Research on Passive Detection Technology of Underwater Target Tone Based on Unmanned Underwater Vehicle

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A beam self-tracking technique used for line-spectrum detection is proposed based on the unmanned underwater vehicle (UUV) sonar array. The main idea of this technique is to introduce the self-tuning filtering characteristics of the adaptive line enhancer (ALE) into the broadband beamforming technique. This proposed technique can adaptively form a real-time tracking beam pointed to a time-varying direction of arrival (DOA) of line spectrum target, while suppressing the interferences and broadband noise. UUV-platform swinging, UUV and targets maneuvering, etc. usually cause the target DOA fast time-varying. In that case, our technique can be applied to obtain the waveform of line spectrum signals with a spatial gain.

Introduction: The line spectrum signals radiated from underwater vessels are of great significance for sonar systems to detect the underwater objects. On the basis of the unmanned underwater vehicle (UUV) sonar array, the waveform of line spectrum signals can be obtained by a conventional broadband beamforming technique with a spatial processing gain, in which the main beam of the beamformer is pointed to the direction of arrival (DOA) of line spectrum. The DOA estimation of the line spectrum signal (unknown frequency and low signal energy) usually requires the DOA to remain stable for a long time, whose estimation result is used to steer the main beam. However, in real underwater environments, the UUV-platform swinging, the rotational motion of UUV, the fast maneuvering of line spectrum target, etc., are inevitable, which induce rapid changes in the DOA of line spectrum[1]. In those cases, the DOA of line spectrum cannot be effectively estimated. Then the main beam direction may deviate from the DOA of line spectrum which would cause a spatial processing gain loss.

In this Letter, we propose a beam self-tracking technique applied to the UUV sonar array for line spectrum detection. The main idea of this technique is to introduce the self-tuning filtering characteristics of the adaptive line enhancer (ALE) [2] into the broadband beamforming technique [3]. Based on the principle of ALE, the structure of the conventional broadband beamformer is reconstructed. This technique does not need to estimate the DOA of line spectrum in advance and can adaptively form a real-time tracking beam pointed to the DOA of line spectrum. Moreover, it can suppress the interferences and broadband noise. The proposed technique is suitable for the line spectrum detection based on the UUV sonar array.

Signal model: Fig. 1 shows a linear UUV sonar array with *M* sensors. We consider the detection of the line spectrum signals in a subregion of interest Θ, whose complementary region is denoted as $\bar{\Theta}$. *H* unknown line spectrum signals impinge on the *M*-element sensor array as plane waves, whose frequencies and amplitudes are respectively denoted as f_h and A_h, $h = 1, 2, ..., H$. The sampling rate is f_s and the sampled signal from the sensor *m* is written as

$$x_m(n)=\sum_{h=1}^{H} A_h \exp\left[j\left(\omega_h n + \varphi_h(n)m\right)\right]+g_m(n),\ m=0,1,...,M-1 \tag{1}$$

where $\omega_h = 2\pi f_h / f_s$ and n is the index of sample points. $g_m(n)$ denotes the broadband noise. $\varphi_h(n) = 2\pi f_h d \sin\left[\theta_h(n)\right]/\mathrm{C}$ denotes the line spectrum phase difference between adjacent sensors, d is the space of adjacent sensors and C is the underwater sound velocity. $\theta_h(n)$ denotes the DOA of line spectrum which is time-varying due to UUV-platform swinging, UUV and targets maneuvering, etc.. We assume, at the *n*-th sampling time, the former *D* line spectrum signals are located inside Θ, i.e., $\theta_h(n) \in \Theta$, *h*=1, 2,…, *D* and the remaining *H-D* line spectrum signals (seen as the interferences) are located outside Θ, i.e., $\theta_h(n) \in \bar{\Theta}$, *h*= *D*+1, *D*+2,…, *H*.

