Pseudo working-point control measurement scheme for acoustic sensitivity of interferometric fiber-optic hydrophones

Zefeng Wang (王泽锋), Yongming Hu (胡永明), Zhou Meng (孟　洲), and Ming Ni (倪　明)

College of Photoelectric Science and Engineering, National University of Defense Technology, Changsha 410073

A novel pseudo working-point control measurement scheme for the acoustic sensitivity of interferometric fiber-optic hydrophones is described and demonstrated. The measurement principle is introduced in detail. An experimental system, which interrogates an interferometric fiber-optic hydrophone with this method, is designed. The acoustic pressure phase sensitivity of the fiber-optic hydrophone is measured over the frequency range of $20-2500$ Hz. The measured acoustic sensitivity is about -156.5 dB re 1 rad/μPa with a fluctuation lower than ±1.2 dB, which is in good agreement with the results obtained by the method of phase generated carrier. The experimental results testify the validity of this new method which has the advantages of no electric elements in the sensing head, the simplicity of signal processing, and wide working bandwidth.

OCIS codes: 060.2370, 060.2420, 230.1150.

Since the first fiber-optic hydrophone was reported by Bucaro *et al.*[1] in 1977, this technology has seen a considerable amount of development. Especially the interferometric fiber-optic hydrophones are extensively used in the measurements for temperature, electric and magnetic fields, acoustic and seismic waves etc. for its high sensitivity, large dynamic range, and convenience for multiplexing[2−7]. The output of an interferometer is a cosine function of the phase difference which will drift because of the low frequency random temperature and pressure fluctuations between the optical waveguides in the two arms. The drift causes random changes in the amplitude of the detected signal (signal fading), which make the signal detection for interferometric fiber-optic hydrophones difficult[2−5].

To recover the phase information from the output intensity of the fiber-optic hydrophone, different signal detection and processing schemes have been developed including phase generated carrier (PGC)[8,9], phase tracking[2,10−12], true heterodyne[2], pseudo heterodyne[13], synthetic heterodyne[14], differential delay heterodyne (DDH)[3,4], optical path matching differential interferometer (PMDI) heterodyne[4,15], interferometer using a 3×3 directional coupler (ITT)[16], and so on. Among these methods, phase tracking and true heterodyne have the advantage of simplicity of operation. However, the use of an active electrical device in phase tracking and the addition of an acousto-optic or integrated optic frequency shifter to one arm of the fiber interferometer in true heterodyne are undesirable in many applications. Synthetic heterodyne also needs an active electrical device. PGC demodulation, DDH, PMDI heterodyne, ITT, and pseudo heterodyne can realize passive detection, but they have the disadvantages of complexities of structures or demodulation. In some applications, a simple passive detection method of wide working bandwidth is required.

In this paper, a novel pseudo working-point control measurement scheme for the acoustic sensitivity of interferometric fiber-optic hydrophones is described. The acoustic pressure phase sensitivity of a Michelson interferometric fiber-optic hydrophone is measured with this new method. Experimental results testify its validity.

A passive homodyne Michelson interferometer is schematically shown in Fig. 1. It is made of PANDA polarization-maintaining fiber manufactured by Corning Inc.. The core diameter of the fiber is 8 μm, and the attenuation at $\lambda = 1550$ nm is 0.43 dB/km.

A sinusoidal signal is used to modulate the laser. The output light intensity signal from the interferometer is converted to voltage signal by the photoelectric detector, and can be written as

$$V = A + B\cos\theta, \tag{1}$$

where θ is the phase difference between the arms of the interferometer. The constants A and B are proportional to the input optical power of the laser and the conversion efficiency of the photoelectric detector, respectively, but B also depends on the mixing efficiency of the interferometer.

