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Applying Different Frequency Dependent and Independent Methods for Examining the Influence of Sea Surface Boundary Conditions on Sound Propagation

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Abstract

By the current research effects of sea surface on the incident sound are investigated based on the empirical and theoretical relations. Surface scattering strength is a coefficient which presents the effects of different variables on the sea surface. These variables include wind speed, surface roughness, frequency, and incident angle among others. Surface scattering strength is discussed and computed based on frequency dependent methods such as Small Perturbation Method (SPM), Chapman-Harris empirical relation, and Ogden and Erskine's experimental tests as well as frequency independent method of Beckman-Spizzichinio. The resulting scattering strengths are applied to calculate the scattered sound intensity. Based on the obtained results, it is concluded that scattering strength is reduced as a result of an increase in wind speed and incident angle. A general reduction is also observed in the scattered intensity, when the incident angle and frequency increase. Presented results may help investigators in different applications such as marine life, sonar performance, oceanography and seismic investigations.

Key Word and Phrases
Sea Surface, Surface Scattering Strength, Plane Wave, Scattered Intensity, Acoustical Surface Roughness.

1. Introduction

In the first half of 20th century and during the First and Second World Wars, different fields of science including acoustics were developed dramatically and industrial applications exhibited an enormous growth. In the First World War, hydroacoustics was applied for military aims and also sound recorder and first version of phones were introduced at the same time. During the Second World War, in addition to the mentioned applications, new concepts such as electroacoustic instruments, sound measurement systems in industrial area and ultrasound and infra sound concepts in the research area appeared. Since then, different theoretical and empirical models have been introduced by acousticians in different areas of acoustic science such as aeroacoustic, hydroacoustic, architectural acoustics, and etc. Because of some similarities between light and sound, some of the important optic laws were utilized in acoustics, such as Snell's law [1].

Sound propagation in the medium faces different complexities, since different features of the sound such as speed, propagation direction, and its range are basically determined by the physical features of the propagation medium. Therefore, studying the environmental properties of the propagation medium (sea and ocean water in this paper) will be essential. Physical properties such as temperature, salt variations, and water density are the most effective ones [1]. In addition, sediment and the sea surface some of the most important environmental properties which should be defined in mathematical models as boundary conditions. Irregularities of sediment's surface and presence of the wind generated waves at the sea surface make these boundaries more complex.

Acousticians mostly categorize the sound based on two different concepts; pressure and wave nature of the sound. This is valid for the considered boundary conditions at the sea surface, too. But due to the presence of different variables and their interactions at the sea surface, sound behavior in this region should be studied beyond just as a simple boundary condition. This approach was initially introduced in 50s. Urick [2] and Marsh [3] were the pioneers who established a new point of view towards the acoustical variations at the sea surface region and proposed their empirical and theoretical approaches, respectively. In the theoretical model proposed by Marsh [3], wave nature of the sound was considered and sea surface acoustical roughness effects on the incident sound was examined, theoretically. Urick *et al.* [4] utilized field studies in order to examine the sea surface effects on the incident sound. Although they did not report enough environmental data for their experimental tests, they could establish a new point of view towards the sea surface study.

Further developed theoretical models such as Small Perturbation Method (SPM) and also other experimental tests were later introduced to overcome the shortcomings of the previous methods. Based on the pressure nature of the sound, Eckart [5] called the sea surface as a '*pressure release boundary*' and developed his mathematical approach. Based on this newly presented concept, even classical models such as Helmholtz-Kirchhoff model was further developed [6]. At end of 80s and early 90s, Kuo [7, 8] developed March's approach based on the wave nature of the sound and included the effects of subsurface bubble clouds in his theoretical relations. Even though his approach considered most of the involved factors at the sea surface such as wind speed, bubbles, surface roughness, and wave height, its complex mathematical relations restricted the application of Kuo's model [9].

There are other experimental approaches which consider only one of the variables which is involved in the sound variation at the sea surface. For instance, Igarashi [10] studied Doppler Effect on the surface scattering, Hall [11] examined scattered sound from the bubbles cloud. McDonald [12] and Prosperetti [13] studied acoustical behavior of the bubbles population, individually. Their results can be used as a part of other more general models such as SPM in order to count bubbles number and sound speed in the bubbly medium.

