBG[6], and shielded polymer coating of FBG[7]. However, such correction methods are likely to work better if the dimensions are reduced while the sensitivity is enhanced. In this letter, we report a new FBG hydrophone with enhanced sensitivity that uses a thin metal cylinder and a piston-like diaphragm. Owing to the greater deformation of the diaphragm with a hard core in the center, thin dimensions and an ultra high sensitivity have been achieved.

2. Principle of Measurement

The proposed FBG hydrophone is shown in Fig. 1. The water comes into the hydrophone from the sensing hole and acts on the surface of the piston-like diaphragms. The diaphragm, which is made of rubber, is pressurized in the axial direction, creating an axial tension strain in the FBG. A hard core, which is made of copper, is affixed at the center of each diaphragm to enhance the sensitivity and to fix the fiber. Several assumptions and design considerations should be stated before the analysis. The operating range is restricted to small displacements so that the linear elasticity theory can be used and only low frequencies (20 Hz to 1000 Hz) are considered to avoid dealing with acoustic scattering. The static pressure sensitivity is assumed to be equal to the dynamic pressure sensitivity[8], [9], so that we can use static mechanics analysis. Because the Young’s moduli of the sensor shell and the hard core (132 GPa) are much higher than that of the rubber (less than 0.1 GPa), and the acoustic pressure we measure is always less than 1 kPa, we only consider the deflection of the rubber diaphragm. Finally, the FBG is considered to be perfectly fixed to the rubber diaphragm.

Fig. 1. Schematic of the hydrophone.

Having stated the assumptions, let us now begin the analysis. The displacement at the center of the diaphragm under the acoustic pressure $p$ is given by[10]

$$w_r = \frac{P}{64D} \left( R^4 - r^4 + 4R^2r^2 \ln \frac{r}{R} \right)$$

(10)

in which the following notation is used:

$$D = \frac{Et^3}{12(1-\mu^2)}$$

(2)

where $R$ is the radius of the diaphragm, $t$ is the thickness of the diaphragm, $r$ is the radius of the hard core, $E$ is the Young’s modulus of the diaphragm, and $\mu$ is the Poisson’s ratio. When the diaphragm deforms under the pressure, it induces the tension force $T$ in the fiber, which can also be
given as

$$T = \varepsilon_f A E_f$$  \hspace{1cm} (3)

where $\varepsilon_f$ is the axial strain in the FBG, $A$ is the cross section area of the fiber, and $E_f$ is the Young’s modulus of the fiber. The displacement at the center of the diaphragm caused by force $T$ is \[^{10}\]

$$w_T = \frac{TR^2}{16 \pi D} \left[1 - \left(\frac{r}{R}\right)^4 + 4 \ln \left(\frac{r}{R}\right) \left(\frac{r}{R}\right)^2 \right]$$  \hspace{1cm} (4)

From $\varepsilon_f = \frac{2(w_T - w_f)}{L}$, where $L$ is the fixed length of the FBG, we obtain the strain in the FBG \[^{11}\]

$$\varepsilon_f = \frac{p}{64 D} R^4 \left[1 - \left(\frac{r}{R}\right)^4 + 4 \left(\frac{r}{R}\right)^2 \ln \left(\frac{r}{R}\right) \right]$$  \hspace{1cm} (5)

The pressure sensitivity, defined as the fractional change in Bragg wavelength, is given by \[^{12}\]

$$\frac{\Delta \lambda_B}{\lambda_B p} = (1 - p_e) \varepsilon_f$$  \hspace{1cm} (6)

where $p_e = 0.22$ is the effective photo-elastic constant of the fiber.