In a Michelson interferometer, the phase difference θ may be written as

$$\theta = 2\pi n l \frac{\nu}{c}, \tag{2}$$

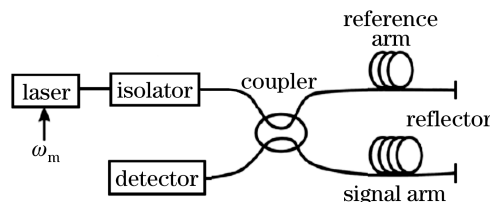where n is the refraction index of the fiber core, l is the

Fig. 1. Sketch of pseudo working-point control scheme.

length difference of the optical fiber between the two arms, c is the velocity of light, and ν is the laser frequency. n and l will vary due to the change of the environmental temperature and the acoustic pressure. In addition, ν will also change as the result of modulation. Therefore, n, l, and ν may be written as $n = n_0 + \Delta n$, $l = l_0 + \Delta l$, and $\nu = \nu_0 + \Delta\nu$, where n_0, l_0, and ν_0 are, respectively, the effective core refraction of fiber, the fiber length difference of the interferometer arms without acoustic pressure applied, and the laser frequency without modulation applied, and Δn, Δl, $\Delta\nu$ are the corresponding changes. Δl includes two items, Δl_s and Δl_n, which due to acoustic signal and all kinds of noises, respectively. Substituting n, l, and ν into Eq. (2) and only reserving the first-order terms, we obtain

$$\theta = \phi_0 + \phi_n + \phi_m + \phi_s, \tag{3}$$

where $\phi_0 = 2\pi n_0 l_0 \nu_0 / c$ is the phase shift induced by the fiber length difference l_0; $\phi_n = 2\pi \nu_0 (\Delta n l_0 + n_0 \Delta l_n)/c$ is the phase shift induced by all kinds of environmental noises (mainly including temperature changes, pressure fluctuations, and mechanism dithering); $\phi_m = 2\pi n_0 l_0 \Delta\nu/c$ is the phase shift induced by the modulation for the laser frequency; $\phi_s = 2\pi n_0 \Delta l_s \nu_0 / c$ is the phase shift induced by the acoustic pressure to be detected.

If the laser is modulated with a sinusoidal voltage signal with a frequency ω_m, then $\Delta\nu = \Delta\nu_0 \sin\omega_m t$, where $\Delta\nu_0$ is the maximum change of the laser frequency corresponding to the maximum modulating voltage. Therefore,

$$\phi_m = C_m \sin\omega_m t, \tag{4}$$

where $C_m = 2\pi n_0 l_0 \Delta\nu_0 / c$ is the maximum phase shift due to the maximum frequency change.

If a sinusoidal acoustic signal with a frequency ω_s is applied on the fiber-optic interferometer, then $\Delta l_s = \Delta l_0 \sin\omega_s t$, where Δl_0 is the maximum change of the length difference of the two arms of the interferometer. Therefore,

$$\phi_s = C_s \sin\omega_s t, \tag{5}$$

where $C_s = 2\pi n_0 \nu_0 \Delta l_0 / c$ is the maximum phase shift induced by the acoustic pressure.

We define the working-point of the interferometer as

$$\phi_p = \phi_0 + \phi_n + C_m \sin\omega_m t, \tag{6}$$

then Eq. (1) becomes

$$V = A + B\cos(C_s \sin\omega_s t + \phi_p). \tag{7}$$

Expanding Eq. (7) in terms of Bessel function produces

$$V = A + B\{[J_0(C_s) + 2\sum_{k=1}^{\infty} J_{2k}(C_s)\cos 2k\omega_s t]\cos\phi_p$$

$$-2[\sum_{k=0}^{\infty} J_{2k+1}(C_s)\sin(2k+1)\omega_s t]\sin\phi_p\}, \tag{8}$$

where $J_k(C_s)$ is the kth order Bessel function of the first kind. After passing through a low-pass filter, which can

eliminate the components above the fundamental frequency, V becomes

$$V = A + BJ_0(C_s)\cos\phi_p - 2BJ_1(C_s)\sin\phi_p \sin\omega_s t. \tag{9}$$

From Eq. (9), we can see that in an adequately short time, V is approximately a sinusoidal signal with a frequency ω_s and a direct current (DC) component for the varying rate of ϕ_p is far slower than ω_s. The amplitudes of DC and alternating current (AC) components of V are given by

$$V_{DC} = A + BJ_0(C_s)\cos\phi_p, \tag{10}$$

$$V_{AC} = 2BJ_1(C_s)\sin\phi_p. \tag{11}$$

If the constants A, B are known, the working-point ϕ_p can be calculated from Eq. (10) by assuming that $J_0(C_s) \approx 1$; and the signal amplitude C_s can be gotten by submitting ϕ_p into Eq. (11)[12].