Other experimental works have been conducted to study sound behavior at the sea surface. Chapman *et al.*[14] proposed an empirical relation which was a criteria in order to verify the results of mathematical techniques. Ogden and Erskine (O/E) [15, 16] examined sound scattering from the sea surface through an extensive sea tests which was called Critical Sea Tests 1-7 (CST 1-7). Up to today, their experimental tests are the most complete field studies in which sea surface effects on the incident sound is examined. These studies were done during 1989 to 1995 in the Gulf of Mexico and can currently be considered as the most reliable source of verification for the theoretical approaches.

In this paper, fundamentals of the mentioned theories are explored and discussed. Then, these studies are utilized in order to calculate the surface scattering strength. Subsequently, the obtained surface scattering strength is used to compute scattered intensity. These studies are conducted for different physical parameters such as frequencies, wind speeds, and grazing angles. Presented results may help investigators in various applications such as marine life, sonar performance, oceanography and seismic investigations.

2. Sound Scattering from the Sea Surface

As mentioned earlier, important variations of the incident sound can occur due to the complexities of the sea surface. Therefore, it is necessary to examine the sea surface individually and in more details. Details of parameters like wind speed, surface irregularities, and sub-surface bubbles population are the most crucial elements [1]. Sound scattering from the sea surface can be investigated through two different approaches; frequency dependent approach and frequency independent approach. In the following subsections, each type will be discussed and the corresponding formulations will be presented.

Since realistic sea surface is not smooth particularly in underwater acoustics, it is described in statistical terms. Two parameters are required for this definition:

(1) The roughness height *h*, or root mean square of the surface from a plane, defined as $h^2 = \overline{y^2(x)}$, where *y(x)* is the height of the surface at a point *x* relative to the mean surface and the bar represents an average of y(x) over many points.

(2) A correlation distance determined by:

$$\rho(\xi)=\frac{\overline{y(x)\,\mathrm{y(x+\xi)}}}{h^2} \tag{2.1}$$

For theoretical traceability, $\rho(\xi)$ is commonly assumed to be $\rho(\xi)=\exp(\frac{-\xi^2}{T^2})$, where *T* is a constant called the correlation length. Both *T* and *h* are generally functions of direction in the plane of the surface.

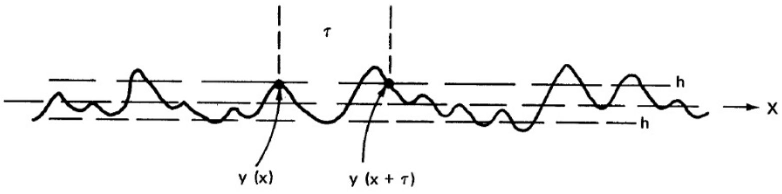


Fig. 1 Cross-section in the x direction of a random surface [2].

For random surfaces, the scattering is quantitatively described by a scattering coefficient *s*, and $S=10\log s$, is called surface scattering strength. If a plane wave of intensity I_i is the incident on a small area *A* of a rough surface at angle of incidence θ_1, the scattered intensity at distance *r* at angle θ_2 is given as:

$$I_s=\frac{sA}{r^2}I_i \tag{2.2}$$

Based on angles θ_1 and θ_2, Beckman and Spizzichinio [17] derived the following relation:

$$s(\theta_1,\theta_2,\beta)=\frac{F^2\cos^2\theta_1\cot^2\beta}{\pi(\cos\theta_1+\cos\theta_2)^2}.\exp\left[\frac{-(\sin\theta_1-\sin\theta_2)^2}{(\cos\theta_1+\cos\theta_2)^2}\cot^2\beta\right] \tag{2.3}$$

where:

$$F=\frac{1+\cos\theta_1\cos\theta_2-\sin\theta_1\sin\theta_2}{\cos\theta_1(\cos\theta_1+\cos\theta_2)} \tag{2.4}$$

