

A low-cost and broadband-response fiber-optic hydrophone by using metal diaphragm reflection

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Abstract: A broadband-response fiber-optic hydrophone based on Au-coated stainless steel diaphragm and an encoded narrowband filtering function based on the Fourier transform and matrix multiplication are demonstrated. Sensitivity of 0.13 mV/Pa , 0.19 mV/Pa , 0.11 mV/Pa and 0.17 mV/Pa can be achieved at 8 KHz, 25 KHz, 200 KHz and 1 MHz, respectively. The advantages of simple fabrication, broadband-response, low-cost, and linear response make our fiber-optic hydrophone a perfect candidate for enormous economical manufacturing.

1. Introduction

The word hydrophone consists of hydro (pertaining to water) and phone (pertaining to sound). As such, a hydrophone is simply a device for detecting sound signal in water. In the field of ultrasonic, unlike transducer, hydrophone is commonly used to describe a device that is purely a receiver of ultrasound. Approximately 70% of the Earth's surface is covered by ocean. In recent years, as people pay more and more attention to the marine resources, hydrophones have become a research hotspot. According to the sensitive mechanism involved, hydrophones can be divided into piezoelectric hydrophones [1, 2] and fiber-optic hydrophones [3-10].

Since 1970s, Bucaro [3] et al. from the US Naval Laboratory jointly published the first article about fiber-optic hydrophone, fiber-optic hydrophones have developed rapidly due to their obvious military application potential. Compared with traditional piezoelectric hydrophones, fiber-optic hydrophones have many advantages, such as small size, high sensitivity, broadband-response, anti-electromagnetic interference, suitable for underwater variable environment, convenient for long-distance transmission and large-scale array production. Various techniques and structures such as Fabry-Perot Interference (FPI) [4-6], Fiber Bragg Grating (FBG) [7, 8], Mach-Zehnder Interferometer (MZI) [9] and Fiber Collimator [10, 11] have been proposed and applied now.

In this paper, a low-cost, broadband-response and diaphragm-based fiber-optic hydrophone is proposed, fabricated and tested. We use MATLAB to encode a narrowband filtering function based on Fourier transform and matrix multiplication to obtain ideal filtering effect in the data processing stage. Experimental results demonstrate that the system exhibits advanced performances on broadband-response and function filtering.

2. Hydrophone preparation and testing

In this paper, we demonstrate a fiber-optic hydrophone based on Au-coated stainless steel diaphragm $30\mu\text{m}$ in thickness and 7mm in diameter. The schematic diagram and optical image of our fabricated fiber-optic hydrophone are shown in Fig.1. A stainless steel diaphragm is used as the sensing element after carefully polished, Au-coated and glued between two quartz tubes (ID: 7mm, OD: 20mm). A collimator with a diameter of 3.2 mm was precisely perpendicular to the reflective diaphragm and adhered to the inner wall of the quartz tube. A stainless steel pipe was fixed outside the quartz tubes for protection. After carefully sealed, a fiber-optic hydrophone based on Au-coated stainless steel diaphragm was fabricated.

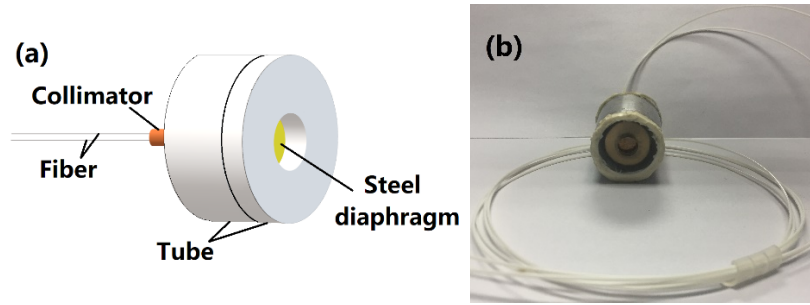


Figure 1. Schematic diagram (a) and optical image (b) of our fiber-optic hydrophone

To examine the performance of the fabricated fiber-optic hydrophone (FOH), dynamic pressures measurement was performed. The schematic of acoustic pressures measurement system is shown in Fig.2. In the experiment, we used piezoelectric transducers (PZT, mono-crystalline longitudinal wave probe) with center frequency of 8 KHz, 25 KHz, and 200 KHz and 1 MHz driven by a function generator and a power amplifier as signal sources. The FOH and PZTs were placed face to face in the fixed position of the water tank. The collimator used in FOH can be simultaneously used as a transmitting fiber and a receiving fiber. One end of the collimator was connected to a laser source with wavelength and power fixed at 1550 nm and 4.0 mv, the other end was connected to a photodetector (PD) and an oscilloscope to display the feedback waveform in real time. Finally, we used a computer for further data processing.