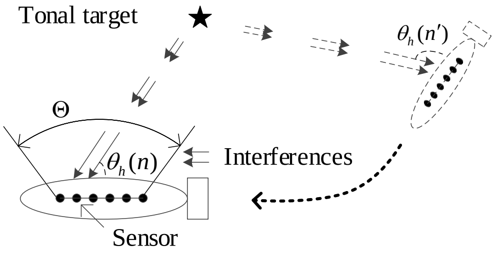


Fig. 1 *UUV sonar array diagram*

Proposed technique: A conventional broadband beamformer is shown in Fig. 2. The pre-delays τ_m, *m*=0, 1, …, *M*-1, are selected to steer the main beam to the target DOA which is known a priori. Following the steering delays, the tapped delay lines (TDLs) are employed to constrain the noise power and the interferences. However, in the case of the line-spectrum target DOA $\theta_h(n)$ changing rapidly, $\theta_h(n)$ cannot be effectively estimated in advance. The conventional broadband beamformer is not suitable for the case. Since the steering delays can be merged into the TDLs, the main beam can be steered by adjusting the tap weights[4]. Thus, a broadband beamforming structure without pre-steering (shown as the TDLs parts in Fig.2) is employed in the proposed beam self-tracking technique and it is given by $\mathrm{y}(n) = \mathbf{W}^H \mathbf{X}$, where $\mathbf{W} = \left[w_{0,0}, \cdots, w_{0,M-1}, w_{1,0}, \cdots, w_{1,M-1}, \cdots, w_{L-1,M-1}\right]^T$, and $\mathbf{X}(n) = \left[\bar{\mathbf{x}}_0^T(\mathrm{n}), \cdots, \bar{\mathbf{x}}_m^T(\mathrm{n}), \cdots, \bar{\mathbf{x}}_{M-1}^T(\mathrm{n})\right]^T$, $\bar{\mathbf{x}}(\mathrm{n}) = \left[x_0(\mathrm{n}), \cdots, x_m(\mathrm{n}), \cdots, x_{M-1}(\mathrm{n})\right]^T$. Then, the weight vector $\mathbf{W}$ is adaptively updated by means of the self-tuning filtering characteristics of ALE to keep the main beam pointed to $\theta_h(n)$, which does not need to estimate the DOA of line spectrum in advance.

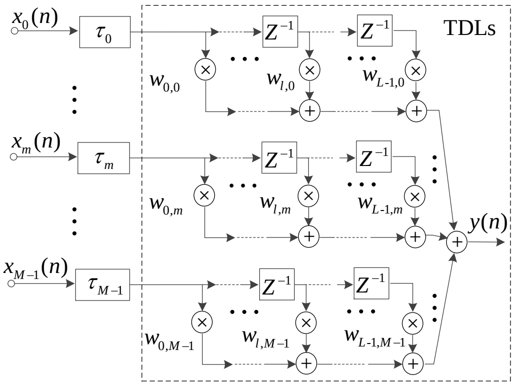


Fig. 2 *Conventional broadband beamformer*

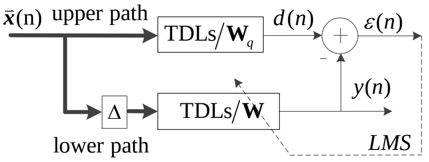


Fig. 3 *Block diagram of the beam self-tracking technique*

Fig. 3 shows the self-tracking beamformer block diagram, which includes the upper and lower processing paths. A fixed time delay Δ is inserted in the lower path to decorrelate the wideband components between the two paths. The line spectrum components, because of their periodic nature, remain correlated with each other[2]. $\mathbf{W}$ is iteratively updated by the least-mean-square (LMS) algorithm [2] aiming at minimizing the error cost function $\xi(\mathbf{W}) = E\left\{\left|d(\mathrm{n}) - \mathbf{W}^H\mathbf{X}(n\text{-}\Delta)\right|^2\right\}$. The update formula of $\mathbf{W}$ is given by

$$\mathbf{W}(n+1) = \mathbf{W}(n) + \mu\varepsilon(n)\mathbf{X}(n) \tag{2}$$

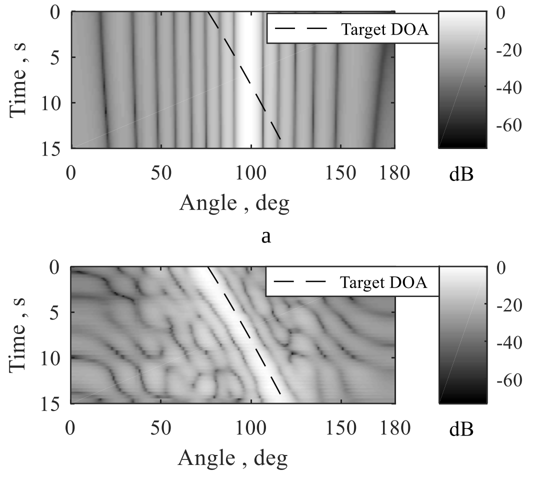
where $\varepsilon(n) = d(\mathrm{n}) - \mathbf{W}^H(n)\mathbf{X}(n)$ is the residual error and μ is the step size. The desired signal $d(\mathrm{n})$ is expressed as $d(\mathrm{n})\text{=}\mathbf{W}_q^T\mathbf{X}(n)$, where $\mathbf{W}_q = \left[w_{q\_0,0}, \cdots, w_{q\_0,M-1}, w_{q\_1,0}, \cdots, w_{q\_1,M-1}, \cdots, w_{q\_L-1,M-1}\right]^T$. The fixed weight vector $\mathbf{W}_q$ is chosen so as to eliminate the interferences in $\bar{\Theta}$ and pass the signal of interest in Θ (convex optimization tools are widely utilized to find $\mathbf{W}_q$ [5]). In addition, the weight vector $\mathbf{W}$ can be projected into Θ by multiplying a project matrix $\mathbf{BB}^H$ to further suppress the interferences, where $\mathbf{B}$ is designed by the discrete prolate spheroidal sequences-based approach as described in [1, 6].

