Near-field Multi-source Localization and Signal Enhancement for Fiber-optic DAS

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Abstract: The near-field multi-source localization and enhancement based on array signal processing (ASP) method are proposed for the distributed acoustic sensing (DAS), and it has been demonstrated with high positioning accuracy and great signal enhancement. © 2023 The Author(s)

1. Introduction

Nowadays, the DAS technique has been employed in the applications of the intrusion target detection due to the advantages of the large-scale distributed measurement and rapid response [1]. But most conventional DAS only obtains the position of the vibration signal along the one-dimensional direction of the sensing fiber, in which the actual three-dimensional spatial position information of the target source is indistinct. On the other hand, the signal enhancement is also significant for the target recognition in the perimeter intrusion prevention projects, but almost all the conventional signal enhancement methods are only based on the single sensing channel, such as the wavelet denoising (WD) and deep learning [2], where the available information for the target signal enhancement is finite, and they are even always not effective for the multi-source aliasing conditions.

Fortunately, the distributed sensing fiber deployed in DAS application can be equivalent to the array composed by a series of point sensors with a specific array steering vector (ATV). In recent years, some studies about the target source localization and signal enhancement based on the ASP method for DAS have been reported, but they are all conducted under the far-field condition [3-4], in which the distance from the target source to the deployed sensing fiber need to satisfy the far-field condition $r > 2D^2/\lambda$ (the λ and D are respectively the wavelength of the target source and the array aperture of the sensing fiber) and many related works achieve the special condition by shrinking the array aperture with dense spiral of the sensing fiber. But in many practical application scenarios, the array aperture of the sensing fiber or sensing cable is very large, it is very difficult to meet the far-field condition. For instance, if the D and λ are respectively 100 m and 3 m, the far-field distance (FFD) is away from the sensing fiber array more than 6 km underwater as shown in Fig. 1 (a). Therefore, the target source localization and enhancement under the near-field condition need to be investigated.

In this paper, we further investigate the near-field model of the DAS system, and the near-field multi-source localization and signal enhancement are both achieved in lab and field test with high performance assisted with the near-field ASP method, in which the near-field multiple signal classification (NF-MUSIC) algorithm and minimum variance distortionless response beamformer (MVDR-BF) are respectively employed for the near-field multi-source localization and target signal enhancement. The positioning errors of the lab test are no more than 0.01 m and 0.2°m, and the signal enhancement can reach 5 dB with only 5 sensing channels. So, it is firmly believed that the proposed near-field ASP-assisted DAS can be further widely applied for the near-field multi-target detection, localization, recognition, and early-warning in the applications such as the perimeter security.

2. Method and Principle

2.1. Near-field Model of the DAS

The phase-sensitive optical time domain reflectometry (φ-OTDR) based on the polarization diversity reception and heterodyne detection is employed as the interrogator in this work as shown in Fig. 1 (b), and the backscattering enhanced optical fiber (BEOF) with backscattering enhanced points (BEPs) is employed as the sensing fiber to improve the signal-to-noise ratio (SNR) of the DAS system. As illustrated in Fig. 1 (c), compared to the array aperture of the whole sensing fiber, the single sensing channel with a length of only a few meters still can be thought in the far-field range of the target source. So, when a single-frequency acoustic source is imposed on the sensing fiber, the output of the m-th sensing channel can also be approximately calculated by the strain integral with the far-field model, which can be further expressed as:

$$\Delta\phi_m(t) = \frac{2\xi}{k\cos\alpha}\left[\exp(0.5jkd\cos\alpha) - \exp(-0.5jkd\cos\alpha)\right]\exp\left[j\left(wt - \varphi_m\right)\right] + n_m(t) \tag{1}$$

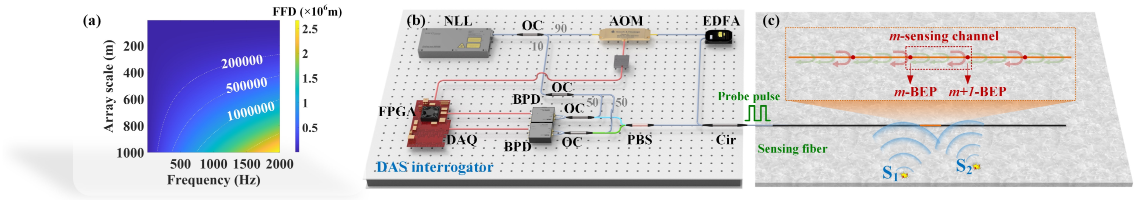

Fig. 1. (a) The relationship between the FFD and array scale; (b) The configuration of the employed DAS; (c) The near-field model of the BEOF-assisted DAS.

