Surface and Underwater Surveillance based on Highly Sensitive Distributed Fiber-optic Hydrophone

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Abstract: We report field test results of surface and underwater surveillance based on fiber-optic distributed acoustic sensing (DAS) and highly sensitive distributed fiber-optic hydrophone (DFOH). Various intrusive targets like boat, frogman and etc. are detected.

1. Introduction

Since the beginning of the 21st century, the terrorist attacks in waters still occur from time to time, which all have caused deadly consequences. Therefore, all the countries and regions in the world are paying more and more attention to the surface and underwater surveillance, especially in the key water areas and ports [1]. Based on the analysis and summary of previous cases, the means or methods of the terrorist attacks in waters usually contain frogman, remote operated vehicle (ROV), surface speedboat, and etc. Nowadays, the hydrophone is the most important and effective equipment for surface and underwater surveillance applications, and since fiber-optic hydrophone (FOH) was proposed by the US Naval Research Laboratory in 1977, it has been proved its application value in the past decades due to the higher sensitivity and stability than piezoelectric hydrophone [2]. Besides, the FOH is also convenient to form an array due to its simple network. However, in recent years, with the improvement of underwater target noise reduction level, the surface and underwater surveillance has become more and more difficult, and the FOH array formed by interferometer or distributed feedback (DFB) fiber laser are both difficult to meet the higher application demands including higher detection sensitivity, lower noise level and larger scale [3-4].

In recent years, fiber-optic DAS technology has been developed rapidly due to its superiorities containing simple network, long distance, fast response, and etc., and it has been widely used in perimeter intrusion detection on the land [5]. In our previous work, we have proposed and demonstrated a highly sensitive DFOH with backscattering enhanced optical fiber (BEOF) as sensing fiber and achieved distributed hydroacoustic sensing based on phase sensitive time domain reflectometry (φ-OTDR) in the laboratory [6]. In this paper, we report the field test results of surface and underwater surveillance based on DAS and sensitive DFOH with BEOF, which exhibit excellent performances and potential for applications. The DFOH can be laid surrounding the key water areas and ports for the application of surface and underwater surveillance. Then, reporting and monitoring various emergency intrusive targets including boat, frogman, ROV instantaneously can allow quick action to be taken, which can prevent the potential danger and damage to the facility of the key water areas and ports.

2. System setup and Principle

So far, the acoustic signal is the only form of energy which can be transmitted long distance underwater, therefore, the position and feature information of the surface and underwater intrusive targets can be acquired through detecting the radiated acoustic noise generated by themselves.

As demonstrated in Fig. 1(a), the surface and underwater surveillance system based on φ-OTDR and DFOH with BEOF consists of dry end and wet end. The dry end is an integrated DAS system with polarization independent [7]., which can realize signal modulation, acquisition, and demodulation in real-time, and the wet end is the DFOH with BEOF proposed in our previous work [6], which can realize distributed hydroacoustic signals detection. The dry end and wet end can be linked by a transmission fiber cable to realize signal transmission.

Before field test, the acoustic pressure sensitivity of DFOH is calibrated by vibrating liquid column method, the calibrated frequency response from 5Hz to 2kHz is exhibited in Fig. 1(b), and a relatively flat frequency response with a fluctuation about 4 dB is demonstrated, of which the average acoustic pressure sensitivity is about −137 dB *re* 1rad/(μPa·m).

Besides, to satisfy the practical application requirement in the sea, the noise equivalent pressure (NEP) of the system based on φ-OTDR and DFOH with BEOF should as low as the level of the Deep Sea State Zero (DSS0) [8], which generally is 50 dB re 1μPa/Hz$^{1/2}$ at 1 kHz. So, the noise PSD of the system is tested to assess the NEP, and the result is shown in Fig. 2(a), from which it can be seen that the noise power spectral density (PSD) at 1 kHz is about −90 dB *re* rad^2/Hz. Considering the acoustic pressure sensitivity of the proposed DFOH at 1 kHz is −138 dB *re*

1rad/(μPa·m), so the NEP is evaluated about 48 dB *re*:1μPa/Hz$^{1/2}$ at 1 kHz, which is lower than the level of the DSS0 and indicates this system can detected the slight hydroacoustic signal under sea ambient noise.

