ESTIMATION OF POSITIONS OF LOCAL NARROW-BAND SOURCES ON A SHIP HULL USING A VERTICAL ANTENNA ARRAY

Orlov D. A., Rodionov A. A. and Turchin V. I.

Institute of Applied Physics of the Russian Academy of Sciences,
Nizhny Novgorod, Russia
E-mail: alexr@hydro.appl.sci-nnov.ru

Abstract

A method for estimation of positions of local narrow-band sources on a moving ship, allowing one to identify the mechanisms making the greatest contribution to its sound pressure level, is proposed in the paper. The actuality of this problem is related to strengthening the requirements imposed on the sound pressure level of ships because of ecological and other requirements. The method is based on space-time filtering of the signal received by the elements of a vertical antenna array. The ship is supposed to move straightly and uniformly at a short distance from the array; the track parameters are supposed to be known. The results of the method testing with the use of the data obtained in sea experiment are presented in the paper. The testing has shown that the source localizing precision is close to the theoretically achievable one.

An analysis of the method error is performed in a wide frequency range using numerical modeling.

Keywords: Acoustic array systems and processing, source localization and parameter estimation.

1. INTRODUCTION

Nowadays, the norms imposed on ships' sound pressure level (SPL) have a growing tendency to strengthen because of various factors such as ecological requirements [1]. This means that there is a need not only for reliable methods for measuring the SPL of ships (see, for example, [2]) but also for methods for identifying the mechanisms making the greatest contribution to the SPL. A great contribution to the total SPL of a ship is typically given by the so-called narrow-band components (NBC) which are the spectrum components produced by narrow-band sources, usually representing specific ship mechanisms such as engine or propeller. Therefore, the mechanisms making the greatest contribution to the SPL can be identified by means of localizing the corresponding NBCs.

In the present paper, a method for estimation of positions of NBCs on a ship hull using the signal received by a vertical receiving array is proposed. It is supposed that each NBC is produced by a point monopole or dipole source, and the medium can be modeled as free space or half-space.

The scheme of the experiment and the method are described in Section 2. The method precision is analyzed using numerical modeling in Section 3. The results of experimental testing of the method are given in Section 4.

2. THE METHOD

A typical scheme of the experiment is shown in Fig. 1. A ship is supposed to move straightly and uniformly at a short distance from a vertical array. The use of a vertical array allows, due to its spatial selectivity, to increase the signal-to-noise ratio and, therefore, it allows for detection of weaker sources (and/or under greater interference) than it is possible by means of a single hydrophone.

The j-th snapshot at the array output, after narrow-band filtering at the frequency f, which is chosen to be close to the NBC frequency (so that the signal from the NBC, taking into account the Doppler effect, is inside

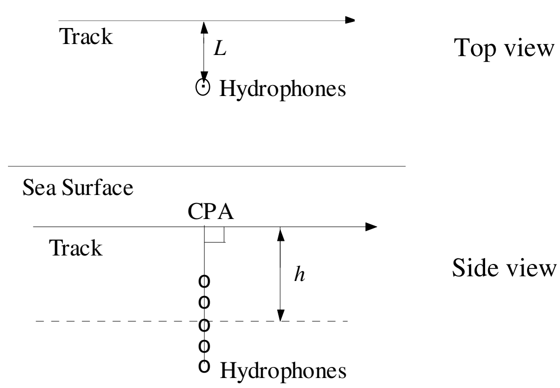

Fig. 1. Scheme of the experiment.

the filter passband), can be expressed as

$$\mathbf{x}_j = \theta_0 \mathbf{s}(t_j, \boldsymbol{\theta}) + \boldsymbol{\xi}_j, \quad j = 1, ..., J, \qquad (1)$$

where the $N \times 1$ vector $\boldsymbol{\xi}_j$ is assumed to be isotropic white Gaussian zero-mean noise (N is the number of hydrophones in the array), the $N \times 1$ vector $\mathbf{s}(t_j, \boldsymbol{\theta})$ represents the deterministic component with the known space-time shape depending on the vector of unknown parameters $\boldsymbol{\theta}$ including the exact NBC frequency f_0 and the track parameters, θ_0 is the unknown complex amplitude. It is well known that, in this case, the optimal processing is matched space-time filtering [3], so that determining of unknown parameters represents maximization of correlation coefficient between the received signal and the model signal:

$$K(\boldsymbol{\theta}) = \frac{\left| \sum_j \mathbf{s}^H(t_j, \boldsymbol{\theta}) \mathbf{x}_j \right|}{\sqrt{\sum_j \mathbf{x}_j^H \mathbf{x}_j \cdot \sum_{n,j} \mathbf{s}^H(t_j, \boldsymbol{\theta}) \mathbf{s}(t_j, \boldsymbol{\theta})}} \to \max_{\boldsymbol{\theta}}, \quad (2)$$

where H denotes the Hermitian transpose. The model of deterministic signal can be chosen as either

$$s_n(t_j) = \frac{1}{r_n(t_j)} \exp\left\{ i\kappa_0 r_n(t_j) + i2\pi(f - f_0)t_j \right\} \quad (3)$$

or

$$\begin{aligned} s_n(t_j) = \left(i\kappa_0 - r_n^{-1}(t_j) \right) z_n r_n^{-2}(t_j) \times \\ \times \exp\left\{ i\kappa_0 r_n(t_j) + i2\pi(f - f_0)t_j \right\} \end{aligned}. \quad (4)$$

Here, z_n is the depth of the n-th hydrophone, $r_n(t_j)$ is the current distance from the NBC to the n-th hydrophone (it depends on the unknown parameters of the track), $\kappa_0 = 2\pi f_0 / c$ is the wavenumber, f is the filtering frequency, f_0 is the exact NBC frequency, c is the sound speed in water. The Eq. (3) corresponds to a monopole source; the Eq. (4) corresponds to a vertical dipole. At low frequencies, the surface reflection can be taken into account: it is close to the mirror-like one, and the surface reflection coefficient can be assumed to be –1. This leads to appearance of additional summands in (3) and (4).

Note that the distance $r_n(t_j)$ depends on several parameters which are common for several NBCs (these parameters describe movement of the ship). The parameter which is different for different NBCs is CPA time (CPA is the closest point of approach); the difference of this parameter between various NBCs, taking into account the obtained ship velocity V, allows one to determine the NBCs' relative position. In practice, it is more convenient to determine the ship track independently, using a special method (such as the one presented in [4]) utilizing a special tone source placed on the ship. In this case, the NBC's position can be counted off from the known position of the special source. The distance $r_n(t_j)$ can be then expressed as

$$r_n(t_j) = \sqrt{L^2 + z_n^2 + [V(t_j - t_0) - X]^2}, \qquad (5)$$

where V is the ship velocity, t_0 is the CPA time of the special source, X is the shift of the NBC source with respect to the special source (the NBC positions that are closer to the ship stern correspond to positive X). Accordingly, the track parameters L, h, V, t_0 are supposed to be preliminarily determined using the special source for tracking; the parameters related to the NBC are the shift X (with respect to the special source) and the frequency f_0. The limits of frequency search can be made narrow enough if a preliminary rough spectrum estimate is used (the result of this estimation can be chosen as the filtering frequency f); the limits of search of the shift X are given by the ship length and the position of the special source for tracking. Then, the task of localizing of the NBC becomes a maximization of K over the two parameters:

$$K \to \max_{(X, f_0)}. \qquad (6)$$

3. Analysis of Localization Precision Using Numerical Simulation

The localization method considered in this paper belongs to the class of the so-called inverse aperture synthesis methods [5]. The synthesized aperture, in our case, is represented by the ship track. It is well known that precision of source localization depends for synthesized aperture on its spatial resolution as well as the signal-to-noise ratio. The number of hydrophones in the array does not influence on the spatial resolution because a vertical array does not possess selectivity in the direction of the ship track. However, the presence of multiple hydrophones increases the effective signal-to-noise ratio. As it is known that, if the distance between the CPA and the array is greater than the wavelength, the spatial resolution is close to $\lambda/2$, where λ is the NBC source wavelength [6]. In Fig. 2, the dependence of the spatial ambiguity function width on frequency, obtained by means of numerical modeling, is demonstrated. The solid line shows the dependence of $\lambda/2$ on