To obtain A and B, we collect enough data, among which there must be a group of maximum and minimum. They are marked as $V_{\max}$ and $V_{\min}$ respectively. From Eq. (1), we know that $V_{\max} = A + B$ and $V_{\min} = A - B$, therefore

$$A = (V_{\max} + V_{\min})/2, \tag{12}$$

$$B = (V_{\max} - V_{\min})/2. \tag{13}$$

To test this new method, an all polarization-maintaining Michelson interferometric fiber-optic hydrophone is measured in a standing-wave tube, as shown in Fig. 2. The standing-wave tube was composed of a steel pipe and an underwater loudspeaker. The pipe was 125 mm in inner diameter, 500 mm in length, and 4 mm in thickness. According to the theories of acoustic waveguides, the first cut-off frequency of the tube filled with water in theory is about 7000 Hz. The acoustic pressure phase sensitivity of the fiber-optic hydrophone was obtained by a comparative measurement method[11,17]. The standard piezoelectric hydrophone chosen for the test was a CS-3 hydrophone of 10-mm diameter (Institute of Acoustics, Chinese Academy of Sciences). A single frequency sinusoidal signal, generated by an AFG3022 arbitrary function generator (Tektronix, USA), was used to provide sound signal through an amplifier [B&K2713 (Brüel & Kjær, Denmark)] to the underwater loudspeaker. To ensure the validity of the experimental results, the acoustic centers of the two hydrophones must be located at the same depth. The light source was a type of fiber ring laser with the center wavelength of
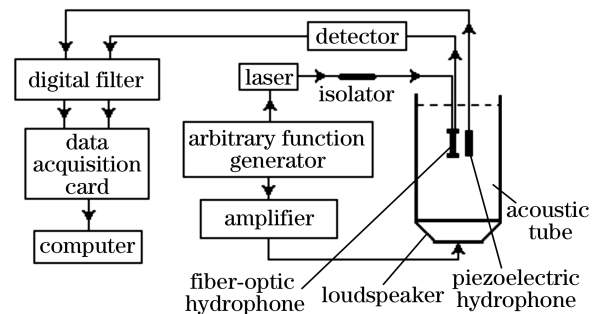

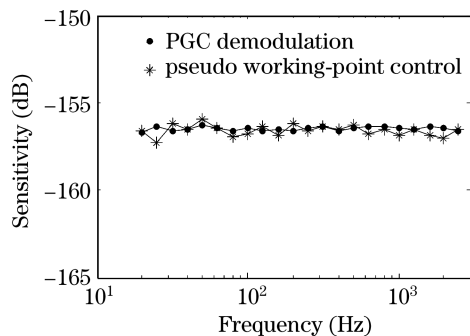Fig. 2. Schematic diagram of the experimental setup.

Fig. 3. Frequency response of acoustic pressure phase sensitivity. The reference is 1 rad/μPa.

1550 nm and the laser line-width of about 1.5 kHz[18]. The wavelength control element was a piezoelectric ceramic cylinder coiled with several meters of fiber. The linear modulation rate of the ceramic cylinder was 4.38 nm/MV. The phase modulation coefficient of the system composed of the laser and the Michelson interferometer was 0.5 rad/V. In experiment, the laser was modulated with a low frequency and big amplitude sinusoidal wave which was also generated by AFG3022. The modulation frequency $\omega_m = 2\pi$, and the modulation depth $C_m = 3.5$ rad. The output optical signal of the fiber-optic hydrophone was changed to voltage signal by a photoelectric detector. The outputs of the detector and the piezoelectric hydrophone were sent to a digital filter Stanford SR650. Then the two outputs from the filter were acquired simultaneously into computer through a data acquisition card AD-Link PCI9812 for processing.

