AN UNDERWATER TARGET CLASSIFICATION SCHEME BASED ON THE ACOUSTIC BACKSCATTER FORM FUNCTION

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***ABSTRACT**: By using the acoustic scattering form function, a method for classifying underwater spherical shell targets in an open ocean environment is proposed. The resulting backscatter signal from an incident wideband signal is used to illustrate some of the salient scattering features such as mid-frequency enhancement (MFE). A shell classification technique is then developed. An affine transformation of a template form function is used in the classification scheme. It is shown that the proposed scheme is robust against uncertainties in the material properties and noise.*

1. INTRODUCTION

The physics of acoustic scattering and its associated signal processing in an underwater environment have a number of interesting applications that are also of practical importance. From the point of view of active sonar, the scattering of acoustic energy from a target can reveal not only information about its range and range rate, but, potentially, can also be used to identify the target. In fact, one major problem facing active sonar, especially when operating in littoral environments, is the large number of potential false targets. This makes the classification of sonar returns an imperative issue. In this paper, we investigate a method for classifying underwater targets using the form functions of acoustic scattering. For simplicity, spherical shell targets in an open ocean environment are used to illustrate the underlying ideas. It is hoped that these ideas can be extended to include more complicated targets and environments in future work.

2. TARGET MODEL

Consider a stationary elastic spherical shell of radius a and thickness h immersed in open ocean at a range r from the transmitter. Suppose the shell is ensonified by a monochromatic source of frequency f and pressure p_0. The resulting backscatter pressure p_s, measured at the source, can be expressed as [1]

$$p_s = \frac{p_0 a}{2r}\left[\frac{2}{ka}\sum_{n=0}^{\infty}(2n+1)(-1)^n c_n\right]e^{ik(2r-ct)} , \qquad (1)$$

where $k = 2\pi f/c$, t is the time variable, and c is the velocity of sound in sea water. The term in square brackets is known as the *form function* $F(f;a,h)$ which describes the scattering process of the target. The coefficients c_n are given by the ratio of the determinants of two 6×6 matrices. The matrix elements depend on the target geometry (a,h) as well as on the material properties: density, Young's Modulus and Poisson's ratio. Note the computation of c_n requires the evaluation of high order spherical Bessel functions and for $n > 50$, special methods are necessary to obtain numerically stable results [2].

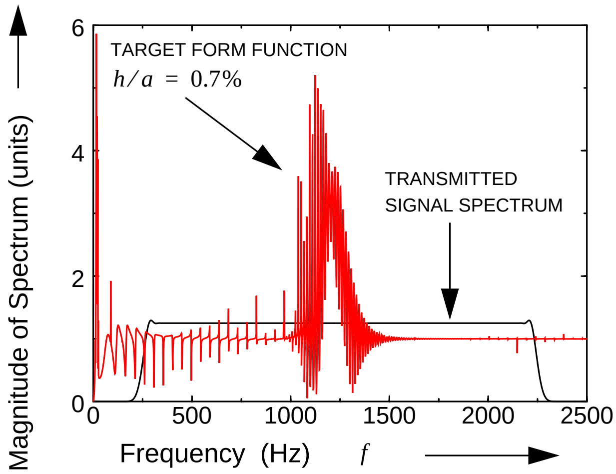

Figure 1: The Magnitudes of Target Form function and the Transmitted Signal Spectrum

Figure 1 shows the magnitude of the computed form function of a tungsten carbide spherical shell having a relative thickness (h/a) of 0.7%. The shell radius was selected such that $2\pi a/c = 0.17s$. In Figure 1, the area around $1200Hz$ is known as the *mid-frequency enhancement* (MFE) region. The MFE frequency f_{MFE} can be related to the shell thickness h by the following expression [3].

$$f_{MFE} = \beta c/(2\pi h) . \qquad (2)$$

The parameter β depends on the material properties. As can be seen, equation (1) shows that the shell radius a introduces a scaling effect into the form function while equation (2) shows that the form function peaks at a frequency which is determined by the shell thickness h. Using equations (1) and (2) it is possible to approximately relate the form functions resulting from two different shell geometries (a_0, h_0) and (a_1, h_1) via the following transformation

$$F(f;a_0, h_0) \cong F(a_0(f - f_s)/a_1;a_1, h_1) \quad , \qquad (3)$$

where f_s is given by

$$f_s = \beta c[a_1/(a_0 h_1) - 1/h_0]/(2\pi) \ . \qquad (4)$$

3. BACKSCATTER SIGNALS

There are two significant contributions to the backscatter pressure field of an elastic shell. These are outer scattering and a component (Lamb waves) which results from the internal vibrations exciting the shell resonance. Outer scattering consists of specular reflection and creeping waves. This component does not change with varying shell thickness or material composition. In contrast, Lamb waves depend on material composition and shell geometry. Because of this dependency, Lamb waves can be used for target classification purposes. Of particular interest for classification is the Lamb waves around the MFE region which contributes a very strong resonance component to the backscatter signal [4].