Substituting (5) for $\varepsilon_f$ in (6), the sensitivity of the hydrophone is

$$\frac{\Delta \lambda_B}{\lambda_B p} = \frac{(1 - p_e) R^4}{64 D} \left[1 - \left(\frac{r}{R}\right)^4 + 4 \left(\frac{r}{R}\right)^2 \ln \left(\frac{r}{R}\right) \right]$$  \hspace{1cm} (7)

From (7) we can find that the radius of the hard core has a significant effect on the sensitivity when the radius of the diaphragm is restricted to a small size (for example, the radius of the diaphragm is 4 mm in our configuration). From (2), we find the Young’s modulus of the diaphragm also has a significant effect on the sensitivity, because the Young’s modulus of the rubber varies widely (from 1 MPa to 10 GPa)\[^{13}\]. To predict the likely gain in sensitivity of the FBG hydrophone, the effects of the Young’s modulus of the diaphragm and the radius of the hard core are evaluated. The values of the parameters in our evaluation are shown in Table 1, and the result is shown in Fig. 2.

As Fig. 2 demonstrates, the Young’s modulus has significant effect on the sensitivity. If the Young’s modulus is low, the highest sensitivity appears when the ratio of $r/R$ is about 0.3. Furthermore, the lower the Young’s modulus is, the higher the ratio of $r/R$ that yields the maximum sensitivity becomes. On the other hand, if the Young’s modulus is higher than 50 MPa, the predicted sensitivity monotonically decreases without having a maximum when the radius of the hard core increases.

### Table 1: Parameters used in the configuration

<table>
<thead>
<tr>
<th>Parameter Value</th>
<th>Parameter Value</th>
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<tbody>
<tr>
<td>$L$ 8 cm</td>
<td>$t$ 1 mm</td>
</tr>
<tr>
<td>$A$ 0.0123 mm$^2$</td>
<td>$R$ 3.5 mm</td>
</tr>
<tr>
<td>$r$ 1.2 mm</td>
<td>$\mu$ 0.45</td>
</tr>
<tr>
<td>$E_f$ 72 GPa</td>
<td>$\lambda_B$ 1527 nm</td>
</tr>
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</table>

**Fig. 2.** Predicted sensitivity of the sensor for the static pressure.

### 3. Experiments and Results

Two types of hydrophones were fabricated and tested. Commercially available FBGs were used with a reflective wavelength of about 1527 nm. The Young’s moduli of the polyurethane rubber we used, T-805 and EU 2500, are 17 MPa and 70 MPa, respectively. The outer radius of the metal cylinder is 5 mm and the radius of the hard core is about 1.2 mm. Other parameters of the hydrophones are shown in Table 1.

The hydrostatic pressure test was carried out first. As mentioned above, this experiment is based on the assumption that the static pressure sensitivity of the sensor is equal to the dynamic pressure sensitivity. The sensor was installed within a high pressure vessel fed by a hydraulic pump. The pressure induced Bragg wavelength shift was monitored by a high accuracy FBG interrogator (PI Optics, PI03B). The results are shown in Fig. 3.

Fig. 3 demonstrates that the fabricated sensors have linear response to the static hydraulic pressure. The measured sensitivity and the calculated sensitivity are shown in Table 2. A pressure sensitivity of 7 nm/MPa has been achieved when the radius of the hard core is 1.2 mm.
and the outer radius of the hydrophone is 5 mm. This sensitivity is approximately 2010 times higher than that measured with a bare FBG[14] or 107 times higher than that measured with a hard coated FBG[15]. This sensor may also be used as a hydraulic sensor.

![Fig. 3. Bragg wavelength shift of the sensor with the static pressur.](image)

Table 2: Sensitivity of the hydrophones (nm/MPa)

<table>
<thead>
<tr>
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<th>£=17 MPa</th>
<th>£=70 MPa</th>
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<tbody>
<tr>
<td>Calculated</td>
<td>6.88</td>
<td>2.16</td>
</tr>
<tr>
<td>Experimental</td>
<td>7.04</td>
<td>3.79</td>
</tr>
</tbody>
</table>

The static measured sensitivity is in the same order of magnitude as the calculated value. The discrepancy between the experimental result and the calculated is thought to be the dimension errors in manufacturing the diaphragm and the hard core. The edge effect created when fixing the diaphragm onto the steel tube would also induce the discrepancy.

