Experimental Research of an All-Polarization-Maintaining Optical Fiber Vector Hydrophone

Jianfei Wang, Hong Luo, Zhou Meng, and Yongming Hu

Abstract—This paper reports a new-style all-polarization-maintaining optical fiber vector hydrophone (OFVH) that is composed of a three-component optical fiber accelerometer and an optical fiber hydrophone. In order to make the OFVH small and compact in volume, the orthogonal and unitized structure of the three-component optical fiber accelerometer is adopted. The sensitivity and the operating frequency band of the accelerometer are increased by this proposed structure. The signal fading caused by the random phase shift in the interferometer is eliminated by phase-generated carrier technology. Calibration results show that the acceleration sensitivity is 32.6 dB re rad/g and its fluctuation is less than 1.4 dB over the frequency range of 20–2000 Hz. The phase sensitivity of the optical fiber accelerometer is —155 dB re rad/μPa at 1000 Hz. This OFVH has an excellent directivity; its maximum asymmetric index is less than 0.4 dB and its directivity index is greater than 45 dB. The excellent performance of this new-style OFVH for use in source localization measurements is also proved by the sea trial.

Index Terms—Accelerometer, directivity, optical fiber vector hydrophone (OFVH), phase sensitivity, polarization-maintaining optical fiber.

I. INTRODUCTION

VECTOR hydrophones and vector hydrophone arrays, which can be used to measure the acoustic pressure and the particle velocity (or acceleration and pressure-gradient) at the same time [1], have improved the detection and localization of acoustic signal compared to conventional omni-directional hydrophones and hydrophone arrays. There has been considerable interest devoted in the applications of vector hydrophones and vector hydrophone arrays, such as in the fields of well logging [2]–[4], underwater ambient noise measurement [5], [6], maritime target discrimination [7], and permanent reservoir monitoring [8]–[11]. However, the conventional electrical vector hydrophones, e.g., those based on piezoelectric or capacitive accelerometer, while the other is launched into the pressure sensor and a one beam is launched into the insensitive interferometer, while the other is launched into the pressure sensor and the three axes of the accelerometer by couplers. The returned lights are detected by their corresponding detectors D. The polarization-maintaining optical fiber Michelson interferometer is used as the active sensing element. Three interferometers are wrapped on orthogonal (x, y, and z) and unitized moving-mass accelerometer, converting vibrations to fiber strain variations; One is wrapped on a pressure sensor mandrel, detecting the

Fig. 1 shows the structure of the OFVH system proposed in this paper. It is constituted of a light source, a sensing head, and a system for signal detecting and processing. The sensing head is formed up by an optical fiber pressure sensor and a three-component optical fiber accelerometer. The light from the narrow linewidth fiber laser is split into two beams by a coupler C. One beam is launched into the insensitive interferometer, while the other is launched into the pressure sensor and the three axes of the accelerometer by couplers. The returned lights are detected by their corresponding detectors D. The polarization-maintaining optical fiber Michelson interferometer is used as the active sensing element. Three interferometers are wrapped on orthogonal (x, y, and z) and unitized moving-mass accelerometer, converting vibrations to fiber strain variations; One is wrapped on a pressure sensor mandrel, detecting the
pressure signals of targets, and the insensitive interferometer is used for common noise reduction. All the interferometers are path-imbalance interferometers with the path difference 5 m. The long arms of the interferometers are 14 m.

A. Optical Fiber Accelerometer

As aforementioned, 3-D acceleration sensing is usually achieved by using three single axis optical fiber accelerometers [2]–[4], [8]–[11]. This method is easy to implement, and has been used extensively in reservoir monitoring. In this paper, the 3-D acceleration sensing is realized by using an orthogonal and unitized structure instead, as shown in Fig. 1. This proposed structure could detect the 3-D accelerations at the same point, and could be made more compact in structure. Therefore, it would be more suitable for array applications.

