A SIMPLE FUNCTION FOR MODELLING THREE-DIMENSIONAL SCATTERING STRENGTH FROM THE OCEAN SURFACE

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Both the rough air-sea interface and entrapped air bubbles due to wave breaking scatter sound in all directions and contribute to so-called reverberation in active sonar. There are monostatic sonar systems where the source and receiver are at the same position, bistatic sonar systems where the source and receiver are separated, and multistatic sonar systems involving multiple sources and receivers at different positions. In monostatic situations, reverberation is mainly due to backscattering. In bistatic and multistatic situations, forward and out-of-plane scattering are significant contributors. The empirical Chapman-Harris formula is often used to predict surface backscattering strength in monostatic sonar. To better predict reverberation from the sea surface in bistatic or multistatic sonar, a three-dimensional scattering formula that includes a forward scattering lobe will be desirable. Following earlier work, in this paper the separable form of backscattering models are extended by including an expression of forward scattering lobe obtained under the Kirchhoff approximation, taking into account shadowing effects. Comparison with another more sophisticated model shows that shadowing corrections are important at low grazing angles. The formula obtained here is simple and includes scattering effects from both the roughness of the sea surfaces and the sub-surface bubbles. It may be useful for modelling multistatic surface reverberations.

INTRODUCTION

Wind generates rough sea surfaces. Wave breaking under strong winds also produces entrained air-bubbles below the sea surface. Both roughness of the sea surfaces and the trapped air bubbles scatter sound from sonar and lead to surface reverberation.

Scattering occurs out-of-plane as well as within the vertical plane containing the source and receiver. Modelling active sonar reverberation from the sea surface requires assessment of the surface scattering strength. For monostatic sonar where the transmitter and receiver are co-located, the reverberation is mainly due to backscattering. For multistatic sonar where multiple transmitters and receivers are spatially distributed, there are additional contributions to the received reverberation from forward and out-of-plane scattering.

The empirical Chapman-Harris formula [1] of surface scattering strength is often used for modelling monostatic sonar reverberation. To more accurately predict reverberation in multistatic active sonar systems, formulas for three-dimensional scattering are desirable. Gauss et al (2000, 2002) [2,3] presented a semi-empirical surface scattering strength (SESSS) model that combines incoherent scattering from the rough air-sea interface with scattering from the bubble clouds.

This work follows the approach in Ellis and Crowe (1991) [4] and Caruthers and Novarini (1993) [5] where backscattering models are extended by using the so-called separable approximation, and then combined with a term obtained under the Kirchhoff approximation to obtain a three-dimensional scattering function. In this paper we use the empirical Chapman-Harris formula [1] as our backscattering model. We further modify the expression obtained using the shadowing factor in Torrance and Sparrow (1967) [6] and compare the results with those of Gauss et al (2000,2002) [2,3].

Due to the empirical nature of the Chapman-Harris backscattering model, the expression obtained here includes the effects of both the roughness of the sea surfaces and the sub-surface bubbles. The formula is simple to use in multistatic active sonar performance models.

CHAPMAN-HARRIS BACKSCATTERING MODEL

In underwater acoustics, the ability to scatter sound from extended objects such as the sea surface is often characterized by a scattering strength, which is defined as the ratio in decibels of the intensity of the sound scattered by a unit surface area (normally chosen 1 m^2), referred to a unit distance (normally 1 m), to the incident plane wave intensity. Based on measurements using explosives, Chapman-Harris (1962)[1] give the following empirical fit to measured surface backscattering strength in dB for wind speeds up to 15 m/s and frequencies from 400 to 6400 Hz,

$$S = 3.3\beta\log_{10}(\theta/30) - 42.4\log_{10}\beta + 2.6,\quad \text{dB} \tag{1}$$
$$\text{for}\quad \beta = 107\,(U f^{1/3})^{-0.58},$$

where θ is grazing angle in degrees, U is wind speed in m/s, and f is frequency in Hz.