After the hydrostatic pressure test, we carried out the acoustic test. A standard piezoelectric (PZT) hydrophone and the fiber optic hydrophone were put into the water tank together. The acoustic source on the other side of the water tank was fed by a frequency generator. The PZT hydrophone and the fiber optic hydrophone were placed 5 cm apart, which is very close compared to the minimum acoustic wavelength of 1.5 m. The local sound pressure is measured by the PZT hydrophone. The size of the water tank is smaller than half of the acoustic wavelength in the water. Thus, we consider the local acoustic pressure of the two hydrophones to be the same when they are placed close to each other.

Fig. 4 shows the schematic of the demodulation system for a single hydrophone. The network is illuminated with an amplified spontaneous emission (ASE) light source with a 40 nm bandwidth (1520-1560). The commercially available FBG used in our configuration has a center wavelength of 1527 nm, a peak power reflectivity of ~60%, and a spectral bandwidth of ~0.12 nm. The light reflected from the FBG becomes the light source of the unbalanced Mach-Zehnder interferometer (MZI). The optical path difference (OPD) of the unbalanced MZI is 7 mm. A PZT fiber stretcher in one of the MZI arms in the demodulator is used to induce a phase-shift carrier signal on the sensor output signals to enable passive recovery of dynamic phase-shift information using phase generated carrier (PGC) demodulation[16]. The test is performed in the frequency range from 20 Hz to 1000 Hz. The results when the signal is 73 Hz are shown in Fig. 5. The frequency response of the hydrophone is shown in Fig. 6.

![Fig. 4. Demodulator system.](image)

Fig. 5 shows that the noise floor of the hydrophone is about $10^{-3}$ pm/√Hz for 7 mm OPD of MZI at 1 kHz. For practical applications, the hydrophone sensitivity goal is the level of the acoustic background noise of the quiet ocean, which is called deep-sea state zero (DSS0). At 1 kHz, the DSS0 level is 100 μPa/Hz$^{1/2}$. In our configuration, a sensitivity of 7 nm/MPa is achieved, which results in a minimum detectable acoustic signal of 140 mPa/Hz$^{1/2}$ at 1 kHz. This level of detection is three orders higher than the current PZT hydrophones and the target noise floor of DSS0. However, because the presented structure greatly enhanced the wavelength-to-pressure sensitivity, we believe that the target noise floor of DSS0 would be achieved by replacing the FBG with a DFB fiber laser to reduce the noise floor of the hydrophone[17].

![Fig. 5. Demodulation result of the FBG hydrophone.](image)

![Fig. 6. Frequency response of the hydrophone.](image)
Ideally, the frequency response should be flat, however as Fig. 6 shows, the frequency response varies across the measured bandwidth. This variation is believed to be the mechanical resonance of the rubber diaphragm and the hard core. But Fig. 6 demonstrates that when the Young’s modulus is higher, the frequency response will be flatter. This is thought to be because when the Young’s modulus is lower, the viscoelasticity of the polymer will become more significant and the natural frequency of the sound-induced vibration modes of the diaphragm will become lower. A balance should be found between the sensitivity and the frequency response, which requires further investigation.

4. Conclusions

We have shown a novel technique for enhancing the pressure sensitivity of a fiber Bragg grating hydrophones using a piston-like diaphragm with a hard core in the center. The theoretical analysis shows that the Young’s moduli of the diaphragm and the radius of the hard core have a significant effect on the pressure sensitivity. By optimizing these two parameters, a pressure sensitivity of 7 nm/MPa has been achieved when the radius of the hard core is 1.2 mm and the outer radius of the hydrophone is 5 mm. The hydrostatic test results are in good agreement with the theoretical analysis. The in-water acoustic test gives the frequency response of the two types of hydrophones. We found that when the Young’s modulus of the diaphragm is higher, a flatter frequency response will result. Because of its thin dimensions, this hydrophone is expected to be used in the towed hydrophone arrays.

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References


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