Also, *β* is the slope angle of the surface such that the rms of the slope is $\frac{1}{2}\tan^2\beta$. Cox and Munk [18] conducted a study on the glitter pattern of the sun on the sea surface and found that the slope angle is approximately related to the wind speed by the relation:

$$\frac{1}{2}\tan^2\beta=0.003+(5.12\,\mathrm{W}\times10^{-3}) \tag{2.5}$$

where W is the wind speed in meters per second. For back-scattering, $\theta=\pi-\theta_1$. Equation (2.3) reduces to:

$$s(\theta)=\frac{\cot^2\beta}{4\pi\sin^4\theta}.\exp(-\frac{\cot^2\theta}{\cot^2\beta}) \tag{2.6}$$

in which θ is the angle of the incidence wave with the horizontal (grazing angle) plane. As observed, all of the mentioned relations are independent of frequency. Equation (2.3) should be applied for a surface in the range:

$$\frac{2\pi h}{\lambda}(\cos\theta_1 + \cos\theta_2) >> 1 \tag{2.7}$$

Although all the presented relations in this subsection are frequency independent, based on equation (2.3), it can be implied that this approach is restricted to high frequencies, high grazing angles, and very rough surfaces.

2.2 Frequency Dependent Approach

Since the mentioned models in the previous subsection do not take the crucial factor of frequency into account, it becomes necessary to propose a more general approach. Frequency dependent approach takes frequency into account as an essential environmental factor. Different conducted studies in this area can be categorized into three different types of numerical, theoretical, and empirical methods.

2.2.1 Numerical Methods

Numerical methods based on the pressure and wave natures of sound take different approaches. Recently, numerical method is not only used extensively in hydroacoustics, but also in other branches of the acoustics. Finite Element Method (FEM) is one of the useful numerical methods which can be used to solve wave equations in propagation medium. Mesh free approaches such as Helmholtz-Kirchhoff integral equation can also be solved numerically and pressure variation can be obtained in the medium. However, numerical investigation of sound propagation is not the focus of the current study.

2.2.2 Theoretical Methods

Theoretical methods such as different branches of Small Perturbation Method (SPM) can be considered as one important approach to study incident sound. SPM theories were established by Marsh [2] and Bass [19]. Later, different acousticians continued and developed their techniques to introduce more accurate models. Marsh [2] developed a general theory of scattering from irregular surfaces and by using a suitable mathematical calculation of sea surface, offered qualitative account of reverberation. Kou [7], [8] developed Marsh's perturbation method and proved usefulness of Marsh-Kuo's perturbation method compared with experimental data. Another type of perturbation method was suggested by Bass [19] which divides a velocity potential field into mean and scattered velocity potential fields. His method resulted in a particular reflection process which satisfies the conservation of energy, approximately. Another approach was reported by Brekhovskikh and Lysanov [20] which was simple and physically appealing. Brekhovskikh and Lysanov [20] and Marsh *et al.* [21] went beyond the perturbation approximation in order to get a closed-form solution for the scattering loss.

Considering an incident plane wave emitted towards the sea surface. If the sea surface is perfectly smooth, almost the entire energy of the incident sound would be reflected due to a huge difference between air and water acoustic impedances. For a smooth air-water interface, intensity ratio of the reflected sound to the incident sound is only 0.0002 [22]. This implies that almost the entire sound remains in the water and is reflected as a plane wave from the air-water interface. However, in a case that air-water interface is considered acoustically rough, most portion of the sound will be refracted rather than being reflected. In this state, reflection coefficient between the scattered sound and the incident sound will be less than 1 and the scattered intensity based on the surface roughness level will be decreased. Rayleigh parameter R is a criterion in order to determine the acoustical surface roughness level and is defined as follows:

$$R = 2kh\sin\theta \tag{2.8}$$

where $k = \frac{2\pi}{\lambda}$ is the sound wave number, h is rms of the surface height, and θ is the grazing angle. In the case $R << 1$, surface is considered acoustically smooth, but when $R >> 1$, the surface is known to be acoustically rough. Different possible patterns of the surface scattering are shown in Fig. 2.

