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Atomic decomposition of geometric acoustic scattering from underwater target

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ABSTRACT

Underwater target detection and recognition is currently a key technology of intelligent acoustic equipment. In the active detection of quiet small underwater targets, an aliasing of distortions between highlight echoes exists in both time and frequency domains. The interference of cross-terms from multi-components in time–frequency domain results in a decline in resolutions of highlight. To solve the problem, the chirplet atom decomposition method is applied to the extraction of geometric highlights when using the linear frequency modulation signals based on the theory of highlight model of echoes from sonar target. The orthogonal matching pursuit algorithm is also added to obtain the time–frequency form of the highlight echoes without cross-term interference. The analytical result of the simulation and data processing are consistent with the theoretical acoustic scattering highlight model, which proves that the proposed method can effectively extract the characteristics of underwater target geometric highlights and improve the detection and identification ability of underwater targets.

1. Introduction

Underwater target detection and recognition technology is an important research field in modern underwater acoustics. A comprehensive understanding of target echo characteristics is required to achieve the objective of terminal systems and improve their feature extraction capability when dealing with target echo data. For the task of underwater target detection and recognition, the sound imaging and echo analysis methods [1] based on the acoustic scattering theory are commonly applied. The theoretical research on acoustic scattering on simple shape targets, such as spherical and finite-length cylinders, have been completed and extended to more complex geometric shapes in which underwater target structures have been simulated [2–4]. Target echo is the result of the interaction of transmitted signals from active sonars and targets, while echo signal contains modulated information that reflects the target characteristic [5]. Tang proposed a three-parameter transfer function model based on the amplitude factor, delay and phase transition which can describe the highlights of sonar target echoes. Compared with the strict theoretical method of acoustic scattering [6], the highlight model is widely applied as an approximation model in engineering projects. The target is equivalent to a reflector which consists of a series of highlights by the model in high-frequency conditions, and unlike the reflections of convex surface optics of incident lights, a target echo can be described as the superposition of sub-echoes of each highlight [7] including the geometric scattering highlights formed by geometric structures of acoustic scattering targets and the elastic scattering highlights formed by acoustic scatterings and echoes from incident acoustic resonances [8]. In actual conditions, the mechanism of elastic scattering is more complex than that of geometric scattering. Sets of circumferentially propagating surface elastic waves form only when an incident plane soundwave angle that deviate from the normal incidence direction is less than 45° for a water-immersed cylinder [9]. Therefore, designing the geometric scattering feature is one of the most feasible methods in engineering. A theoretical delay between each highlight and the staggering on the time axis can be used as a criterion for target recognition.

The linear frequency-modulated (LFM) signal is a widely adopted transmission signal when the active sonar is used for target detection. The LFM signal has a large time–bandwidth product that meets the conditions of long-distance transmission. However, the echo signal is overlapped in both time and frequency domains when active sonars transmit LFM signals. Neither the traditional analysis in the time domain nor that in the frequency domain [10] can obtain the information that can accurately investigate the characteristics of targets, leading to

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the indistinguishability of different scattering highlights [11]. Although extracting relevant information from each domain has advantages, the joint time and frequency representation may reveal some inherent related features that are not highly observable in single domain representations [12]. Consequently, joint time–frequency analysis methods, such as the short-time Fourier transform (STFT), fractional Fourier transform, wavelet transform, Winer–Vile distribution and so on, are widely used to analyse and process target echoes. However, in linear time–frequency methods, the resolution of STFT is limited by the time–frequency uncertainty principle [13]. The wavelet method applied in similar areas also encounters the same problem [14]. Bilinear time–frequency transforms or Cohen class time–frequency representations, such as the Wigner–Ville transform, can effectively localise broadband and transient signals in terms of time and frequency [15]. Bilinear time–frequency transforms or Cohen class time–frequency representations, such as the Wigner–Ville transform, can effectively localise broadband and transient signals in terms of time and frequency [16]. Obtaining an accurate result despite the time–frequency resolution or cross-term interference based on the method above remains to be a limitation.

For the problem in which the geometric information of an underwater target cannot be obtained completely by the original structural acoustic identification theory [9], a scheme to obtain the time–-frequency structure of geometric scattering highlight is required. In this study, the suppression method of the cross-term interference between the highlight echoes on the time–frequency plane is investigated when the LFM signal is transmitted for the detection task. The chirplet atom is selected as the basis vector and used to characterise the LFM signal because it matches well with the LFM signal in time–frequency domain. Chirplet atom decomposition is applied to the echoes combined with the orthogonal matching pursuit (OMP) algorithm to achieve the sparse representation of the chirp signal. The time–frequency distribution of highlight echoes without cross-term interferences can then be obtained. The results of the simulation and the processing of anechoic pool experiment data verify the effectiveness of the method.