Principally, the three-component optical fiber accelerometer is based on six elastic material cylinders loaded with a seismic mass. The polarization-maintaining optical fiber is tightly wrapped around each of the elastic material cylinders. A constant tension is applied during the wrapping process. The two face-to-face cylinders form the two arms of an optical fiber Michelson interferometer. When the hydrophone is under axial vibration, one of the cylinders is compressed while the other one is expanded, leading to a variation in circumference of the cylinder. This effect then causes a change of the length of the fiber wrapped on the cylinder, and, consequently, leads to a phase shift in the optical fiber interferometer. When the hydrophone is under vertical vibration, the two face-to-face cylinders have the same deformation. No phase shift is introduced in the optical fiber interferometer. Therefore, no signal would be detected in the optical fiber Michelson interferometer. Hence, the different axes of the accelerometer are only sensitive to the axial vibration, resulting in an excellent directivity of the OFVH.

Conventionally, the elastic material of an optical fiber accelerometer is a plastic or rubber. This consequently limits the operating temperature and life of an OFVH for the sensor is strongly temperature dependent and the plastic or rubber is feasible to aging. To overcome these limitations, cupreous thin-walled annuluses are used instead as the elastic material. The lengths of the thin-walled annuluses are 3 cm, their outside diameters are 2 cm, and their thicknesses are 1 mm. Experimental results of such fabricated optical fiber accelerometer show that the noise floor of each axis of the accelerometer is about \(-110 \text{ dB/Hz}^{1/2}\) at 1000 Hz, while its acceleration sensitivity is around 32.6 dB re rad/g over the frequency range from 20 to 2000 Hz. Therefore, the phase resolution of the interferometer is \(3.2 \times 10^{-6} \text{ rad}\), and the acceleration resolution is \(7.4 \times 10^{-6} \text{ g}\) at 1000 Hz.

B. Pressure Sensor

In this OFVH system, an optical fiber air-backed mandrel hydrophone proposed in [15] is used to monitor the acoustic pressure signal. The mandrel material of the pressure sensor is aluminum. Its length is 5.5 cm and its outer diameter is 1.3 cm. Its phase sensitivity is \(-144.3 \text{ dB re rad/μPa}\) over the frequency from 20 to 2000 Hz and its noise floor is about \(-11! \text{ dB/Hz}^{1/2}\) at 1000 Hz. So the phase resolution of the interferometer in this pressure sensor is \(3.2 \times 10^{-6} \text{ rad}\), and the pressure resolution of this pressure sensor is 51.88 μPa.

C. Insensitive Interferometer

To reduce the noise floor of this OFVH, a noise suppression scheme based on an adaptive noise canceller is used in this paper. A pressure insensitive reference optical fiber Michelson interferometer, which is wrapped on a solid aluminum cylinder with length of 5.5 cm and outer diameter of 1.3 cm, is added as a reference sensor. Its structural parameters are the same as those of the other sensing fiber optic interferometers. The noise floors of the pressure and acceleration signal, which are highly correlated with the reference signal, can be cancelled by the normalized least root mean square error algorithm [16]. The results of a lake trial [17] show that this scheme can effectively reduce both the noise floor of the pressure and the accelerometer channels, which can suppress the 50 Hz and its high-order harmonics of the electromagnetic interference by 15–25 dB, and the flat phase noise above 500 Hz by about 3 dB. Therefore, the proposed method can improve efficiently the system’s minimum detectable signal ability.

In order to achieve high accuracy of the signal detection, several additional techniques are applied to the OFVH proposed in this paper. Specifically, the influences of the temperature and pressure are eliminated by the push–pull structure. The signal fading caused by the random changes in the state of polarization of the guided beams is prevented by using the all-polarization-maintaining optical fiber interferometer. Besides, the signal fading induced by random phase shift in the interferometer is eliminated by phase-generated carrier technology [18]. The dynamic range of the signal demodulation system is about 120 dB at 1000 Hz. The narrow linewidth fiber laser with central wavelength of 1550 nm is used as the light source. The laser frequency modulation is adopted with modulation frequency \(\omega_0 = 12.5 \text{ kHz}\).

III. THEORY ANALYSIS

A. Acceleration Sensitivity and Natural Frequency

Generally, the analysis of the three-component optical fiber accelerometer is based on a single elastic material cylinder loaded with a seismic mass. Fig. 2 shows the elastic material cylinder wrapped with fiber; the radius of the cylinder is \(R\), and its length is \(H\). Since the aforementioned accelerometer is...
performed in a push–pull way, its induced phase shift is twice as the phase shift induced by a single elastic material cylinder, assuming the same deflection of the seismic mass. However, the overall sensitivity at frequencies well below the natural frequency of the mass spring assembly does not change as in the two-cylinder version, that is, twice the force is required in order to achieve the same deflection. The only change occurs in the natural frequency of the accelerometer assembly, which is larger by a factor of \( \sqrt{2} \) in the double elastic material cylinder version because of the doubled stiffness.