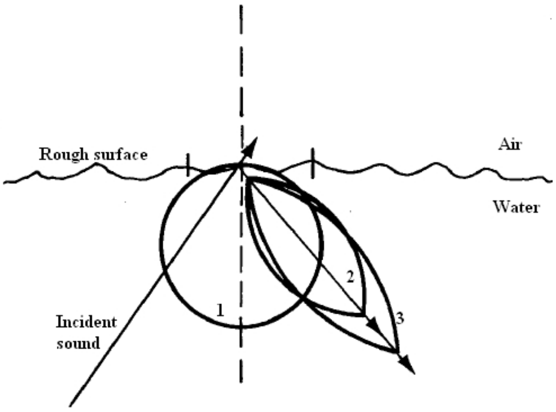


Fig. 2 Surface scattering patterns from the rough surface in three different roughness levels [2].

Scattered field in different directions is defined as follows [2]:

$$\sin\theta_m = \sin\theta + m\tfrac{\lambda}{\Lambda} = \sin\frac{mK_w}{k_a}; m = 0, \pm1, \pm2, ... \tag{2.9}$$

where $k_a = \frac{2\pi}{\lambda}$ and $K_w = \frac{2\pi}{\Lambda}$ are the sea surface and the sound wave lengths, respectively. Also, different angles θ_m are shown in Fig. 3. Total number of the angles is determined by the following relation [2]:

$$\left|\sin\theta_m\right| << 1 \tag{2.10}$$

There are some disagreements about accuracy of Rayleigh's parameter. Rayleigh assumed that scattered sound in all directions is a collection of waves with different modes at angles θ_m. This prediction is examined by different acousticians and different conclusions are drawn [2]. Urick [2] states that differences between conclusions are mostly due to the various amplitudes of the considered mode. For instance, based on Eckart's scattering theory, amplitude coefficients are determined as follows:

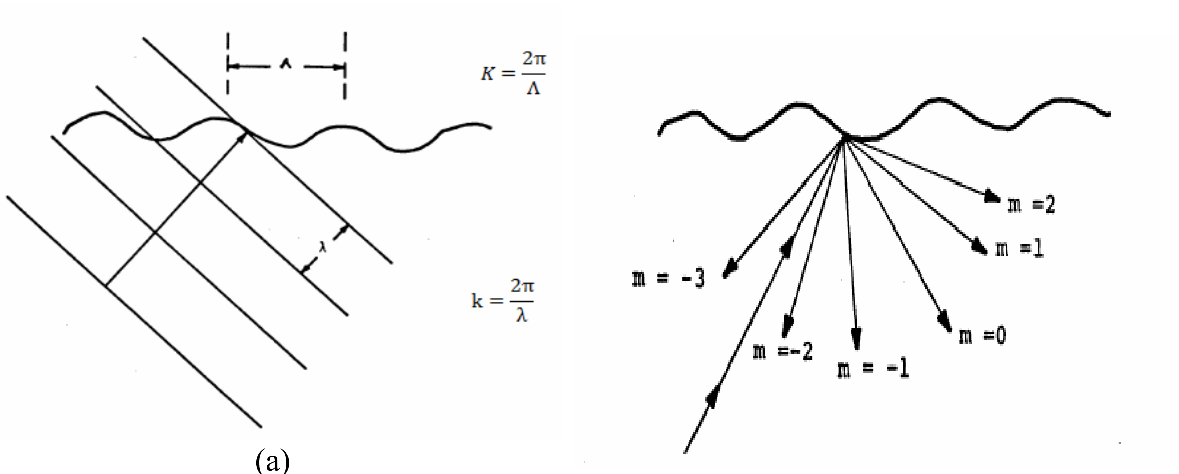
$$A_m = \frac{c + c_m}{2c} J_m\left[\left(c + c_m\right)hk_a\right] \tag{2.11}$$

where A_m is the coefficient of m^{th} mode, $c = \cos\theta$, and $c_m = \cos\theta_m$. However, based on different values of θ, h, and $k_a = 2\pi / \lambda$, different theories are generally in agreement with each other [2].