2. Study on geometric acoustic scattering model of underwater target

The acoustic scattering mechanism of underwater targets determines the property of the target echo signal. In characterising echo signals, the integral equation method, Rayleigh normal series solution, resonance scattering theory and other strict theoretical solutions have been used in early research. The strict theoretical method can reveal the mechanism of target acoustic scattering, but it only obtains the exact solution of several simple targets. In practical engineering circumstances, the physical acoustic method (Kirchhoff approximation) is generally used. The theory of highlight model of echoes from the sonar target is built based on the physical acoustic method.

Theoretical research and experiments indicate that the target echoes of scatterers can be linearly superimposed by a series of sub-echoes when the incident acoustic wave is in the high frequency. In addition, the sub-echoes can be scattered from a series of specific points. Each sub-echo decomposed by the target echo is considered to be transmitted by the scattering points of the target called highlights. The total target echo is equivalent to the linear superposition of these highlights. The differences in the structures of these highlights can be used as an important criterion in distinguishing underwater acoustic scattering and provide theoretical basis for underwater target detection and recognition. Highlights are divided into geometric and elastic highlights according to their formation mechanisms. Geometric highlights are affected by the shape of the target and the acoustic properties of surface materials, including the specular reflection highlight produced by convex-smooth surface and corner reflections produced by angular positions, by which the specular reflection dominates. Geometric highlights exist when the incident wave-front is tangential to the target surface and the monostatic sonar is in the far field. Elastic highlights are caused by the interaction of soundwaves and the elastomer surface, and they are related to the internal structure of the target. The mechanism of elastic highlight is complex and can only be generated when the soundwaves are incidental on specific parts of an object as described above. Furthermore, a spectral dispersion phenomenon accompanies such scatterings.

The formation of a target echo is a physical process that occurs when the incident soundwaves act on the target. When the small amplitude wave is selected as the transmitted signal, the formation of geometric echo obeys the linear acoustic law. This phenomenon means that the scattering signal of the geometric echo has the same characteristics in the frequency domain as that of the incident signal, as reported in existing research. In this circumstance, the target can be equivalent to a linear invariant system, whereas the echo can act as the response of the system. When the transmit signal is a linear FM signal, the mathematical expression is $\cos(2\pi t(f_0 + kt/2))$. According to the highlight model, the target echo can be expressed as follows:

$$P(t) = \sum_{n=1}^{N} \{A_n \cos[2\pi(t-\tau_0)(f_0 + \frac{k}{2}(t-\tau_n)) + \varphi_n]\} + \sum_{n=1}^{M} \{A_{me} \cos[2\pi(t-\tau_0)(f_{me} + \frac{k}{2}(t-\mu_{me})) + \varphi_{me}]\}. \quad (1)$$

The two parts of the expression are the geometric highlight and the elastic highlight components. In Eq. (1), A_n, τ_n, φ_n represent the amplitude factor, delay and phase of the nth geometric highlight component, respectively; and k is a rate consistent with the transmit signal parameter; and A_{me}, τ_{me}, φ_{me} denote the corresponding parameters of the elastic highlight component.

According to the basic research on target scattering, the transmission function of the highlight acoustic scattering model based on phase-angle jump, delay and amplitude factors can be described as

$$H(\mathbf{r}, \omega) = A(\mathbf{r}, \omega) e^{j\omega\tau} e^{j\varphi}, \quad (2)$$

where φ is the phase transition factor which is related to the geometry of the scatterer; τ is the time delay determined by the highlight structure and the reference point of the sound path (i.e. one of the bases of the target highlight recognition which varies with the azimuth of the incident soundwave); and $A(\mathbf{r}, \omega)$ is the amplitude factor which reflects the amplitude modulation of the incident soundwaves at different frequencies. For non-single shape targets, the multi-highlight transfer function can be expressed as a superposition of a single highlight transfer function as follows:

$$H(\mathbf{r}, \omega) = \sum_{m=1}^{N} A_m(\mathbf{r}, \omega) e^{j\omega\tau_m} e^{j\varphi_m}. \quad (3)$$

Eq. (3) is a geometric highlight transfer function, where m is the number of highlights. When the highlight model is used to analyse the target in engineering projects, the echo signal represents a set of parameter values with different azimuths, in which the geometric highlights dominates the target echo. Thus, when the signal-to-noise ratio (SNR) is low in engineering projects, it is essential to recognise the target from the geometric highlights of the acoustic scattering target.

The experimental model in this study is a cylindrical and hemispherical welding model. The schematic diagram is shown in Fig. 1.

In far-field condition, the incident soundwave is equivalent to the plane wave, and the angle between the scattering and the soundwave is denoted as θ. In Fig. 1, the numerically marked edges 1–4, cylinder 5, spherical surface 6 and end-face 7 of the column can produce specular or angular scattering echo. According to the three parameters of the highlight scattering model, all kinds of acoustic scattering echo vary with the angle between the incident sound and the cylinder. The analytical expression of the scattering sound field of the highlight is acquired with the physical acoustic method (Kirchoff approximation).