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Experimental investigation of comparison of optical fiber acoustic sensor with standard hydrophone in shallow water

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ABSTRACT

In this paper, we present experimental results of one optical fiber acoustic sensor in shallow water. Output trend of sensor is investigated primarily comparing with the change of acoustic amplitude of transmitter and then the frequency response of sensor is determined. The results show that, the optical fiber sensor has linear trend comparing with a standard hydrophone and its frequency response is similar to that of hydrophone. The results show that the optical fiber sensor output has equal trend comparing to a standard hydrophone. The results also show that, the frequency response trend of optical fiber sensor at 0.7- 5 kHz range is similar to that of a standard hydrophone.

1. Introduction

Optical fiber sensors can be defined as a means through which the physical, chemical and biological measures interact with light guided through an optical fiber to produce a modulated optical signal with information related to the measurement [1]. Some of the advantages of fiber sensors over conventional electronic sensors are lightweight, EMI resistant, high sensitivity [1,2], multiplexing capability and etc. Depending on the light property that is modified, optical fiber sensors can be mainly classified into four main categories as Intensity-modulated sensor, Phase-modulated (interferometric) sensor, Polarization-modulated (polarimetric) sensor and Wavelength-modulated (spectrometric) sensor[1]. Optical fiber sensors are capable to measure many physical, chemical and biological quantities [2]. Acoustic wave is an important physical quantity that can be detected by optical fiber sensors [3,4]. In one of these investigations about optical fiber acoustic sensing, by fiber Bragg grating sensor packaged polymer material, underwater acoustic has been detected and acoustic sensitivity equal to -153dB re 1μPa, was obtained, at 500Hz frequency of acoustic pressure [5]. Currently, numerous works in interferometric optical fiber acoustic sensor can be found including interferometric configurations such as Mach-Zehnder [6,7], Michelson [8,9], Sagnac[10,11],and Fabry-Perot [12,13]. In other report, an investigation on the influence of material properties on the performance of an interferometric optical fiber is performed. Simulation results show young modulus of mandrel layers and thickness of layers will influence pressure sensitivity of sensor [14]. For example, in reference 9, an experimental optical fiber acoustic sensor based on Michelson interferometer using phase generated carrier demodulation method has been implemented. The proposed sensor can detect acoustic signal in range of 1-5 kHz. The implemented optical fiber Fabry Perot acoustic sensor in reference 13, can also detect the acoustic signal in range of 8Hz-10kHz in laboratory scale when the ambient noise is very low. However, so far no comprehensive report has been made on the implementation of an optical fiber hydrophone based on heterodyne demodulation method and polymer coating on sensor in the real environment and compared with conventional hydrophones.

In optical fiber sensors coated with polymer, the optical fiber is wrapped around a coil as a sensing element. Since the optical coupling in the fiber is weak, a long fiber is generally used to increase the induced optical phase change. Pressure sensitivity is a complex function of a Young's modulus, Poissons' ratio, and the cross-sectional area of an outer coating. In the case of sensor with mandrel, a thin jacket fiber is typically wrapped around a compliant mandrel. The optical fiber then measures the pressure induced strain in the mandrel. It is important to maximize the scale of the sensor in order to maintain a high sensitivity and a flat pressure response. So, composite concentric mandrel has some improvements over the fiber wrapped mandrel even though bounded by some structural limitations[14]. In a composite fiber wrapped around the mandrel of MZI Sensor, a thin jacket fiber is typically wrapped around a compliant mandrel and thin elastic polyurethane is coated over the fiber as protection during operation. The optical fiber measures the pressure-induced strain in the mandrel and protecting layer. Sensors with mandrel are important because they are easy to produce and they exhibit a high sensitivity.