So far, different methods have been developed to analyze the structure shown in Fig. 2, such as the work presented in [19] and [20]. Following the displacement vector algorithm presented in [19], the equivalent Young’s modulus \( E' \) and the equivalent Poisson ratio \( \mu' \) of the elastic material cylinder wrapped with fiber, respectively, can be expressed by

\[
E' = \frac{1 - \mu - 2 \cdot \mu' \cdot \mu}{1 - \mu - 2 \cdot \mu^2} \cdot E \\
\mu' = \frac{\mu}{X}
\]

(1) (2)

where \( E \) and \( \mu \) are the Young’s modulus and the Poisson ratio of the elastic material cylinder without wrapped fiber, respectively. The factor \( X \) describes the influence of the wrapped fiber on the relation between the longitudinal and radial strains of the cylinder. It has the form of [21]

\[
X = 1 + \frac{(1 + \mu) \cdot (1 - 2 \mu)}{E} \cdot \frac{E_f \cdot S_f \cdot N}{H \cdot R}
\]

(3)

where \( E_f \) and \( S_f \) are the Young’s modulus and the cross-sectional area of the fiber, respectively, \( N \) is the number of fiber turns around the cylinder. Generally, \( X \) is a large value. Equation (1) implies that the equivalent Young’s modulus \( E' \) is determined mainly by the parameters of \( \mu \) and \( \mu' \). As regards (2), it is clear that the equivalent Poisson ratio \( \mu' \) is in inverse proportion to the factor \( X \). It should be noted that \( X \) is directly proportional to the number of fiber turns \( N \). Wrapping the cylinder with multilayer of fiber would increase the sensing length, but decrease the equivalent Poisson ratio \( \mu' \) at the same time. That is, increasing the number of fiber turns could not greatly enhance the sensitivity of the accelerometer. However, when the elastic material cylinder is not full of the wrapped fiber, the sensitivity of the accelerometer is to be enhanced by the increase of fiber length.

When the signal frequencies are well below the natural frequency, the acceleration sensitivity of the optical fiber accelerometer \( M_a \) is given by [21]

\[
M_a = \frac{\Delta \phi}{a} = \frac{4 \pi n \mu' \cdot m L}{\lambda_i \pi R^2 E'} \cdot \left[ 1 - \frac{1}{2} \pi^2 [(1 - \mu_f) p_{12} - \mu_f p_{11}] \right]
\]

(4)

where \( \Delta \phi \) is the optical phase shift, \( a \) is the particle acceleration, \( n, \mu_f, \) and \( L \) are the refractive index, the Poisson ratio, and the length of the fiber, respectively. \( \lambda_i \) is the wavelength of light, \( m \) is the mass of seismic mass, and \( P_{11} \) and \( P_{12} \) are the Pockels coefficients of the fiber core material. The natural frequency of the accelerometer \( f_0 \) can be written as [21]

\[
f_0 = \frac{1}{2 \pi} \sqrt{\frac{2 E' \pi R^2}{m H}}
\]

(5)

The acceleration sensitivity in whole-band frequency is given by [19]

\[
M_a(f) = \frac{M_a f^2}{\sqrt{(f^2 - f_0^2)^2 + (f \cdot f_0/Q)^2}}
\]

(6)

where \( f \) is the signal frequency and \( Q \) is the quality factor that describes the damping properties.

The parameters \( m, R, \) and \( E' \) are needed to be selected in designing an OFVH for certain application. It is interesting to see that when the specific parameter is in the numerator/denominator in (4), it is in the denominator/numerator of (5). That is, the natural frequency \( f_0 \) and the acceleration sensitivity \( M_a \) are interacting with each other in an inverse way. Therefore, high sensitivity and large natural frequency are difficult to achieve at the same time. Compromise should be made in practical applications.