Perturbation theory is one type of frequency based method. In perturbation theory's approach developed by Thorsos [23], it was found that it provides more adequate description of the data at high frequencies for calm seas and at lower frequencies for all wind speeds. In this condition, air-water interface scattering is the dominant mechanism (Based on O/E conclusion). Based on perturbation theory, the scattering strength is obtained as in:

$$S_{pert.} = 10\log_{10}\left[1.61\times10^{-4}\tan^4\theta.\exp\left(-\frac{1.01\times10^6}{f^2U^4\cos^2\theta}\right)\right] \tag{2.12}$$

where $S_{pert.}$ is the surface scattering strength resulting from perturbation theory (dB), f is the frequency (Hz), θ is grazing angle (degrees), and U is the wind speed (knots).



(a)

(b)

Fig. 3 Sund scattering from the rough sea surface: (a) surface waves and sound wave lengths, (b) reflection patterns according to Rayleigh prediction.

2.2.3 Experimental Methods

Experimental models which have been conducted especially after the Second World War are considered another approach for examining the sea surface. As mentioned earlier, Ogden and Erskine's experimental approach [15], [16] is the most recent and complete one. Through using submerged detonators as a sound source and underwater sound receivers, they analyzed sound scattering from the sea surface. These studies were done at low frequency range and at various wind speeds and grazing angles. They concluded that there are three different regimes in sound scattering from the sea surface which are as follows:

1) In the first regime, results are generally consistent with the scattering from a rough surface.

2) In the second regime, results are generally consistent with the scattering from subsurface bubble cloud.

3) Third regime forms a transition zone between the other two regimes.

For relatively calm seas at high frequencies and for all wind speeds at lower frequencies, perturbation theory is found to give an accurate description of surface scattering. For rougher seas and higher frequencies, the Chapman-Harris empirical curves are adequate predictors of the levels of surface. Between these two regimes, there is a transition region where the scattering strengths are more difficult to predict as they depend on the details of the surface and wind characteristics.

These observations lead to the idea that there are two mechanisms that dominate the scattering of sound from the surface. In the perturbation theory regime, air-water interface scattering is the dominant mechanism. However, in the Chapman-Harris regime, another mechanism such as scattering from subsurface bubble clouds must dominate the scattering process. The transition region is then the part of the frequency and wind speed domain where the two effects compete [15], [16].

Chapman–Harris [14] proposed an empirical relationship which can adequately describe surface backscattering for rougher seas at higher frequencies where scattering from bubble clouds is presumed to dominate the scattering process (Ogden and Erskine [15], [16]). The Chapman–Harris [14] empirical relationship is defined as:

$$S_{CH} = 3.3\beta \log\left(\frac{90-\theta}{30}\right) - 42.4\log\beta + 2.6 \tag{2.13}$$

$$\beta = 158\left(Uf^{1/3}\right)^{-0.58} \tag{2.14}$$

In the transition region, where these two effects are competing, the scattering strengths depend upon the details of the surface and wind characteristics. Ogden and Erskine [15, 16] proposed a formula for computing the total scattering strength at the sea surface (S_{total}) as a combination of perturbation theory ($S_{pert.}$) and the Chapman–Harris empirical relationship (S_{CH}) as follows:

$$S_{total} = \alpha S_{CH} + (1-\alpha)S_{pert.} \tag{2.15}$$

$$\alpha = \frac{U - U_{pert.}}{U_{CH} - U_{pert.}} \tag{2.16}$$

This formula is valid for grazing angles (θ) less than 40°, for wind speeds (U) less than $20 \;\; ms^{-1}$, and over the frequency range 50 to 1000 Hz. Also, U_{CH} and $U_{pert.}$ can be obtained through the following relations:

$$\begin{aligned} U_{pert.} &= 7.22 && 50Hz < f < 240Hz \\ U_{pert.} &= 21.5 - 0.0595f && 240Hz < f < 1000Hz \end{aligned} \tag{2.17}$$