In this paper, the optical fiber acoustic sensor is tested on a scale beyond the laboratory. In this paper, the primarily output trend of sensor comparing with the change of the voltage amplitude of acoustical transmitter is shown. Then frequency response of optical fiber sensor is investigated at different frequency comparing with a standard hydrophone. It must be noted that, comparative study is made between underwater optical fiber sensor and standard hydrophone in this paper. In fact, in this investigation, an optical fiber acoustic sensor has been implemented in a real environment considering environmental noise and intrinsic noise of system. Several methods have been used to increasing the signal to noise ratio. The first solution is to measure the phase change of light using heterodyne demodulation method. The phase change measurement of light reduces the dependence of the output acoustic signal on changes in pressure and temperature in the environment. Using the heterodyne demodulation method as a method that allows reducing the electronic noise of the system, it is effective in improving system performance and it is considered as second strategy for increasing signal to noise ratio. Also, in this study, in order to reduce the noise level of the phase and the relative intensity of the laser as an optical transmitter, a laser with a very low line width of ~ kHz is used.

2. Experimental setup and detection method

Acoustic signal extraction using phase method detection is used to detect the small signal phase shifts eliminating the signal fading caused by large environmental drifts which is achieved by introducing a large amplitude phase shift at a frequency outside of the signal band. These large amplitude signals carry the signals of interest as sidebands. Scheme of experimental setup, is shown in fig. 1. Laser is launched to Erbium doped fiber amplifier (EDFA); then the amplified light is transmitted into two acousto-optics modulators (AOM) to generate optical pulse. One AOM shifts the laser frequency amount to 100MHz and another AOM shifts the laser frequency amount to 110MHz. These shifts construct heterodyne signal. These pulses are launched to interferometry setup. The pulses sequence adjusts the way these two pulses are launched to fiber input repetitively. It is shown in fig. 2 that some part of first pulse propagating through long arm (sensor arm), overlaps with some part of second pulse propagating through short arm (reference arm). The influence of interference of these two pulses, heterodyne carrier pulse, is induced at detector. This technique is named pulsed reflectometric architecture (PRA).

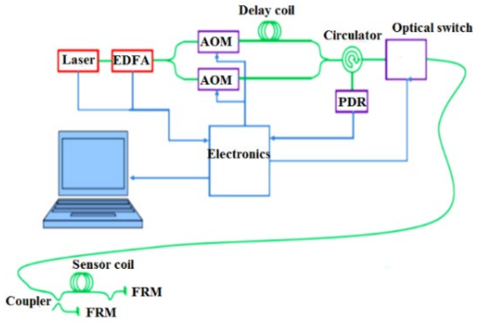

Figure 1. Scheme of experimental setup

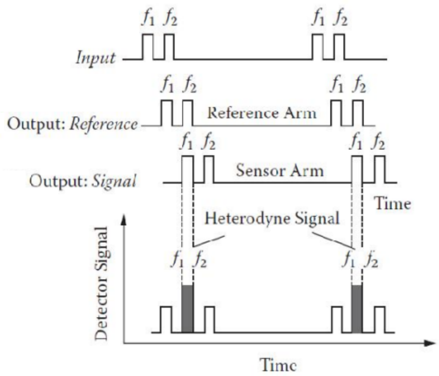

Figure 2. Manner of generation heterodyne pulses[15]

These pulses have optical frequency f_1 and f_2. Time delay τ between these two pulses is equal to time difference of light propagation through two arms of interferometry setup. By applying dynamical pressure on sensing fiber, the phase modulation $\phi(t)$ on heterodyne signal is induced. This input phase can be obtained by with conventional detection methods [15]. The electrical current of optical detector due to heterodyne pulse can be derived. In heterodyne method, two optical pulses interfere together at input of photodiode. One of these pulses is modulated at frequency f_{100} (100 indicate 100MHz frequency shift) and final frequency of signal is $f_c + f_{100}$. f_c is laser frequency and is about 193THz. The second pulse is reference and is modulated at frequency f_2 and final frequency of reference is $f_c + f_{110}$ (110 indicate 100MHz frequency shift).