### B. Phase Sensitivity

Generally, phase sensitivity is one of the most important parameters that characterize the properties of an optical fiber hydrophone. It is very desirable for the acceleration sensitivity to be transformed into the form of phase sensitivity, since the latter is important in comparing the performance of a traditional optical fiber hydrophone with an optical fiber accelerometer. The phase sensitivity \( M_p \) of the optical fiber hydrophone has the expression of

\[
M_p = \frac{\Delta \phi}{p}
\]

(7)

where \( \Delta \phi \) is the optical phase shift, in unit of rad, and \( p \) is the acoustic pressure, in unit of micropascal. The acceleration signal, which is detected by the OFVH, is generated by acoustic pressure. In the frame that the detection range is longer than the wavelength of the acoustic wave, the acoustic wave can be considered as a simple harmonic wave. Hence, the acceleration \( a \) can be written as

\[
a = \frac{\dot{\omega} \cdot \rho_c \cdot c_0}{\rho \cdot c_0^3} \cdot p n
\]

(8)

where \( \omega \) is the angular frequency of the acoustic wave, \( \rho_0 \) is the density of the propagation medium, \( c_0 \) is the acoustic velocity, and \( n \) is the unit directional vector. By substituting (7) and (8)
Fig. 3. All-polarization-maintaining OFVH.

Fig. 4. Testing of the OFVH.

Equations (4) and (9) show that the phase sensitivity of the optical fiber accelerometer is directly proportional to the angular frequency. Meanwhile, the acceleration sensitivity of the optical fiber accelerometer and the phase sensitivity of the traditional optical fiber hydrophone are constant values in the operating frequency band.

IV. CALIBRATION RESULTS

Fig. 3 shows the new proposed OFVH. An optical fiber hydrophone is inserted to the vector hydrophone for testing acoustic pressure. The outside shell material of the OFVH is aluminum and the outside diameter is 120 mm. By using (4) and (5) and the structure parameters given for this OFVH, the theoretical natural frequency \( f_n \) and the acceleration sensitivity \( M_a \) are calculated to be 3600 Hz and 33 dB re rad/g, respectively.

This new proposed OFVH is tested in the National Hydroacoustics Metrology Station, Hangzhou, China. Fig. 4 shows the calibration principle of this OFVH. Both the OFVH and the standard piezoelectric hydrophone are placed in the same depth of the liquid column. The sensitivity of the standard piezoelectric hydrophone is \(-180\) dB re V/\(\mu\)Pa, and the calibration frequency is from 20 to 2000 Hz.

The measured phase sensitivities of the three axes of the optical fiber accelerometer and the optical fiber hydrophone are shown in Fig. 5. The phase sensitivities of the three axes of the optical fiber accelerometer are at the value about \(-155\) dB re rad/\(\mu\)Pa at 1000 Hz. It can be found that their phase sensitivities are almost the same, with fluctuations between two different axes within a value less than 0.5 dB. The phase sensitivity of the optical fiber hydrophone is \(-144.3\) dB re rad/\(\mu\)Pa over the frequency range from 20 to 2000 Hz. It is clear from Fig. 5 that the phase sensitivity of the optical fiber accelerometer is frequency dependent [see Fig. 5(a)], while the phase sensitivity of the optical fiber hydrophone is nearly a constant value over the measured frequency [see Fig. 5(b)]. These observations are in good
agreement with the results predicted by the theoretical analysis presented in (4) and (9).

Once the phase sensitivity of the accelerometer is obtained, its corresponding acceleration sensitivity can be calculated by (9). Fig. 6 plots the acceleration sensitivities of the three axes of the accelerometer in frequency from 20 to 2000 Hz. Their sensitivities are around 32.6 dB re rad/g, with fluctuations at different frequencies less than 1.4 dB. This result validates the theoretical analysis presented in this paper, since its measured result is almost the same as the theoretical one aforementioned.

The directional pattern of the OFVH is obtained by rotating the OFVH around its center and measuring the magnitude of its output signal at the same time. Fig. 7 shows the directional pattern of the OFVH measured at 63 Hz. At other frequencies, the directional patterns are quite similar with the one presented in Fig. 7. The directivity index of the OFVH is greater than 45 dB and the maximum asymmetric index is less than 0.4 dB. That is to say, the OFVH is sensitive to the axial vibration and not sensitive to the vertical vibration.

From the measurement results shown in Figs. 5--7, one can find that the accelerometer is quite competent in terms of uniformity of the sensitivities of its three axes. Besides, this OFVH is shown to have a high sensitivity in wide frequency range, and have an excellent performance in the directivity. Therefore, this kind of OFVH could be very promising for many practical applications, e.g., in the fields of underwater ambient noise measurement and maritime target discrimination.