A real-time system of data collecting and processing was programmed with Labview and Matlab. The test results show that the sound field on the same plane in the tube is not uniform any longer when the sound frequency is up to 3000 Hz, and the basis of the comparative measurement method is destroyed. In addition, the method requires that the measurand must change great faster than the environmental noise and the modulation signal. Therefore, to obtain adequate measurement precision, the acoustic pressure phase sensitivity M was measured over the frequency range of $20 - 2500$ Hz, and the results are shown in Fig. 3. The results obtained with the system in this paper and a standard system of PGC demodulation are shown in the figure for comparison. It is shown that the two curves are in agreement with each other and the average acoustic pressure phase sensitivity is -156.5 dB re 1 rad/μPa. The frequency response fluctuation is about ±0.6 dB over the frequency range of $60 - 2500$ Hz, while over the range of $20 - 60$ Hz the fluctuation is about ±1.2 dB, and the lower the frequency, the bigger the fluctuation. It is because that the lower the frequency, the less the cycles of the same length of effective data, then the bigger the demodulation errors. The experimental results testify the validity of this new method.

In conclusion, we have demonstrated a novel acoustic sensitivity measurement scheme, pseudo working-point control, for interferometric fiber-optic hydrophones. This method uses a continuous sinusoidal signal with low frequency and big amplitude to modulate the laser frequency. As a result of modulation, the working-point of the interferometer is compelled to scan from 0 to 2π slowly. Therefore, the fiber-optic hydrophone will not work at insensitive point for a long time. Simultaneously the fluctuation of the laser power can be compensated. This method has the advantages of no active elements or frequency shifter in the sensing head, the simplicity of demodulation, and the wide working bandwidth. But it requires that the measurand must change great faster than the environmental noise and the modulation signal. The acoustic sensitivity of an interferometric fiber-optic hydrophone is measured with this new method. The experimental results show that this new method is feasible. It may be widely applied to signal measurements of other interferometric fiber optical sensors.

References

1. J. A. Bucaro, H. D. Dardy, and E. F. Carome, Appl. Opt. **16,** 1761 (1997).
2. T. G. Giallorenzi, J. A. Bucaro, A. Dandridge, G. H. Sigel, Jr. J. H. Cole, S. C. Rashleigh, and R. G. Priest, IEEE Trans. Microwave Theory and Techniques **30,** 472 (1982).
3. P. Nash, IEE Proc. Radar Sonar Navig. **143,** 204 (1996).
4. X. Gao, Optical Fiber Electric Cable (in Chinese) (1) 48 (1996).
5. G. A. Cranch, P. J. Nash, and C. K. Kirkendall, IEEE Sensors Journal **3,** 19 (2003).
6. C. Kang, Z. Huang, C. Tong, and K. Wei, Acta Opt. Sin. (in Chinese) **27,** 1156 (2007).
7. Z. Song, X. Wang C. Cao, and Y. Hu, Chinese J. Lasers (in Chinese) **34,** 957 (2007).
8. A. Dandridge, A. Tveten, and T. G. Giallorenzi, IEEE Trans. Microwave Theory and Techniques **30,** 1635 (1982).
9. M. Ni, Y. Hu, Z. Meng, and S. Xiong, Laser Optoelectron. Progress (in Chinese) **42,** (2) 33 (2005).
10. Z. Meng, Y. Hu, S. Xiong, Y. Liu, M. Ni, and X. Zhang, Chinese J. Lasers (in Chinese) **29,** 415 (2002).
11. Z. Wang, H. Luo, S. Xiong, M. Ni, and Y. Hu, Acta Opt. Sin. (in Chinese) **27,** 654 (2007).
12. Z. Wang, L. Huang, H. Luo, M. Ni, Z. Li, and Y. Hu, J. Optoelectron.·Laser (in Chinese) **18,** 977 (2007).
13. L. B. Liokumovich and S. I. Markov, Proc. SPIE **4316,** 56 (2000).
14. J. H. Cole, B. A. Danver, and J. A. Bucaro, IEEE J. Quantum Electron. **18,** 694 (1982).
15. T. K. Lim, Y. Zhou, Y. Lin, Y. M. Yip, and Y. L. Lam, Opt. Commun. **159,** 301 (1999).
16. Z. Zhao, M. S. Demokan, and M. MacAlpine, J. Lightwave Technol. **15,** 2059 (1997).
17. Z. Wang, H. Luo, S. Xiong, M. Ni, and Y. Hu, Chinese J. Lasers (in Chinese) **34,** 105 (2007).
18. Z. Meng, Z. Hu, Y. Hu, S. Xiong, and C. Cao, Proc. SPIE **6552,** 65521C (2007).