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High resolution time-delay estimation of underwater target geometric scattering

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ABSTRACT

The geometric scatterings carry the information of the shape of an underwater target. While the time-delay of the weak geometric scattering exists in the received signal cannot be obtained accurately by the conventional time-delay estimation methods because of the limit of the main-lobe width and the interferences from the side-lobe. In this paper, we propose a high resolution time-delay estimation (HRTDE) scheme consisting of two steps. Firstly, when a linear-frequency-modulated (LFM) pulse is transmitted by sonar, the dechirping method transforms the geometric scatterings with different time-delays into multiple single-frequency components respectively, in which the frequency of the dechirped signal shows a linear relationship with the time-delay of the geometric scattering. Then the multiple signal classification (MUSIC) algorithm is adopted to increase the spectrum resolution when multiple single-frequency signals exist in the dechirped signal and the frequency interval is smaller than the frequency resolution limit of the Fourier transform. Simulation results show that the main lobe of the proposed scheme is sharper and with less interference from the side-lobe, compared with the conventional time-delay estimation methods. The results from the anechoic pool experiment demonstrate that the proposed scheme achieves a better time-delay estimation performance for the weak geometric scattering generated by the bottom edge of the underwater target model than match filter based methods.

1. Introduction

Extracting effective feature is essential for underwater target detection. The acoustic scatterings generated by an underwater target with thin shell can be divided into two categories, one is the geometric scattering, and the other is the elastic scattering. Currently, the potential for developing an elastic scatterings based methodology for underwater artificial target detection has become a hot research area [1–4]. However, the mechanism of the elastic scatterings is more complex compared with the geometric scatterings. For a finite elastic cylinder immersed in water, there are sets of circumferentially propagating surface elastic waves formed, only if the cylinder is excited by a plane sound wave as the incident angle deviating from the normal incidence direction is less than 45° [5,6]. Therefore, for now, using the geometric scattering feature to recognize underwater man-made target is still one of the most feasible methods for engineering applications.

The geometric scattering and its associated features have been extensively studied. A wide range of calculation methods for the geometric scattering field of an underwater target have been developed, such as the exact solution method, the Kirchhoff approximation and the plate element method. The Kirchhoff approximation can describe the major characteristics of target geometric scattering under the condition that a high frequency incident sound field exists. The plate element method has been introduced into the geometric scattering researches in recent years, which is more adaptable to deal with the underwater targets with more complex shape, compared with the Kirchhoff approximation.

The generation of the geometric scattering follows the law of linear acoustics, which means that the scattering signal has the same characteristics in frequency domain as the incident signal. As the active sonar transmits a wide-band pulse mostly, several signal processing methods based on the time-frequency characteristics for the geometric scattering feature extraction have been studied, such like the time-frequency analysis [7], the canonical correlation analysis [8,9] and the wavelet transform [10–12]. For studying the varying pattern of the geometric scattering characteristics with the changes of the sound wave incident angle,

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the structural acoustic identification theory has been proposed, which has become a major experimental research method of underwater target acoustic scattering [13–16]. However, the original structural acoustic identification theory in [13–16] is based on the Fourier transform with a limit of the frequency resolution. As a result, the weak geometric scatterings are hardly to be distinguished from the received signal when they are immersed by the strong ones. Therefore, the geometric scattering information of an underwater target cannot be obtained completely by the original structural acoustic identification theory.

In this paper, we propose a HRTDE scheme to obtain the complete time sequence structure of the geometric scattering of an underwater target, which consists of two steps. Firstly the dechirping method transforms the geometric scatterings with different time-delay into multiple single-frequency components respectively when a LFM pulse is transmitted by sonar, in which the frequency of the dechirped signal shows a linear relationship with the time-delay of the geometric scattering. Then the MUSIC algorithm is adopted to increase the spectrum resolution when multiple single-frequency signals exist in the dechirped signal and the frequency interval is smaller than the frequency resolution limit of the Fourier transform. Performance of the proposed scheme is verified by both simulations and the anechoic pool experiment.

2. Proposed method

2.1. Acoustic scattering characteristics of a benchmarking model

Fig. 1 shows a typical benchmarking model of an underwater target. This model is a 2.0 m long cylinder of 0.5 m outer diameter, with one hemispherical and one flat end cap.

There are totally seven geometric scattering centers existing on the model. The label and location of each scattering center is shown in Fig. 1. Scattering center #1, #2, #3 and #4 belong to the edge scattering. Scattering center #5 belongs to the cylindrical scattering located at the side center of the cylinder. Scattering center #6 belongs to the hemispherical scattering located at the intersection between the hemisphere and the line going through the center of the hemisphere as shown in Fig. 1. Scattering center #7 belongs to the plane scattering located at the center of the model's flat end cap. The incident angle of the sound wave θ is shown in Fig. 1. As the incident sound field is a plane wave, the θ for all of the scattering centers are equal.

The observable scattering centers in the received signal vary with the θ which follows a rule as bellow:

(1) Scattering center #6 is observable under $\theta = 0^\circ$.
(2) Scattering center #1, #4 and #6 are observable under $0^\circ < \theta < 90^\circ$.

