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Multi-beam Beamforming for Bearing and Frequency Estimation in Passive SONAR Detection

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Abstract—— **Multi-beam beamforming technique has been a useful method for detecting target signals and estimating target bearing in passive detection. To find target bearings, however, the frequency information of the target signal has to be given. In this paper, a simple but powerful method is proposed to simultaneously extract both frequency and bearing information without any prior information about the target signals. The proposed method adjusts multiple multi-beams using duplicate beamforming. Then, the gain ratio of the beamformer outputs is compared to estimate the signal parameters. Simulation results show that the proposed method can be effectively used to estimate the bearing and frequency of an incoming target signal using only the pre-formed multiple beams as in a conventional passive sonar system.**

Keywords—SONAR, Beamforming; parameter estimation; duplicate beam; multi-beam beamformer

I. Introduction

Passive sonar systems aim to find a target signal and extract parameters from the received signal. For this purpose, a conventional sonar system uses a set of spectral beams to enhance the signal-to-noise ratio (SNR) and to find the bearing (or angle) of incoming signals [1]. These beams are designed to steer toward the predetermined directions followed by the energy detector. The largest energy appears on one of the beams that has the steering angle closest to the bearing of the incoming signal.

Due to its robustness and simple structure, the delay and sum beamformer (DAS) has been the most popular method for implementing passive sonar beamformers [1]. However, the DAS beamformer suffers from large spectral width of the main beam, which hinders fine estimation of the target bearings. To cope with this problem, this paper proposes a parameter estimation method using gain comparison between pre-formed beams. The gain difference of the adjacent beams depends on the bearing of the incoming signals. Using this fact, the gain comparison has been applied to several radar and sonar detection systems [2]. These methods use the output signals of a set of pre-formed multi-beam to find the gain difference of adjacent beams and to estimate the bearing of the incoming signals. This paper additionally considers the fact that the beampattern characteristics of a delay-based beamformer also depend on the frequency of the incoming signals. Based on this, we found that the frequency information can be also extracted from the pre-formed beams. To obtain both the bearing and the frequency of the incoming signals, we used a duplicate beam in a similar manner to the multi-beam method. The gain differences of both the duplicate beam and multi-beam are used to estimate the bearing and frequency of the narrowband incoming signals simultaneously.

This paper is organized as follows. Section II presents the main details of the proposed method using duplicate and multi-beam beamforming. Simulation results are covered in section III, and section IV concludes the paper.

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II. Multi-beam and Duplicate Beamformng

A. Joint Duplicate and Mult-Beam Beamforming

The output of a conventional beamformer can be obtained by combining weighted and delayed versions of input signals:

$$y(t) = \sum_{m=0}^{M-1} w_m x_m (t - \tau_m) + n(t), \tag{1}$$

where τ_m and w_m are the time delay and weight for input signal $x_m(t)$ at the mth sensor among total M sensors, respectively, and $n(t)$ represents additive white Gaussian noise. The time delay can be implemented by a tapped delay line. Multi-beam beamforming uses a set of beams that steer toward multiple pre-determined bearings. Each beam has its own beam output signal. Using gain ratio of the adjacent beams the more precise bearing estimation result can be obtained. The gain ratio between the beamformer l and beamformer (l+1) can be expressed using the gain of each beamformer, G_l and G_{l+1}, as follows:

$$p_{l,l+1} = \frac{p_l}{p_{l+1}} = \frac{G_l \sigma_s^2}{G_{l+1} \sigma_s^2} = \frac{G_l}{G_{l+1}}, \tag{2}$$

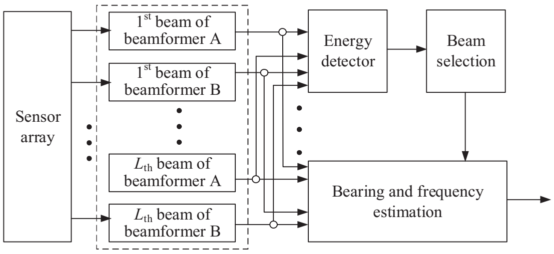

Fig. 1. The entire configuration of the proposed method.

where p_l means the output power of the beamformer l and σ_s^2 is the input signal power.