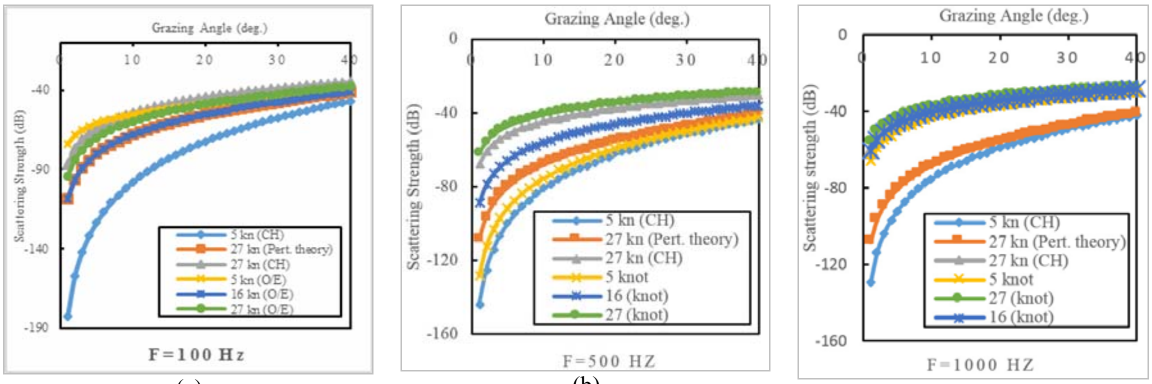
$$U_{CH} = 20.14 - 0.034f + 3.64\times10^{-5}f^{2} - 1.33\times10^{-8}f^{3} \tag{2.18}$$

In the next section, different approaches are adopted in order to calculate surface scattering coefficients under different conditions based on various physical factors.

3. Parametric Study on Wind Speed, Grazing Angle, and Frequency

Perturbation theory, Chapman-Harris (CH), and Ogden and Erskine (O/E) empirical relations were presented in the previous section. These relations are able to calculate surface scattering *s* based on different physical factors such as wind speed *U*, incident angle θ_1 (or grazing angle, $\theta = 90 - \theta_1$), and frequency *f*.

Results of surface scattering strength at three different frequencies 100 Hz, 500 Hz, and 1000 Hz are shown in Fig. 4. In addition, in Fig. 4-a, results of surface scattering at 100 Hz by the methods of Chapman-Harris (CH), Ogden-Erskine (O/E), and perturbation theory are presented. As evident in this figure, at constant frequency 100 Hz, an increase in wind speed and grazing angle causes a decrease in absolute value of the surface scattering strength *S*. In Fig. 4-b, surface scattering results are shown at frequency 500 Hz. At this frequency, the trend of variations of for surface scattering strength is the same as that of 100 Hz frequency. However, since frequency has increased, overall absolute values of the surface scattering strengths are reduced. In Fig. 4-c, frequency is increased to 1000 Hz. In this figure, contrary to the previous cases at wind speed 27 knot, there is a gap between the values of surface scattering strength obtained by perturbation theory and the other two empirical relations. Ogden and Erskine [16] stated that perturbation theory is valid at low frequencies (below 1000 Hz), when speed is relatively low. Therefore, based on their conclusion, this difference is justified. On the other hand, in Figs. 4-a and 4-b, which present results at frequencies 100 Hz and 500 Hz, respectively, results of perturbation theory are more similar to the empirical results. Based on the nature of perturbation theory, which provides more accurate results at lower frequencies, these trends are reasonable.