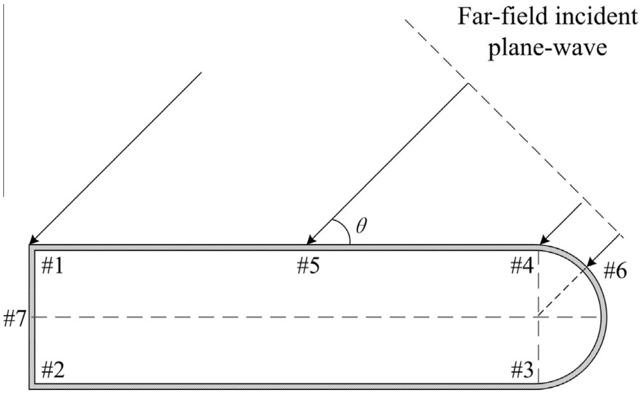

Fig. 1. A sketch map of a typical benchmarking model.

(3) Scattering center #5 is observable under $\theta = 90^\circ$.
(4) Scattering center #1, #2 and #4 are observable under $90^\circ < \theta < 180^\circ$.
(5) Scattering center #7 is observable under $\theta = 180^\circ$.

Under the condition of high-frequency approximation, each scattering center generates an acoustic highlight. The transfer function of the ith acoustic highlight $H_i(\vec{r},\omega)$ relies on three factors: the amplitude, the time-delay and the phase jump, which is defined as

$$H_i(\vec{r},\omega) = A_i(\vec{r},\omega)\exp[j(\omega\tau_i + \varphi_i)] \tag{1}$$

where $\vec{r}$ is the vector of scattering direction, $A_i(\vec{r},\omega)$ is the amplitude-frequency response factor, τ_i is the time-delay factor and φ_i is the phase factor. The direction of the $\vec{r}$ is reversed to the incident direction of the wave when a monostatic sonar is used.

2.2. The HRTDE based on the MUSIC algorithm

If the amplitude-frequency response factor $A_i(\vec{r},\omega)$ and the phase factor φ_i in Eq. (1) are ignored, a geometric acoustic highlight can be considered as a time-delay copy of the transmitted signal. The impulse response of the ith acoustic highlight in time-domain can be simply described as

$$h_i[n] = a_i[\tau_i]\delta[n-\tau_i] \tag{2}$$

where $a_i[\tau_i]$ is the scattering intensity factor. The transmitted LFM pulse $s[n]$ with the FM-range of $f_0 \sim f_1$ is

$$s[n] = \exp[j\cdot 2\pi(f_0 + 0.5kn)n], \quad n = 0,1,\ldots N \tag{3}$$

where the frequency modulation rate is $k = (f_1 - f_0)/N$. Based on Eqs. (2) and (3), the ith geometric scattering can be described as

$$\begin{aligned} x_i[n] &= s[n] * h_i[n] \\ &= \exp[j\cdot 2\pi f_0(n-\tau_i) + j\pi k(n-\tau_i)^2] \end{aligned} \tag{4}$$

For estimating the time-delay of the geometric scattering in Eq. (4), the dechirping method is adopted in this paper. The copy of the transmitted signal is multiplied by the conjugated geometric scattering. Let τ_{ref} denote the time-delay of the reference signal $s_{ref}[n]$ and $R_{ref} = \tau_{ref}c/2$ denote the corresponding sound duration, where c is the sound velocity in water. The reference signal is given as follows

$$s_{ref}[n] = \exp[j\cdot 2\pi f_0(n-\tau_{ref}) + j\pi k(n-\tau_{ref})^2] \tag{5}$$

The result of $s_{ref}[n]$ multiplied by conjugated $x_i[n]$ is

$$\begin{aligned} y_i[n] &= s_{ref}[n]\cdot x_i^*[n] \\ &= \exp[j\cdot 2\pi kn(\tau_i-\tau_{ref})]\exp[j\pi k(\tau_{ref}^2-\tau_i^2)]\exp[j\cdot 2\pi f_0(\tau_i-\tau_{ref})] \end{aligned} \tag{6}$$

Eq. (6) consists of three items, one is single-frequency item, and the other two are phase modulation items. Ignoring the two phase modulation items, Eq. (6) can be treated as a single frequency signal with the frequency related to the time-delay of the geometric scattering τ_i .

The reference point becomes the starting point of the observation window by setting $\tau_{ref} = 0$ in Eq. (6). Then Eq. (6) is converted to

$$y_i[n] = \exp[j\cdot 2\pi k\tau_i n]\exp[j\cdot 2\pi(f_0\tau_i - 0.5k\tau_i^2)] \tag{7}$$

It can be seen that τ_i is related to the frequency $f_i = k\tau_i = 2kR_i/c$ in Eq. (7), where R_i is the distance between the ith geometric scattering and the reference point. Therefore, the time-delay of the ith geometric scattering can be estimated by applying the Fourier transform to Eq. (7).