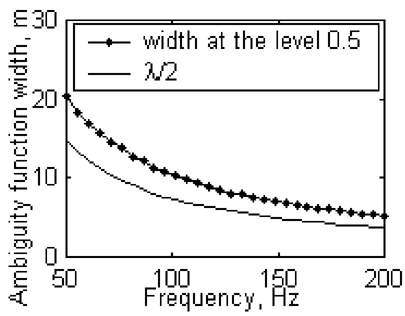

Fig. 2. Dependence of spatial resolution on frequency.

frequency. As it follows from Fig. 2, the spatial resolution is close to its theoretical value.

4. EXPERIMENTAL RESULTS

For testing the method, a sea experiment was performed. A vertical array consisting of 11 hydrophones with the spacing of 3 m was used. The depth of the array center was about 60 m. The distance in horizontal plane between the array and the CPA was in the range 10–30 m. The depth of the special source for tracking, as well as the source of NBC sources, was assumed to be 2 m (the ship's draught was about 2.5 m).

In Fig. 3, the ambiguity functions $K(X, f_0)$ obtained both using the numerical modeling and from the experiment are demonstrated: (a) and (b) are experimental results for the models (4) and (3), respectively; (c) is the theoretical dependence for the model (4); (d) demonstrates the sections of (a) and (c) for the obtained NBC frequency by solid and dashed line, respectively. It follows from Fig. 3 that the ship possessed only one NBC source in the frequency region corresponding to the filter passband; this is confirmed by a good agreement between the shapes of experimental and theoretical ambiguity functions (see Fig. 3d). Comparison between the results of using the models (4) and (3) shows that using a monopole source model leads to somewhat less correlation coefficient, whereas the shape and the position of the global maximum changes insignificantly. As was noted in Section 2, the model can include the surface reflection; however, it was shown that taking the surface reflection into account does not lead to substantial changes in the ambiguity function.

Fig. 4 demonstrates the result of processing of ten experimental records in the case when a ship obtained two NBCs. As can be seen from Fig. 4, the shift estimates are localized in different areas for these NBCs.

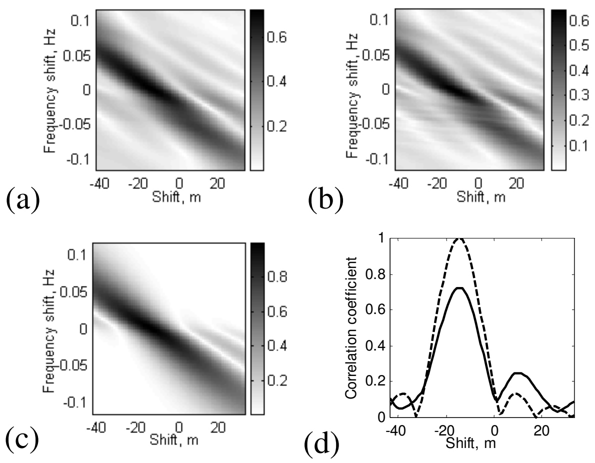

Fig. 3. Ambiguity function $K(X, f_0)$ in dependence on the frequency shift $f - f_0$ and the source shift along the ship hull with respect to the special source position.

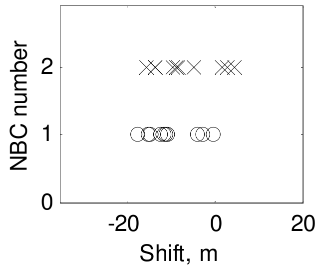

Fig. 4. Estimates of the shift along the ship hull with respect to the special source for two NBCs obtained from ten experimental records.

Three records out of ten give the results shifted with respect to the results obtained from other records so their results can be interpreted as "wrong" estimates. After they were excluded from averaging, the standard deviations for the first and the second NBCs become 2.6 m and 3.8 m, respectively.

5. CONCLUSION

In the present paper, a method for estimation of positions of local narrow-band sources on a ship hull is presented. The method is based on space-time filtering of the signal received by a vertical receiving array. The precision of the method has been estimated using numerical modeling. The results of experimental testing of the method are presented.

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