The reference pulse is reflected by FRM in reference arm of interferometer and signal pulse is reflected by

FRM in sensor arm of interferometer as it have been shown in fig. 1. It is considered $E_s(t)$ and $E_r(t)$ as signal pulse and reference pulse respectively as equation 1 and 2 [8,9].

$$E_s(t) = \sqrt{P}\cos(2\pi(f_c + f_1)t) + \phi_s) \quad (1)$$

$$E_r(t) = \sqrt{P}\cos(2\pi(f_c + f_2)t) + \phi_r) \quad (2)$$

In equation 1 and 2, P is the optical power received by photodiode. ϕ_s and ϕ_r are phase shifts induced by signal and reference pulse in sensor. After interference of these two pulses, photodiode current is obtained through equation 4 [16,17].

$$y(t) = r \times (E_s(t) + E_r(t))^2 \quad (3)$$

$$y(t) = rP(\cos^2(2\pi(f_c + f_{100})t + \phi_s)$$
$$+\cos^2(2\pi(f_c + f_{110})t + \phi_r)$$
$$+2\cos(2\pi(f_c + f_{100})t + \phi_s)\cos(2\pi(f_c + f_{110})t + \phi_r))$$
$$y(t) = \frac{rP}{2} + \frac{rP}{2}\cos(4\pi(f_c + f_{100})t + 2\phi_s)$$
$$+\frac{rP}{2} + \frac{rP}{2}\cos(4\pi(f_c + f_{110})t + 2\phi_r)$$
$$+rP\cos(2\pi(2f_c + f_{100} + f_{110})t + \phi_s + \phi_r)$$
$$+rP\cos(2\pi(f_{100} - f_{110})t + \phi_s - \phi_r)$$

The limitation of changes of frequency laser is equal to inverse of time rise of photo detector. The time rise of photodiode that used in experiment is 0.5 ns, then the most frequency of changes of laser intensity that can be detected by photo detector is 2GHz. The photo diode as a low pass filter, eliminates frequencies above 2GHz, then the terms that including f_c are eliminated and it remains the term including $f_1 - f_2$ as equation 4.

$$i_{pd}(t) = rP + rP\cos(2\pi(f_1 - f_2)t + \phi_s - \phi_r) \quad (4)$$

R, P_1, P_2, V and $\phi(t)$ are detector response, returned power of reflectors to detector, visibility capability and phase change due to acoustical wave applying to sensing fiber.

In part of light detection and light conversion to electrical signal, signal fading due to polarization is an important problem. In our setup to overcome this problem, polarization diversity receiver is used. The field setup is shown in fig. 3.

3. Results and Discussion

In this section, the experimental results are investigated and compared with standard hydrophone. The results show, the detected acoustic frequency using standard hydrophone can be detected with our proposed optical fiber sensor. However the optical fiber sensor output is significantly more than standard hydrophone. The sensor output was measured at frequencies of 0.7 kHz-5kHz. Each data point of Fig.4-10 addresses the average of ten different measurements. The error bar assigned to each data point of Fig.4-10 represents the standard deviation of results.

In fact, the optical pulses after transmission through circulator in fig. 1 and optical link in fig. 3 arrive to optical fiber sensor and conventional standard hydrophone. With applying acoustic signal using acoustical transmitter, optical fiber sensor and standard hydrophone receive acoustical signal. For optical fiber sensor, acoustic signal application causes deformation in optical fiber length and this length change using PDR (polarization diverse receiver) and electronics system is calculated and finally, the acoustic signal is extracted from ambient noise.

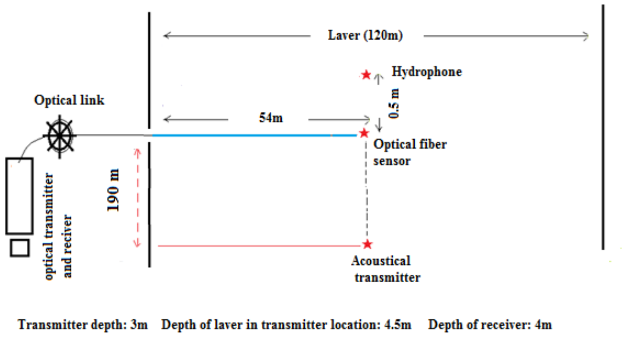

Figure3. Scheme of field setup including optical transmitter and receiver as shown in fig. 1, optical link for, optical fiber sensor as illustrated in fig.1 consist of sensor coil and FRMs, acoustical transmitter and a conventional hydrophone.