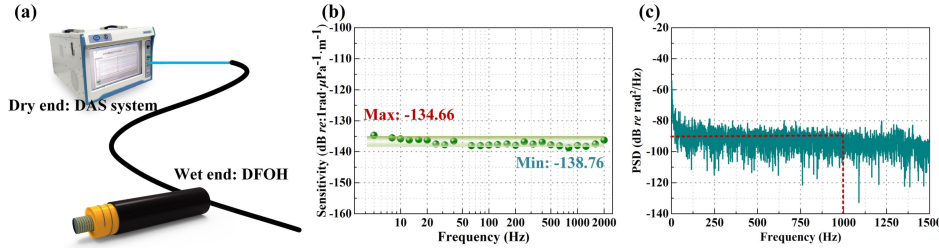

Fig.1 (a) The system based on φ-OTDR and DFOH with BEOF; (b) The calibrated frequency response from 5Hz to 2kHz; (c) The noise PSD of the system.

3. Field Test Results and Discussion

1.1. Lake trial

Before sea trial, the lake trial is carried out in Wuhan, China to test the feasibility of surface and underwater surveillance based on φ-OTDR and DFOH with BEOF. The setup of the lake trial is illustrated in Fig. 2(a), the 100-meter-long DFOH is laid parallel to the lakeshore at a depth of 12 meters and linked to the DAS system by a transmission fiber cable.

Firstly, to verify the performance for surface surveillance, an assault boat is arranged to travel parallel to the DFOH at a uniform speed as shown in Fig. 2(a). Two motions in opposite directions are clearly exhibited in the space-time distribution presented in Fig. 2(b), and the speed of the assault boat is further calculated to be about 2.9 m/s. The recorded time domain signal of sensing channel is presented in Fig. 2(c), in which the signal intensity of the assault boat is obviously higher than the noise level. And further, from the time-frequency distribution presented in Fig. 2(d), it can be seen that the main frequency of the propeller is near 68.5 Hz, and its harmonic frequency signal is also detected. Besides, there is an extremely low frequency range from 3 Hz to 9 Hz, and we speculate it belongs to the waves caused by the assault boat. Then, in order to further verify the performance for underwater surveillance, a small ROV sized 380×348×168mm is adopted as underwater intrusive target. When the ROV suspends underwater near the DFOH, the signal along the whole DFOH is presented in Fig. 2(e), from which it can be seen that the ROV signal is located near the 15th meter of the DFOH. The record ROV signal in the 15m of the DFOH is separately presented in Fig. 2(f), which indicates the propellers of the ROV work intermittently to stabilize position and adjust posture for suspension underwater. From the PSD of the ROV signal presented in Fig. 2(g), it can be seen that although the frequency distribution of the ROV signal is very wide, there are still several characteristic frequencies including 316.67Hz and 715.5Hz.

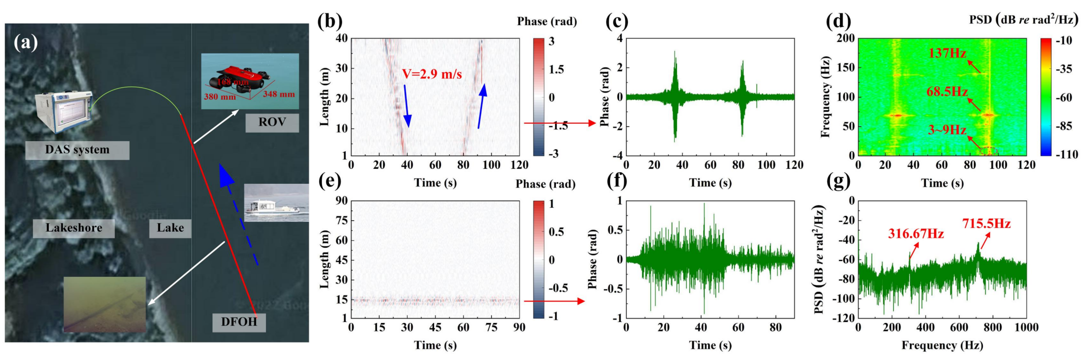

Fig.2 (a) The system setup of the lake trial; (b) The space-time distribution, (c) time domain waveform, (d) and time-frequency distribution of the assault boat in the lake trial; (e) The space-time distribution, (f) time domain waveform, (g) and PSD of the ROV signal.