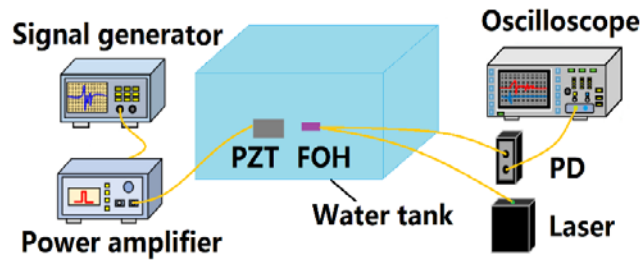


Figure 2. The schematic of dynamic pressures measurement system

3. Results and Discussion

In the dynamic pressures measurement experiment, we used 4 PZTs with center frequencies of 8KHz, 25KHz, 200KHz and 1MHz as sound sources, since each PZT has its specific center frequency. In order to better distinguish the signal amplitude, we use an encoded narrowband filtering function in the data processing stage which will be introduced carefully in the subsequent part. The output signals of FOH after function filtering are shown in Fig. 3. The result indicates that there is a good linear relationship between the acoustic pressures and the output signals at each test frequency. The sensitivity of FOH at 8 KHz can be calculated as the slope of the corresponding curve in Fig.3 (a), which is $0.13mV/Pa$. According to the same method, the sensitivity of FOH at 25 KHz [Fig.3 (b)], 200 KHz [Fig.3(c)] and 1MHz [Fig.3 (d)] can be calculated as $0.19mV/Pa$, $0.11mV/Pa$ and $0.17mV/Pa$.

According to the Fourier transform and matrix multiplication, we used MATLAB to encode a narrowband filtering function in the experiment. Different from existing actual filters and digital filters, the encoded narrowband filtering function cut off the irrelevant signals beyond the passband frequency range, rather than gradually attenuating. Three parameters of sampling rate, low-pass frequency and high-pass frequency determine the filtering effect of the narrowband filtering function. The parameter of sampling rate is determined by the output signal to be filtered and can be selected during the oscilloscope data acquisition phase. Lower sampling rate means smaller spectral resolution, but if the sampling rate is overly low, the waveform of output signal will be distorted. The parameters of low-pass frequency and high-pass frequency are selected according to actual filtering requirements. In this experiment, we use encoded filtering function for specific test frequency points, the narrower the pass-band frequency range we choose, the better filtering effect we obtain. Taking the output

signal of FOH under an incident acoustic pressure of 21Pa at 200 KHz as example. The sampling rate of output signal is 50MHz, the corresponding highest low-pass frequency is 198.5 KHz and the corresponding lowest high-pass frequency is 201.5 KHz. The output signals and corresponding power spectrums of FOH with or without function filtering are shown in Fig.4. Through function filtering, the waveform of output signal becomes smooth and the signal-to-noise-ratio (SNR) increases from 13.48dB to 292.31dB. When the test frequency and sampling rate are constant, the narrowest pass-band frequency range is fixed. However, if the experiment conditions change, we can still obtain ideal filtering effect with high SNR by selecting appropriate narrowband filtering function parameters. The filtering effect and reusability of the encoded filtering function are as expected.

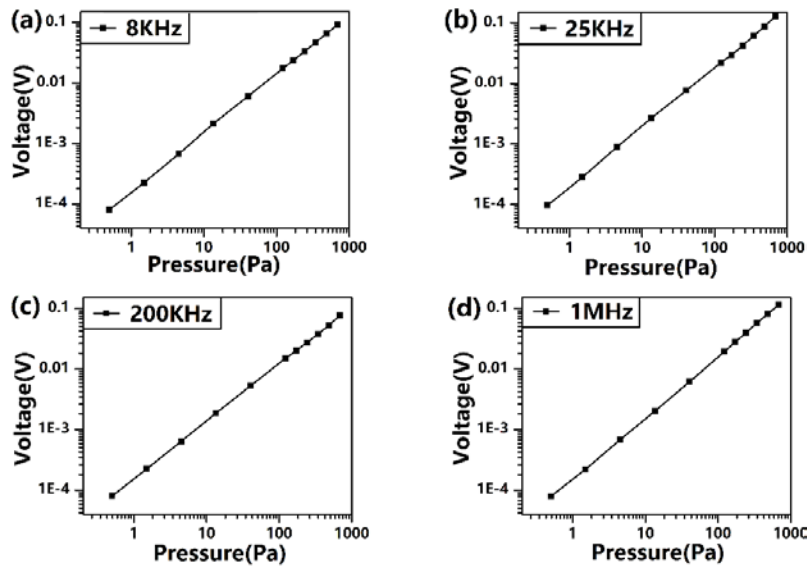


Figure 3. Dynamic response of our fiber-optic hydrophone at 8 KHz, 25 KHz, 200 KHz and 1 MHz