Fig. 4 shows the change of sensor output versus amplitude voltage at 0.7 kHz frequency. This result, shows a nearly linear output of sensor versus various applied voltage of acoustical transmitter over 2-50 V.

Fig. 5 shows the output of standard hydrophone versus output of optical fiber sensor at 0.7 kHz frequency.

Fig. 6 shows the change of sensor output versus amplitude voltage at 1 kHz frequency. This result, illustrates a nearly linear output of sensor versus various applied voltage of acoustical transmitter over 2-50 V.

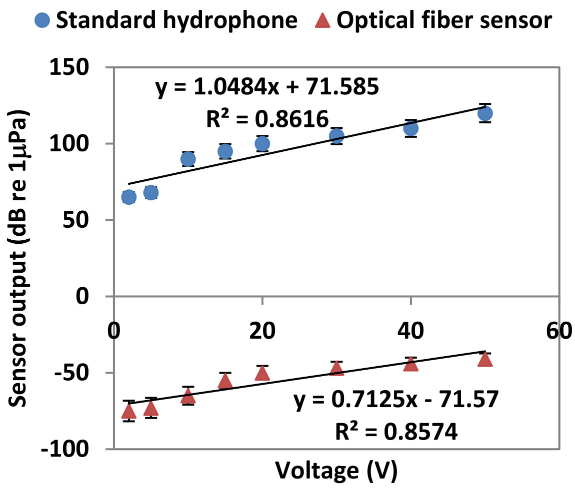

Figure 4. Output of sensors versus amplitude voltage at 0.7 kHz frequency

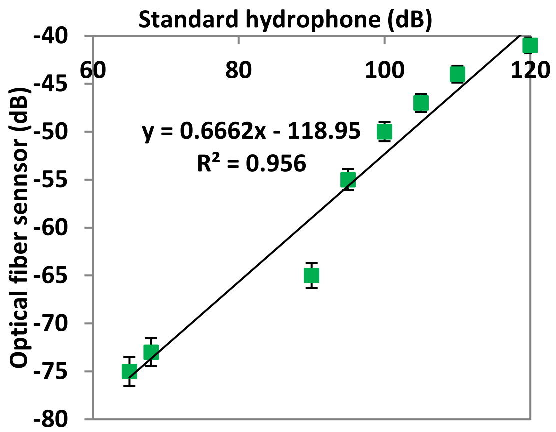

Figure 5. Output of optical fiber sensor versus output of standard hydrophone at 0.7 kHz frequency

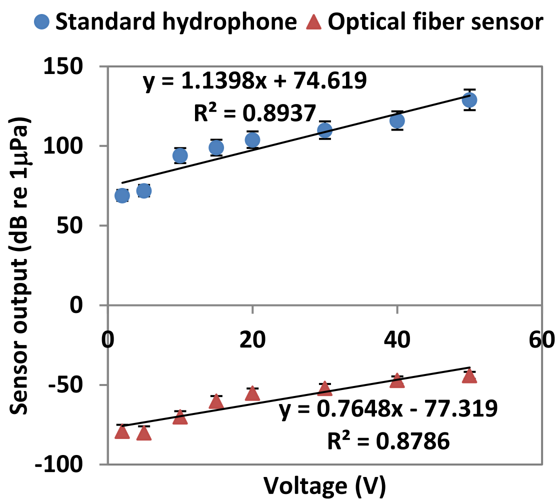

Figure 6. Output of sensors versus amplitude voltage at 1 kHz frequency

Fig. 7 shows the output of standard hydrophone versus output of optical fiber sensor at 1 kHz frequency.

Fig. 8 shows the change of sensors output versus amplitude voltage at 2 kHz frequency.

Fig. 9 shows the output of standard hydrophone versus output of optical fiber sensor at 2 kHz frequency. This result, displays a nearly linear output of sensor versus various applied voltage of acoustical transmitter over 2-50 V.

The sensor output for amplitude of voltage 5V is shown in fig. 10.

It is shown in fig. 4, 6 and 8 that the trend of sensors output versus amplitude of voltage is similar. It is shown in fig. 5, 7 and 9 that the slopes of plots are nearly equal Together.