Where the ξ is the response coefficient of the sensing fiber, $k = 2\pi/\lambda$, w, and α are respectively the wavenumber, angular frequency, and incident direction of the source, d is the interval of the two adjacent BEPs along the BEOF, φ_m is the phase of the acoustic wave arriving at the center position of the m-th sensing channel, and $n_m(t)$ is the additional sensing channel noise. So, the straightly deployed BEOF with equidistant BEPs can be equivalent to the uniform line array (ULA) with a channel spacing of d. Thus, when there are $K(< M)$ sources distributes in the near-field range of the deployed BEOF, the near-field ATV of the DAS can be expressed as:

$$a\left(r_k, \theta_k, \gamma_k\right) = \begin{bmatrix} \frac{r_k}{d_{1,k}(r_k,\theta_k,\gamma_k)}\exp\left\{-jk\left[d_{1,k}\left(r_k,\theta_k,\gamma_k\right) - r_k\right]\right\} \\ \vdots \\ \frac{r_k}{d_{M,k}(r_k,\theta_k,\gamma_k)}\exp\left\{-jk\left[d_{M,k}\left(r_k,\theta_k,\gamma_k\right) - r_k\right]\right\} \end{bmatrix} \tag{2}$$

2.2. Near-field Multi-source Localization and Signal Enhancement

Under the DAS near-field model, the ASP menthods are introduced to achieve the near-field multi-source localization and signal enhancement. Firstly, the NF-MUSIC algorithm is employed for the near-field source localization [5], in which the joint estimation of the distance and direction can be achieved because the ATV of the DAS is orthogonal to the noise subspace of the covariance matrix R_{xx}, so the estimation of the near-field source can be gained by the following spatial spectrum estimation (SSE):

$$\left(\hat{r}_k, \hat{\theta}_k, \hat{\gamma}_k\right) = \arg\max_{r,\theta,\gamma} \frac{1}{a^H(r,\theta,\gamma)U_n U_n^H a(r,\theta,\gamma)} \tag{3}$$

The SSE of the NF-MUSIC algorithm maintains the high resolution and estimation accuracy, which can directly estimate the positions and ranges for all the near-field sources simultaneously without paring algorithms.

After the position estimation of the near-field target source, the MVDR-BF is employed for the target source signal enhancement [6]. The MVDR-BF is an adaptive BF which can adaptively minimize the power of ESA at the desired direction while maximize the signal to interference plus noise ratio (SINR) at the same time. The weight vector of the near-field MVDR-BF can be expressed as:

$$w = \frac{R_{J+n}^{-1} a\left(r_d, \theta_d, \gamma_d\right)}{a^H\left(r_d, \theta_d, \gamma_d\right) R_{J+n}^{-1} a\left(r_d, \theta_d, \gamma_d\right)} \tag{4}$$

Where the R_{J+n} is the covariance matrix of the interference signals and noise, but it is difficult to be obtained in the practical applications, so it is always estimated by the covariance matrix of the DAS sampling date.

3. Experimental Setup and Results

To test and verify the performance of the proposed method in DAS, the experiment was firstly conducted in the laboratory. As illustrated in Fig. 2 (a), the BEOF is wound around the cylindrical transducer to enhance the sensitivity. The diameter of the cylindrical transducer is 50 mm, and the helical BEOF pattern is about 30 laps, whose width is about 30 mm. The sensitivity of each sensing unit is calibrated to be about -113 dB $re:1\ rad/\mu Pa$ at the frequency of 500 Hz and 800 Hz in air. The five sensitivity-enhanced units is in-line arrangement, whose interval is set to be 0.3 m, and the unit3 is set as the reference unit.