For later use, we re-write the Chapman-Harris formula in linear units,

$$b(\theta) = 10^{0.26}\beta^{-4.24}(\theta/30)^{0.33\beta}, \tag{2}$$

where b(θ) is referred to as the backscattering coefficient and is related to the surface scattering strength by S = $10\log_{10}$ [b(θ)].

THE THREE DIMENSIONAL SURFACE SCATTERING FUNCTION

The Model

Following Ellis and Crowe (1991) [4] and Caruthers and Novarini (1993) [5], we extend the Chapman-Harris backscattering formula b(θ) of Eq. (2) to a three-dimensional scattering function by the following formula,

$$m(\theta_i,\theta_s,\phi) = [b(\theta_i)b(\theta_s)]^{1/2} + D(\theta_i,\theta_s)F(\Omega) \tag{3}$$

and

$$F(\Omega) = (8\pi\delta^2)^{-1}(1+\Omega)^2 \exp\left(-\frac{\Omega}{2\delta^2}\right), \tag{4}$$

where $m(\theta_i, \theta_s, \phi)$ is the three-dimensional scattering coefficient, and θ_i,θ_s, are the incident and scattered grazing angles.

The parameter δ is the root-mean-squared slope of the rough sea surface, which can be approximated by the empirical expression of Cox and Munk (1954) [7],

$$\delta^2 = 0.003 + 5.12\times10^{-3}U \pm 0.004. \tag{5}$$

The parameter Ω is a measure of the deflection of the scattering angle from the specular angle,

$$\Omega = \frac{\cos^2\theta_i + \cos^2\theta_s - 2\cos\theta_i\cos\theta_s\cos\phi}{(\sin\theta_i + \sin\theta_s)^2} \tag{6}$$

where ϕ is the scattered azimuthal angle relative to the incident plane.

The first term in Eq. (3) represents so-called separable approximation to the backscattering model $b(\theta)$, the term $F(\Omega)$ represents a forward scattering lobe in the high frequency limit from Gaussian-distributed facets under Kirchhoff approximation (also called the tangent plane approximation)[8,9], and the function $D(\theta_i, \theta_s)$ accounts for shadowing effects on the forward scattering lobe and is discussed below.

The Shadowing Factor

Adjacent facets may obstruct sound incident upon a given facet or the sound reflected by it. This masking and shadowing effect is especially important at low grazing angles. To account for this effect, we adopt the approximate shadowing factor in Torrance and Sparrow (1967) [6],

$$D(\theta_i,\theta_s) = \min\left(1, \frac{2\cos\alpha\sin\theta_s}{\cos\theta_i^{'}}, \frac{2\cos\alpha\sin\theta_i}{\cos\theta_i^{'}}\right), \tag{7}$$

where

$$\theta_i^{'} = (1/2)\cos^{-1}(\sin\theta_i\sin\theta_s - \cos\theta_i\cos\theta_s\cos\phi), \tag{8}$$

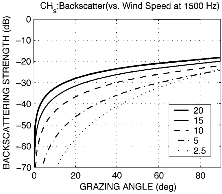
and

$$\begin{aligned} \cos\alpha &= \sin\theta_i\cos\theta_i^{'} + \cos\theta_i\sin\theta_i^{'}\cos\gamma, \\ \gamma &= (\sin^{-1}(\cos\theta_s\sin\phi/\sin 2\theta_i^{'})). \end{aligned} \tag{9}$$

The shadowing factor in Eq. (7) is derived using the assumption that each facet is one side of a V-groove cavity, and sound rays only reflect once (i.e. multiple scattering is ignored).

For backscattering, $\theta_s = \theta_i$, $\phi = \pi$, and the shadowing factor becomes unity.

It is worth pointing out that the empirical nature of the



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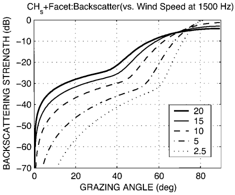

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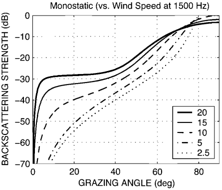

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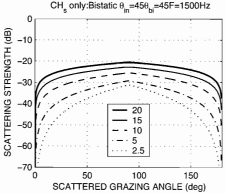
Fig. 1. Surface backscattering strength at 1500 Hz for wind speeds from 2.5 m/s to 20 m/s. (a) Chapman-Harris model (b) Chapman-Harris model plus Kirchhoff facet scattering, (c) SESSS model of Gauss et al [2,3].