It is shown in fig. 10 that frequency response of optical fiber sensor is similar to that of a standard hydrophone. The proposed optical fiber sensor output was measured at frequencies of 1.5 kHz, 1.7 kHz, 1.9 kHz, 2 kHz, 3 kHz, 3.5 kHz, 4 kHz, 4.5 kHz and 5 kHz equal to 100 dB, 102 dB, 85 dB, 88 dB, 85 dB, 101 dB, 105 dB, 110 dB and 120 dB respectively.

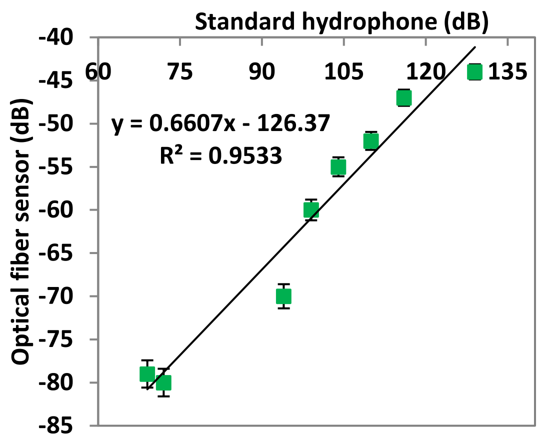

Figure 7. Output of optical fiber sensor versus output of standard hydrophone at 1 kHz frequency

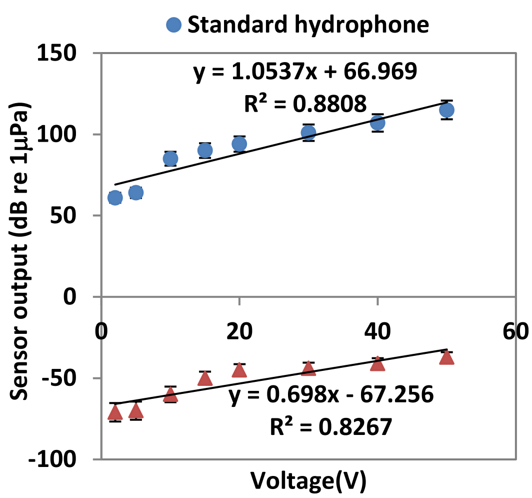

Figure 8. Output of sensors versus amplitude voltage at 2 kHz frequency

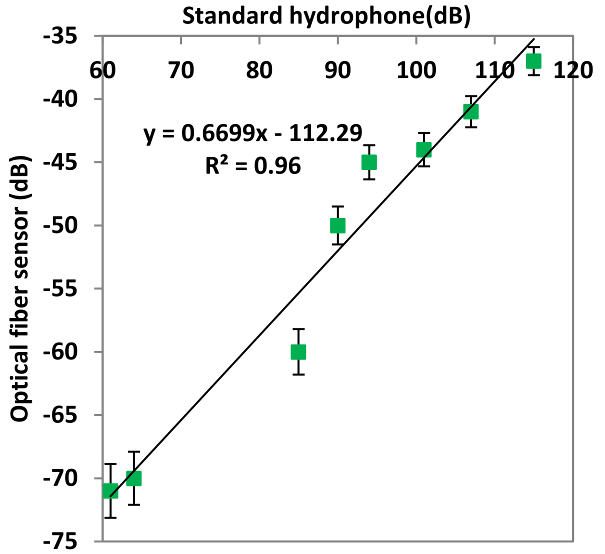

Figure 9. Output of sensors versus amplitude voltage at 2 kHz frequency

4. Conclusions

In this study, an optical fiber acoustic sensor based on the phase detection is implemented in a real environment. A high signal to noise ratio of detected signal is obtained using an effective heterodyne demodulation method. In this paper, an optical fiber sensor output versus voltage amplitude of acoustical transmitter is investigated. The results show that the optical fiber sensor output has equal trend comparing to a standard hydrophone. The results also show that, the frequency response trend of optical fiber sensor at 0.7- 5 kHz range is similar to that of a standard hydrophone.

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