Figure 2 shows the matched filtered output of the simulated backscatter signal resulting from the form function in Figure 1. In the simulations, the received backscatter signal was assumed to be noise free. The transmitted wideband linear FM signal has a duration of $20ms$ and a bandwidth of $2000Hz$. The transmitted signal frequency spectrum is also shown in Figure 1. In Figure 2, the signals arriving after the specular reflection (Lamb waves) are due to the excited resonance near the MFE region. These signals result from the acoustic fields circumnavigating the shell. The time delay between the specular reflection and the m^{th} Lamb wave can be expressed as

$$\tau_m = \frac{2a\pi}{c_g}\left(\frac{1}{2} + m\right) + \frac{2a}{c}\cos\left(\sin^{-1}\frac{c}{c_g}\right) , \qquad (5)$$

where $c_g > c$ is the group velocity of the Lamb waves [4]. By detecting the Lamb waves and evaluating the time delays it is possible to estimate the shell radius. However, such a technique is difficult in the presence of a noisy ocean environment. An alternative shell parameter estimation scheme using a template form function is described in the following section.

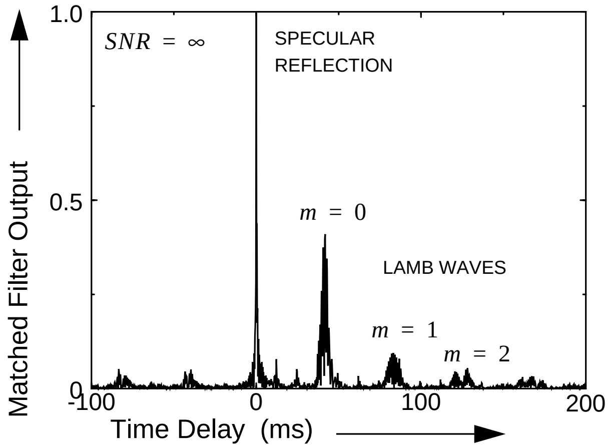

Figure 2: Matched Filter Output for $SNR = \infty$

4. PARAMETER ESTIMATION

Suppose $F(f;a_0, h_0)$ is the form function of a shell target positioned at range r_0. For target classification, it is necessary to estimate the two parameters shell radius a_0 and thickness h_0.

4.1 Shell Thickness Estimation

If the shell material is known the shell thickness can be estimated using equation (2) via the evaluation of f_{MFE} from the received signal frequency spectrum. The value of β depends on the target material composition. It is possible to obtain the value of β from the computation of the form function in equation (1). For iron, aluminium, tungsten carbide, stainless steel and fine sand the value of β is given by 1.15, 1.50, 0.80, 1.20 and 0.95, respectively. Therefore, prior knowledge of material properties is required for an accurate estimation of shell thickness. Nevertheless, by assuming that $\beta \approx 1$, an approximate thickness estimate, which suffices in most applications, can be obtained. It is interesting to note that equation (2) is equally applicable to shells of different shapes [2].

4.2 Shell Radius Estimation

It was shown via equation (5) that the separation of the specular reflection from the Lamb waves is determined by the shell radius. Therefore, by exciting strong Lamb wave resonance in the vicinity of the MFE region, the shell radius could be estimated. The estimation technique is described in the following.

By neglecting the transmitter/receiver and channel gains, the spectrum $Y_r(f)$ of the received signal $y_r(t)$ can be expressed as

$$Y_r(f) = X(f)F(f;a_0, h_0)e^{-j4\pi r_0/c} \quad , \tag{6}$$

where $X(f)$ is the spectrum of the transmitted signal $x(t)$. The true shell parameters (a_0, h_0) can be estimated from $y_r(t)$ as follows. Suppose the shell parameters are (a_m, h_m) such that the form function is $F(f;a_m, h_m)$. The spectrum of the trial received signal $y_m(t-2r_o/c)$ is then given by

$$Y_m(f) = X(f)F(f;a_m, h_m)e^{-j4\pi r_0/c} \quad . \tag{7}$$

(It is assumed that r_0 is known from the target detection process.) Consider the correlation between the actual received signal $y_r(t)$ and $y_m(t-2r_o/c)$ which can be described in the frequency domain as

$$l_m = \int_{-\infty}^{\infty} |X(f)|^2 F(f;a_0, h_0)F^*(f;a_m, h_m)df \quad . \tag{8}$$

The shell parameters can thus be estimated by searching for the peak of $|l_m|^2$ in the (a_m, h_m) domain. However, such a two dimensional search is computationally intensive as it is necessary to calculate a form function for each parameter set (a_m, h_m). In the following a computationally efficient technique is proposed which uses the relation in equation (3).