V. SEA TRIAL RESULTS AND DISCUSSION

To characterize the performance of the new proposed OFVH for source localization measurement, the sea trial of a single OFVH was carried out in the Yellow Sea of China.

A. Experiment Deployment

Fig. 8 shows the deployment of the trial for source localization measurement. A single OFVH and an omni directional sound source are placed 1 km apart at the sea floor, and they are about 35 m in depth. Single frequency continuous signal is radiated by the sound source, which would then be received by the OFVH. In Fig. 8, a compass is used to correct the localization errors induced by the attitude change of the OFVH.

B. Sound Source Localization Measurement

To localize the sound source, the responses of the three accelerometer components are needed to be obtained. These three accelerometer component responses are then steered by appropriate processing to a reference direction. The intensity-based algorithm [22], [23] is a simple direction-of-arrival (DOA) estimation algorithm for a single vector hydrophone. Based on the intensity-based algorithm, the vertical angle $\theta$ and the horizontal angle $\phi$ of the sound source, which are the angles measured with respect to the self-coordinate of the vector hydrophone, are calculated, respectively, by

$$\theta = \arctan \frac{\bar{I}_y}{\bar{I}_x}$$

(10)

$$\phi = \arctan \frac{\bar{I}_z}{\sqrt{\bar{I}_x^2 + \bar{I}_y^2}}$$

(11)

where $\bar{I}_x$, $\bar{I}_y$, and $\bar{I}_z$ are $x$, $y$, and $z$-component of the average acoustic intensity of the vector hydrophone, respectively. This average acoustic intensity has the form of

$$\bar{I}(t) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} p(t)v(t) \, dt$$

(12)

where $p(t)$ is the acoustic pressure, which can be detected by the optical fiber hydrophone, $v(t)$ is the particle velocity, and $T$
is the time record. The particle velocity can be gained by integrating over the particle acceleration, while the latter is detected by the three-component optical fiber accelerometer.

C. Measurement Results

With respect to the measurement shown in Fig. 8, the vertical angle of the sound source approaches zero because the OFVH and the sound source are placed at the same depth. Only the results of the horizontal angle estimation are given in the following.

Fig. 9 shows the horizontal angle estimation result of the sound source obtained by the method of minimum-variance distortionless response beamforming [24]. In comparison with the traditional scalar hydrophones, the OFVH can remove the $180^\circ$ ambiguity in the DOA estimation by using the information of particle velocity of the sound field. The measured horizontal angle is $277^\circ$, which is relatively close to the actual degree of $276.3^\circ$.

Fig. 10 shows the time-bearing display of the horizontal angle estimation obtained by the intensity-based algorithm. The data used in this figure are the same as that in Fig. 9. It can be found that the mean horizontal angle of the sound source is $276.9^\circ$ with angle fluctuation no more than $2.5^\circ$. This result is very similar with the one obtained by Fig. 9.

From Figs. 9 and 10, one can find that the new proposed OFVH has an outstanding performance in the sound source localization measurement. It has the ability to track the trace of target. Therefore, this kind of OFVH could be very promising for surface and underwater target discriminations.

VI. CONCLUSION

A new-style OFVH is presented and studied in this paper. By using cupreous thin-walled annulus as the mandrel material of the accelerometer, the operating temperature and life of this OFVH are obviously extended. Its superiorities in directivity, sensibility, and operating frequency band are manifested by the calibration results. The acceleration sensitivity is 32.6 dB re rad/g and its fluctuation is less than 1.4 dB over the frequency range of 20–2000 Hz. The phase sensitivity of the optical fiber accelerometer is about $-155$ dB re rad/$\mu$Pa at 1000 Hz. The maximum asymmetric index is less than 0.4 dB while its directivity index is greater than 45 dB. These advantages of this new-style OFVH make it very promising in oil and gas detection, as well as in underwater ambient noise measurement and maritime target discrimination. Additionally, the sensitivities of the different axis of OFVH are well guaranteed by using this new structure. Therefore, the new-style OFVH would be quite capable of building large-scale OFVH array for future application. The excellent performance of this new-style OFVH in source localization measurements is proved by the sea trial carried out in this paper.

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