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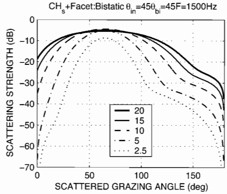

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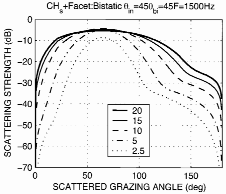

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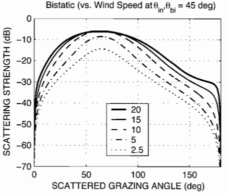

(d)

Fig. 2. Bistatic surface scattering strength versus scattered grazing angle. (a) Separable approximations of Chapman-Harris model (b) Separable approximations of Chapman-Harris model plus Kirchhoff facet scattering; (c) Separable approximations of Chapman-Harris model plus Kirchhoff facet scattering with shadowing effects; (d) SESSS model of Gauss et al [2,3].

Chapman-Harris backscattering model means that the first term in Eq.(3) contains scattering contributions from both the roughness of the sea surface and the sub-surface air bubbles, with azimuthally independent out-of-plane scattering. The second term in Eq.(3) represents scattering contributions from the roughness of the sea surface near the specular forward direction with azimuthally dependent out-of-plane scattering. The overall model in Eq.(3) is a simple function for modelling three-dimensional scattering strength due to roughness of the sea surface and sub-surface air bubbles.

RESULTS

To assess the accuracy of the present model, we compare its results with those from the Semi-Empirical Surface Scattering Strength (SESSS) model [2,3] for two representative cases. The first case is for backscattering and the second case is for a particular configuration of three-dimensional scattering.

Backscattering strength

Figure 1 shows results of comparison of the surface backscattering strength for wind speeds from 2.5 m/s to 20 m/s at an acoustic frequency of 1500 Hz. Gauss et al [2,3] show that at low grazing angles, scattering from sub-surface bubble-clouds dominates when wave breaking is significant. At high grazing angles, scattering is mainly due to ocean surface roughness.

We can see that the Chapman-Harris model plus the diffuse scattering lobe is closer to the results from the SESSS model. However, there are appreciable differences between the two.

We note that the parameters in the semi-empirical SESSS model and the original Chapman-Harris model are fitted using different data sets. It may be possible to obtain better agreements between the present model and the SESSS model if the empirical parameters of the original Chapman-Harris model were re-fitted using the same data set as that used for the SESSS model.

Bistatic scattering strength

Figure 2 shows an example of comparison of the bistatic surface scattering strength for wind speeds from 2.5 m/s to 20 m/s at an acoustic frequency of 1500 Hz. The particular case shown here is for an incident grazing angle of 45 degrees and an azimuthal angle of also 45 degrees. We can see that the shadowing factor improved the agreement at low grazing angles between the present model and the SESSS model.

It is of interest to note that, similar to the present model, the SESSS model is a summation of scattering strengths of azimuthally independent scattering due to air bubbles and azimuthally dependent scattering due to roughness of the sea surface.

SUMMARY

Following earlier work by Ellis and Crowe (1991) [4] and Caruthers and Novarini (1993) [5], a simple expression for modelling three dimensional scattering strength from ocean surfaces was given and compared with another semi-empirical model. The expression combines separable forms of the Chapman-Harris backscattering model with a forward scattering lobe given by a high frequency Kirchhoff approximation. Geometrical shadowing effects of the facets are accounted for by using a separate loss factor.

Three-dimensional scattering data from carefully controlled measurements are needed to ascertain the accuracy of the expression.

The simple expression includes the effects of both the rough air-sea interface and sub-surface bubbles. It may be useful as a sub-model for modelling reverberation in multistatic sonar.

Future work may include improving the shadowing factor [10] and considering other backscattering models such as those in Ogden and Erskine [11,12,13].

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