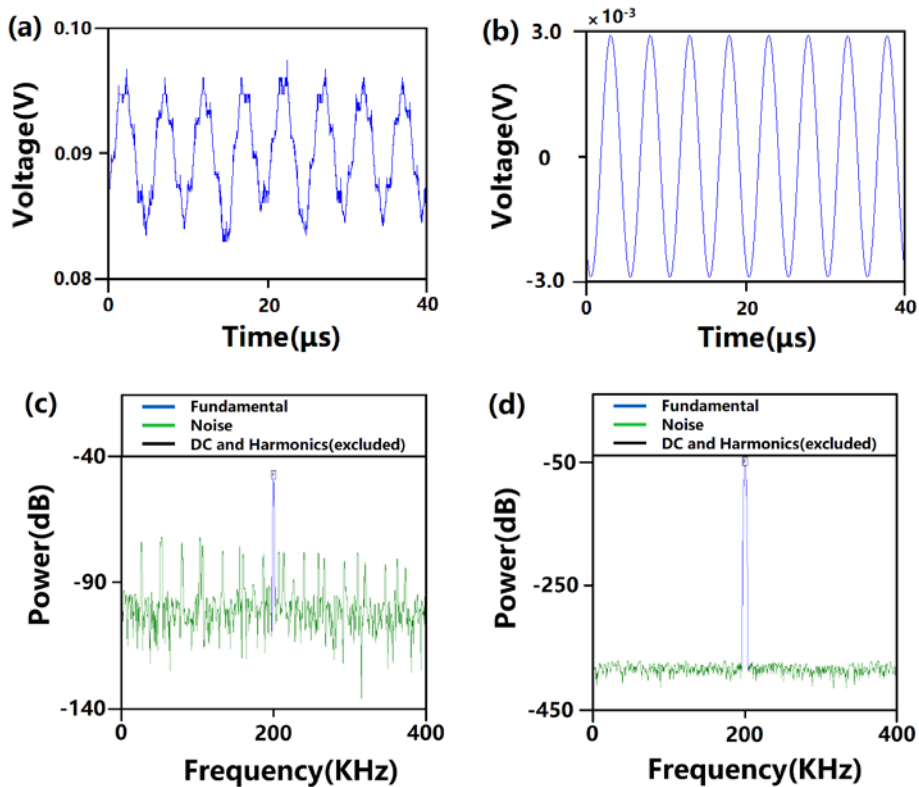


Figure 4. The output signals and corresponding power spectrums of our fiber-optic hydrophone with (b), (d) or without (a), (c) function filtering

However, due to the presence of device and environmental noise, even if no acoustic pressure is applied, the same-frequency noise remains after function filtering. Thus, the noise-limited minimum detectable pressure level in this system is about $17\text{mPa}/\sqrt{\text{Hz}}$, $23\text{mPa}/\sqrt{\text{Hz}}$, $28\text{mPa}/\sqrt{\text{Hz}}$ and $24\text{mPa}/\sqrt{\text{Hz}}$ at 8 KHz, 25 KHz, 200 KHz and 1 MHz, respectively. As the minimum detectable pressure level of the hydrophone is determined by the sensitivity of the hydrophone and the noise level of the system^[9]. In order to detect lower acoustic pressure, we can further reduce system noise and increase hydrophone's sensitivity in subsequent experiments. Since our FOH is diaphragm-based, it may be a good choice to use a reflective diaphragm with larger diameter and thinner thickness^[11] in future experiments.

4. Conclusion

In this paper, a fiber-optic hydrophone based on Au-coated stainless steel diaphragm is proposed, fabricated and tested. A narrowband filtering function based on Fourier transform and matrix multiplication was encoded to obtain ideal filtering effect. Experimental results indicate that the sensitivity of hydrophone are $0.13\text{mV}/\text{Pa}$, $0.19\text{mV}/\text{Pa}$, $0.11\text{mV}/\text{Pa}$ and $0.17\text{mV}/\text{Pa}$ at 8 KHz, 25 KHz, 200 KHz and 1 MHz, respectively. The noise-limited minimum detectable pressure level of system are $17\text{mPa}/\sqrt{\text{Hz}}$, $23\text{mPa}/\sqrt{\text{Hz}}$, $28\text{mPa}/\sqrt{\text{Hz}}$ and $24\text{mPa}/\sqrt{\text{Hz}}$ at 8 KHz, 25 KHz, 200 KHz and 1 MHz, respectively. To further detect lower acoustic pressure, we need to reduce system noise and increase hydrophone's sensitivity in subsequent experiments.

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