First a template form function $F(f;a_1, h_1)$ is computed using an arbitrarily chosen parameter set (a_1, h_1). Using an affine transformation (α, f_0) on the frequency variable, the template form function is then mapped to $F(f;a_m, h_m)$ to form the trial signal $y_m(t-2r_o/c)$ of equation (7). Combining the affine transformation together with the relation in equation (3), equation (8) can be re-written as

$$l = \int_{-\infty}^{\infty} |X(f)|^2 F\left(\frac{a_0}{a_1}(f-f_s);a_1, h_1\right)F^*(\alpha(f-f_0);a_1, h_1)df \tag{9}$$

The maximum of $|l|^2$ occurs when the two form functions in equation (9) are matched, i.e. when

$$\alpha = \frac{a_0}{a_1} \quad ; \quad f_0 = f_s = \frac{\beta c}{2\pi}\left(\frac{1}{\alpha h_1} - \frac{1}{h_0}\right) . \tag{10}$$

Because β, h_0 and h_1 are known, f_0 can be evaluated for each α. Therefore, equation (9) can be expressed as a function of α, i.e. $l = \gamma(\alpha)$ and thus the peak search can be performed using a single variable α. Furthermore, it is only necessary to evaluate the form function only for a single set of parameters (a_1, h_1).

Since the target parameter estimation technique operates by exploiting the resonant Lamb waves it is necessary that the transmitted acoustic signal has sufficient bandwidth to ensonify the MFE region. If the MFE region is not excited, only the specular component would be significant in the received signal, and thus the target parameters could not be estimated. The following two detection hypotheses are used to test whether the MFE region is excited.

Hypothesis H_0: Detection is not from a thin shell:

Since the received signal consists of only the specular component, equation (8) is evaluated assuming that $F(f;a_m, h_m) = 1$ to obtain $\varepsilon^2 = |l_m|^2$. Note that this is the same as the matched filter output.

Hypothesis H_1: Detection is from a thin shell (a_0, h_0):

Using the template form function $F(f;a_1, h_1)$ the right hand side of equation (8) is now maximized to obtain $max(|\gamma(\alpha)|)$.

If $max(|\gamma(\alpha)|) > \varepsilon$ the hypothesis H_1 is selected and target parameter estimation is then performed. The radius a_0 is estimated using equation (10) by using the value of α which maximizes $(|\gamma(\alpha)|)$.

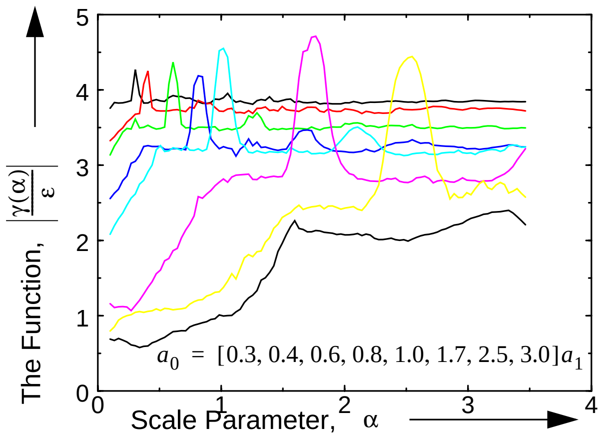

Figure 3: Performance of the Classification Scheme

Results from a simulation example which uses the above target classification scheme are shown in Figure 3. The target is a tungsten carbide shell of 1% relative thickness. The template form function was selected assuming a tungsten carbide shell of 0.7% relative thickness and a radius satisfying $2\pi a_1/c = 0.1s$. In the simulations a noise free ocean environment was assumed. The transmitted wideband signal is the same as that shown in Figure 1. The target radius was varied from $a_0 = 0.3a_1$ to $a_0 = 3a_1$. Figure 3 demonstrates that the target radius a_0 can be estimated by using a peak search on $|\gamma(\alpha)/\varepsilon|$. Note that when $a_0 = 3a_1$ the scale parameter α cannot be deduced as the MFE region of the target form function was not ensonified by the transmitted signal (i.e. H_0).

5. ROBUSTNESS OF CLASSIFICATION

The target radius estimation scheme presented in the previous section utilizes a template form function having the same material properties as the target. It can be shown that the radius estimation scheme is robust to material property variation. For example, using the form function of a stainless steel spherical shell of relative thickness of 1%, performance curves similar to Figure 3 are shown in Figure 4. Figure 4 shows that the radius estimation is robust against the variation of material properties.