Two sound sources are respectively set to be at (0.6 m, 0°) and (0.8485 m, 45°), whose frequencies are respectively set as 500 Hz and 800 Hz. And the general experimental setup meets the near-field conditions. The localization result based on the NF-MUSIC algorithm assisted with the incoherent signal-subspace method (ISSM) [7] is illustrated in Fig. 2 (b), whose errors are no more than 0.01 m and 0.2°. Then, the signal enhancements for the different target sources are further obtained by the near-field MVDR-BF and illustrated in Fig. 2 (c), in which the two narrowband signals at different positions can be separated, and the noise can be suppressed about 5 dB. The results show the proposed method can effectively suppress the aliasing noise and ambient noise, and the separated different target signals both have higher fidelity, which is greatly significant for the further target identification.

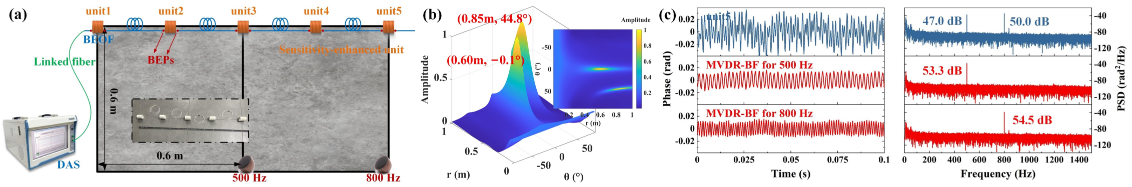

Fig. 2. (a) The setup of the lab test; (b) The result of the near-field multi-source localization results; (c) The signal enhancement for the target source at different positions.

The field test of the underwater acoustic signal detection is further conducted. The test setup is shown in Fig. 3 (a), the ultra-highly sensitive and lightweight fiber-optic hydrophone cable (FOHC) proposed in our previous work is employed for the underwater acoustic signal detection [8]. The channel spacing of the employed FOHC is 1 m. To make certain the employed part underwater is straight as much as possible, the only middle 20 sensing channels is employed, which can be equivalent to be a ULA containing 20 ESUs with an interval of 1 m.

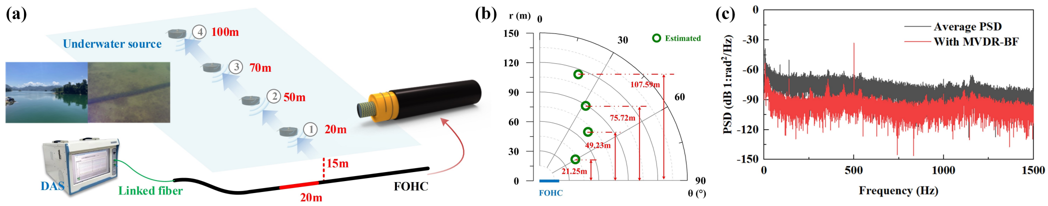

Fig. 3. (a) The setup of the field test; (b) The demonstration of the near-field localization results in the field test; (c) The signal enhancement with 20 sensing channels beamformed.

The underwater source is set to away from the FOHC perpendicularly as much as possible. The 500 Hz sine signal is emitted at the positions with the approximate distances of 20 m, 50 m, 70 m, and 100 m, respectively, which all satisfy the near-field conditions. The estimation of the underwater source at different preset positions is successively achieved by the NF-MUSIC algorithm and shown in Fig. 3 (b), in which the four estimated positions are approximately in a straight line and perpendicular to the FOHC. The error is about a few meters and mainly originates from the actual positions are roughly set, besides, the ambient noise and multi-path effect also can worsen the localization results. Next, the near-field MVDR-BF is utilized to beamform the collected distributed signals for the signal enhancement. The result in Fig. 3 (c) shows the SNR can be averagely improved approximately 16.806 dB after 20 sensing channels added. In general, the sensitivity-enhanced DAS with the proposed method can locate and enhance the near-field source, which is beneficial for the target localization and recognition.

4. Discussion and Conclusion

In this paper, the near-field model of the DAS system is investigated, and the near-field multi-source localization and signal enhancement are both achieved in lab and field test with high performance. The positioning error and signal enhancement in lab test are respectively no more than (0.01 m, 0.2°) and up to 5 dB. Although we only demonstrated incoherent sources, it has proved the DAS can be assisted with various near-field ASP methods to enhance the performance. So overall, the DAS with the near-field ASP method has immense potential to be applied in the perimeter intrusion prevention projects to achieve quick localization, recognition, and early-warning.

5. Acknowledgement

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