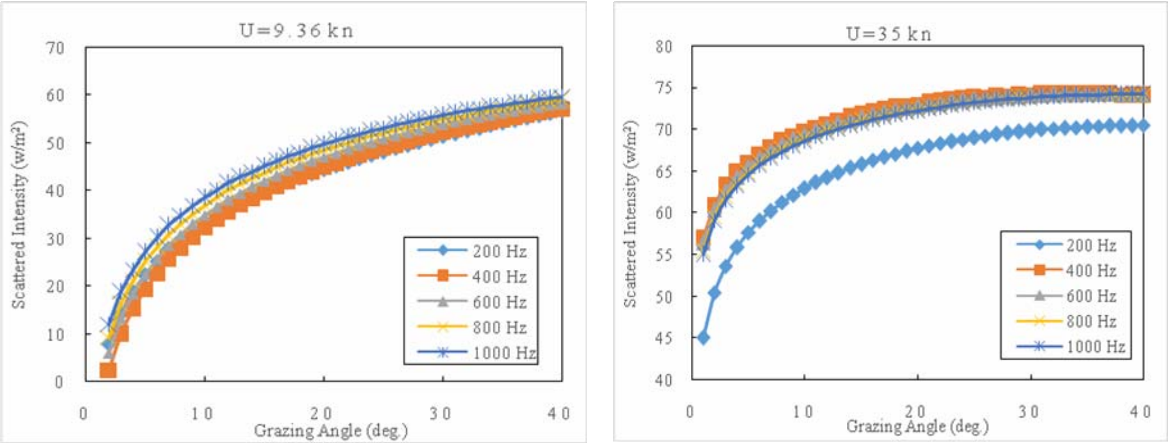
(a) (b) (c)

Fig. 4 Surface scattering strength according to perturbation theory, and Chapman-Harris, and Ogden-Erskine empirical relations at frequencies: (a) *f*=100 Hz, (b) *f*=500 Hz, (c) *f*=1000 Hz.

As mentioned earlier, surface scattering coefficient s is a parameter which determines the sound variation at sea surface and presents the effects of different variables such as wind speed, grazing angle, frequency, and etc. When this parameter is obtained, it can be used as a boundary parameter in different propagation models such as ray tracing to determine the sea surface boundary condition. Here, this parameter is utilized in order to calculate the scattered intensity from the sea surface. In Fig. 5, the resulting scattered intensity from the sea surface by Ogden-Erskine (O/E) approach is illustrated. In this Figure, considering frequency and wind speed as constant, the scattered intensity versus grazing angle is presented. Since wind speed determines surface wave height and subsurface bubble population, by considering wind speed, the effects of these parameters are taken into account in the scattered intensity results. In addition, source condition determines sound intensity. Therefore, the obtained results in Figs. 5-a and 5-b also show performance of a source at different frequencies and in the same environmental conditions (constant wind speed in both Figs. 5-a and 5-b). In Fig. 5, the incident intensity I_i is considered to be $0.0025 \ w/m^2$ and source depth is 10 m. Figure 5-a shows the scattering intensity at calm sea state in which by increasing the grazing angle, scattered intensity increases. Figure 5-b shows the scattering intensity at rough sea state. It is seen that by increasing the grazing angle and frequency, scattered intensity increases. By comparing Figs. 5-a and 5-b, it can be concluded that at higher wind speed of 35 knot, general values of the scattered intensity is higher than its values at lower wind speed of 9.36 knot. At the first look, this result may seem strange because it may be expected that due to more attenuation of the sound at rougher surface, the scattered sound should have lower intensity. However, Etter [1] points out that due to influence of environmental noise on the incident sound which is more effective at higher frequencies, the scattered intensity becomes stronger. This phenomenon results in low quality of the received scattered sounds, but with higher intensity.