A duplicate beam is a pair of beams that have the same steering direction but different beampattern and it can be formed using different weightings with the same time delays for a received array signal. In this paper, we consider Cosine weighting, Hamming weighting, and Uniform weighting (for a conventional DAS beamformer) to produce duplicate beams. When M is odd, the Cosine and Hamming weightings at the mth sensor are respectively defined by:

$$w_{\cos,m} = \sin\left(\frac{\pi}{2M}\right)\cos\left(\pi\frac{m-(M-1)/2}{M}\right), \quad (3)$$

$$w_{ham,m} = 0.54 + 0.46\cos\left(\frac{2\pi m}{M}\right). \quad (4)$$

B. Joint Duplicate and Mult-Beam Beamforming

In order to estimate the frequency and bearing of a target signal, the proposed method additionally uses the ratio of the beamformer output gain of the duplicate beams as follows:

$$p_{l,Dup} = \frac{G_{l,\mathrm{A}}\sigma_s^2}{G_{l,\mathrm{B}}\sigma_s^2} = \frac{G_{l,\mathrm{A}}}{G_{l,\mathrm{B}}}, \quad (5)$$

where $G_{l,\mathrm{A}}$ and $G_{l,\mathrm{B}}$ are the gains obtained from the lth beam of beamformers A and B, respectively. The entire procedure of the proposed method is described in Fig. 1. Here, total $2L$ beams are employed. The parameter estimation can be performed by comparing the calculated gain ratio with the theoretical values. Theoretical values about the gain ratio can be obtained from the beampattern expressions in [1] with varying frequencies and bearings for the lth and $(l+1)$th beams as follows:

$$B_{l,\mathrm{Dup}}(\lambda,\theta) = \frac{B_{l,\mathrm{A}}(\lambda,\theta;\theta_l)}{B_{l,\mathrm{B}}(\lambda,\theta;\theta_l)} \text{ and } B_{l,l+1}(\lambda,\theta) = \frac{B_{l,\mathrm{A}}(\lambda,\theta;\theta_l)}{B_{l+1,\mathrm{A}}(\lambda,\theta;\theta_{l+1})}, \quad (6)$$

where $B_{l,\mathrm{A}}(\lambda,\theta;\theta_l)$ is the beampattern of the lth beam of beamformer A and $B_{l,\mathrm{B}}(\lambda,\theta;\theta_l)$ is the beampattern of the lth beam of beamformer B. Finally, the estimation result can be obtained as follows:

$$(\hat{\lambda},\hat{\theta}) = \arg\min_{\lambda,\theta}\left[\left\{p_{l,Dup} - B_{l,Dup}(\lambda,\theta)\right\}^2 + \left\{p_{l,l+1} - B_{l,l+1}(\lambda,\theta)\right\}^2\right]. \quad (7)$$

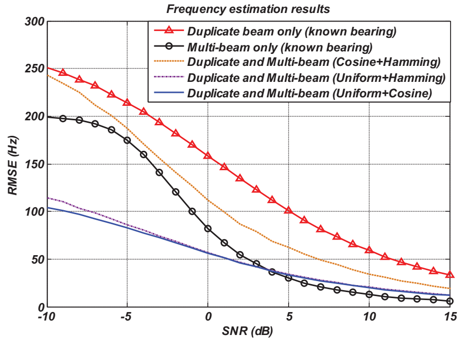

Fig. 2. Frequency estimation results.

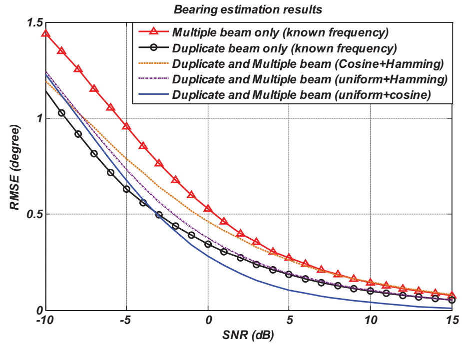

Fig. 3. Bearing estimation results.

III. SIMULATION RESULTS

The simulations were performed under the assumption that 11-element ULA is used and steering directions between adjacent beams are separated by 10º from each other. A narrowband signal with a frequency of 1.2 kHz was used, and the bearing of an incoming signal was 3º. Three different duplicate beam pairs are considered: DAS-Cosine, DAS-Hamming, and Cosine-Hamming are compared with a case where only one multi-beam or duplicate beam is used. Figs. 2 and 3 respectively show the root-mean-square errors of the frequency and bearing estimation results according to the signal-to-noise ratio. The proposed method could achieve the similar estimation performance with the methods which use prior information about target signals.

IV. CONCLUSION

This paper presented an efficient method to estimate the bearing and frequency of incoming target signals. By combining duplicate beam and multi-beam beamforming, the proposed method estimates both parameters simultaneously using pre-formed beamforming and energy detection procedure without any additional processing.

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