Performance analysis: $\mathbf{W}^*$ denotes the optimal solution to minimize the error cost function $\xi(\mathbf{W})$. Under some reasonable assumptions, $\mathbf{W}^*$ can be analytically expressed by means of the undetermined coefficient method described in [7]. Then the beam response function under $\mathbf{W}^*$ is given by

$$\begin{aligned} B_n(\varphi,\omega) = &\sum_{h=1}^{D} \frac{A_h^2}{2\sigma_0^2 + LMA_h^2} \frac{\sin\left[\left(\varphi_h(n) - \varphi\right)M/2\right]}{\sin\left[\left(\varphi_h(n) - \varphi\right)/2\right]} \frac{\sin\left[\left(\omega_h - \omega\right)L/2\right]}{\sin\left[\left(\omega_h - \omega\right)/2\right]} \\ &\times \mathrm{e}^{j(\varphi_h(n)-\varphi)(M-1)/2} \mathrm{e}^{j(\omega_h-\omega)(L-1)/2} \mathrm{e}^{j2\pi\omega_h\Delta} \end{aligned} \tag{3}$$

where σ_0^2 denotes the variance of broadband noise. $\omega = 2\pi f / f_s$ is the angular frequency, $\varphi = 2\pi f \sin(\theta) d / \mathrm{C}$ denotes the spatial frequency. Equation (3) can be seen as the sum of the responses of the *D* beams, in which each beam points to the DOA ($\theta_h(n)$) and frequency (f_h) of one line spectrum located in Θ. Since the real-time updating in **Error! Reference source not found.** keep $\mathbf{W}$ close to $\mathbf{W}^*$, the beam response function of the self-tracking beamformer approximates(3). Therefore, the self-tracking beamformer can adaptively form real-time tracking beams pointed to the line spectrum signals in Θ. Furthermore, the spatial processing gain is obtained and the interferences as well as the broadband noise are suppressed.

Simulations: Assume a uniform linear array with M=20 sensors spaced d=1.36m apart. The subregion of interest Θ is set to be 50°~130°. A 435Hz line spectrum signal (the target of interest) is located inside Θ and the signal-to-noise ratio (SNR) is -20dB. The target DOA varies from 75° to 120° over 15 seconds. Besides, a line spectrum interference of 380Hz is located in the direction of 160° and the interference-to-noise ratio is 0 dB. The sampling rate f_s is 2500Hz. The number of TDL nodes is L=100. The delay Δ is set to 0.01s.

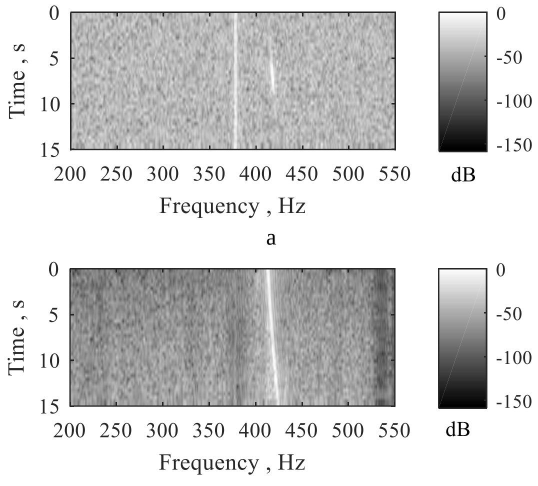


a

b

Fig. 4 *Beam pattern at target frequency bin versus time*
a Conventional beamformer (pointed to100°)
b Self-tracking beamformer

Fig.4a shows the beam pattern of a conventional broadband beamformer, in which a beam pointing deviation from the fast time-varying target DOA is present. When the beam pointing deviation appears, the line spectrum amplitude of target in Fig.5a has a large attenuation. However, the main-beam of the self-tracking beamformer can adaptively track the target DOA, as shown in Fig.4b. Then, in Fig.5b, the line spectrum signal of the target can be observed over the entire time range and the interferences as well as the broadband noise are suppressed efficiently.



a

b

Fig. 5 *Time-frequency analysis of wideband beamformer output*
a Conventional beamformer (pointed to100°)
b Self-tracking beamformer

Conclusion: This letter proposes a beam self-tracking technique to detect the line spectrum signal based on the UUV sonar array. The proposed technique can adaptively form a real-time tracking beam pointed to the DOA of line spectrum and avoids the beam pointing deviation due to UUV-platform swinging, UUV and targets manoeuvring, etc.. Meanwhile, the proposed technique can effectively suppress the interferences and broadband noise. Simulation results verify the effectiveness of the proposed technique.

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