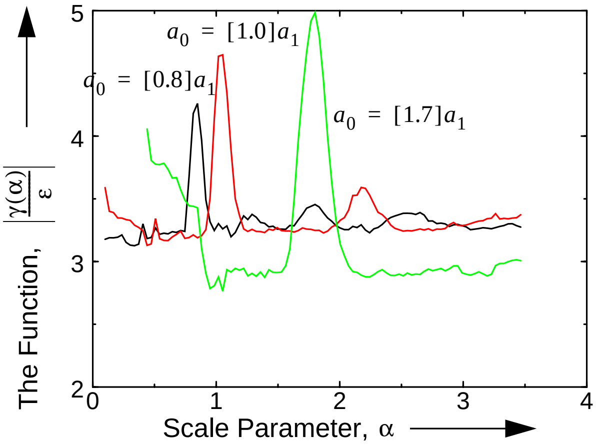

Figure 4: Robustness of the Classification Scheme

In order to demonstrate the performance of the classification scheme under noisy conditions, Figure 5 shows simulation results for 5 different SNR s. The SNR is defined as $\int x^2(t)dt/\sigma^2$ where σ^2 is the power of a zero mean white Gaussian noise process used in the simulations. The target radius was selected as $a_0 = 1.7a_1$ and the template form function is the same as that used in Figure 3.

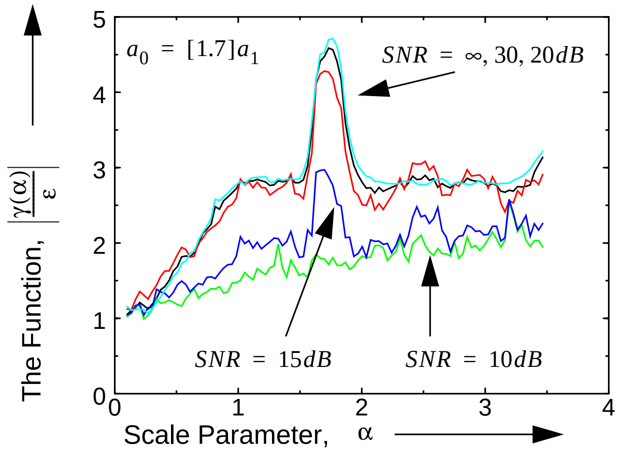

Figure 5: Noise Performance of the Classification Scheme

Figure 5 demonstrates that the proposed classifier can be satisfactorily used when $SNR > 10dB$. Figures 6 shows the matched filter output for $SNR = 15dB$. (This is similar to Figure 2 which shows the matched filter output for $SNR = \infty$.) It can be seen that $SNR = 15dB$ corresponds to a severe noise environment. Figure 5 demonstrate that the proposed classifier provide satisfactory results even for this severe noise condition.

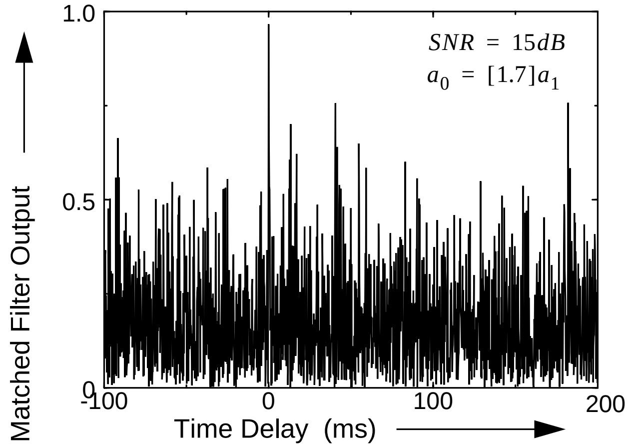

Figure 6: Matched Filter Output for $SNR = 15dB$

6. CONCLUSIONS

A method for classifying underwater shell targets, based on the targets' acoustic scattering properties, has been proposed. The classification method exploits the fact that, for shell targets, the backscatter signal from an incident wideband signal exhibits a resonance phenomenon known as mid-frequency enhancement, and that the signal structure of this phenomenon depends only on the physical attributes of the target. In the case of spherical shells, a computationally efficient method for identifying the radius and shell thickness of the target has also been proposed. It is shown that this spherical shell target classification method is robust against noise and uncertainties in the material properties. Although the paper considers only spherical shells, it is expected that the basic ideas of the classification method can be extended to include more complicated targets and environments.

7. REFERENCES

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