In the lake trial, the intrusive targets containing boat and ROV is tested and recognized, and these intrusive activities can be detected and further reported, which positively exhibit the feasibility of surface and underwater surveillance based on φ-OTDR and DFOH with BEOF.

1.2. Sea trial

Next, the sea trial is carried out in South China Sea for the application of surface and underwater surveillance. As illustrated in Fig. 3(a), one end of the DFOH is fixed on the coast of an island, and the other one end of the DFOH is dragged to the sea and away from the coast, in which the length of DFOH is 300m. There is a small port on the right of the DFOH. The DAS system is placed in a house far away from the coast, and they are linked by a transmission fiber cable.

First of the sea trial, the surface targets with different size are tested in the same way. A small boat and an assault boat are respectively employed to move away from the port, and it should be noted that the assault boat waits for about 90s before moving away. The signals recorded by the DFOH are respectively presented in Fig. 3(b) and (c), and it can be seen that the signal of the assault boat is clearly stronger than the small boat, and from space-time distribution, we can simply and rapidly estimate the speed and direction of target movement, such as the small boat and the assault boat are both moving away from the coast, and the speed along the DOFH direction of the small boat is obviously slower than the assault boat, which are respectively estimated as 1.6m/s and 2.8m/s. Then, after getting these simple features, we can take quick action to the emergency intrusive targets and activities.

Then, the performance of the underwater frogman detection is also checkout, whose action is very covert underwater. The diver is arranged to move underwater, and the recorded signal of the diver is presented in Fig. 3(d), which indicates the diver is away from the coast, and the speed can be roughly estimated about 0.3m/s. Specially, the time domain and frequency domain of the frogman signal is separately presented in Fig. 3(e) and (f), from which the features including intensity and frequency are obvious, and the frequency of the frogman signal is mainly distributed below 300Hz, which is consistent with actual state. Therefore, the results of the system based on φ-OTDR and DFOH with BEOF demonstrating that it can provide an effective scheme for surface and underwater surveillance applications including underwater frogman detection.

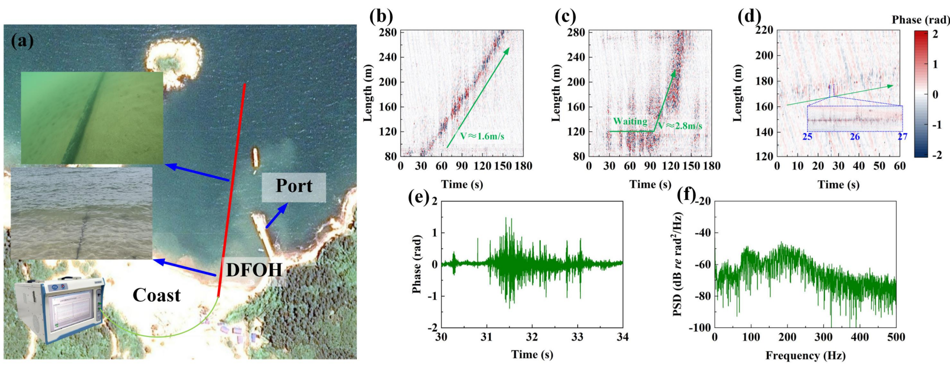

Fig.3 (a) The system setup of the sea trial; The space-time distribution of the (b) small boat, (c) assault boat, (d) and underwater frogman. (e) The time domain waveform, (f) and PSD of the frogman signal.

4. Conclusion

In this paper, the field test and its results of surface and underwater surveillance based on φ-OTDR and DFOH with BEOF is reported, of which the NEP is about 48 dB re:1μPa/Hz$^{1/2}$ at 1 kHz and lower than the level of the DSS0. In the field test various intrusive targets containing boat, frogman and ROV are detected, then the quick action to the emergency intrusion can be taken. The system can provide an effective scheme for the surface and underwater surveillance in the key water areas and ports, including the sea and island.

5. Acknowledgement

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