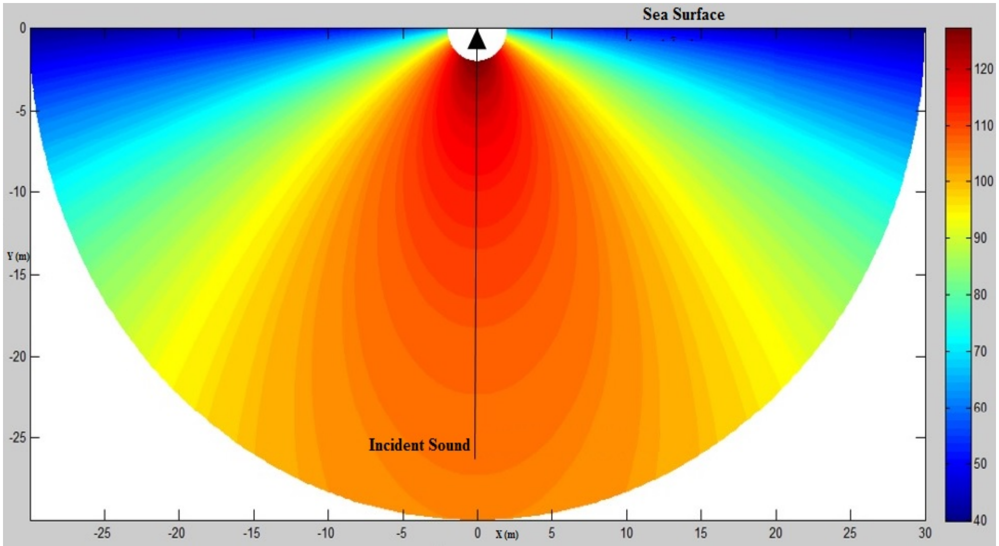
Figure 6 illustrates the scattered intensity patterns from the sea surface at two different grazing angles and surface roughness which are calculated through equation (7). These patterns are found by the method Beckman and Spizzichinio [17] which are independent of the frequency and are functions of the wind speed and grazing angle. In Figs. 6-a and 6-b, wind speeds are 35 knot and 9.36 knot, respectively, and grazing angle is 90 degrees. Also, in Figs. 6-c and 6-d, the scattered intensity are calculated at the mentioned wind speeds of Figs. 6-a and 6-b, but at the grazing angle 30 degrees. Since these patterns are independent of the frequency, noise effects on the scattered sound at higher wind speed (rougher surface) can not be observed. Contrary to the scattering results of frequency dependent methods of Ogden and Erskine's experimental tests, Chapman-Harris empirical relation, and small perturbation Theory, the patterns resulting from frequency independent method (shown in Fig. 6) are capable of presenting sound quality in different underwater coordinates.

Based on the obtained results from different frequency dependent and independent methods and observations of their capabilities, one may choose the best method in order to satisfy the problems requirements based on the governing conditions of each problem.

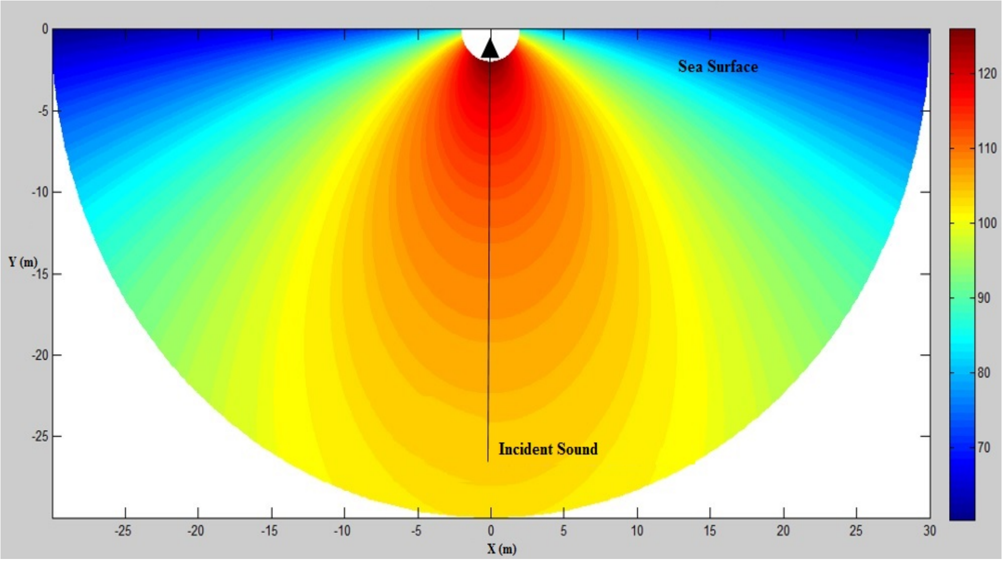


(a) (b)

Fig. 5 Scattered intensity from the sea surface vs. frequency and grazing angle at two wind speeds: (a) 9.36 knot, and (b) 35 knot.



(a)



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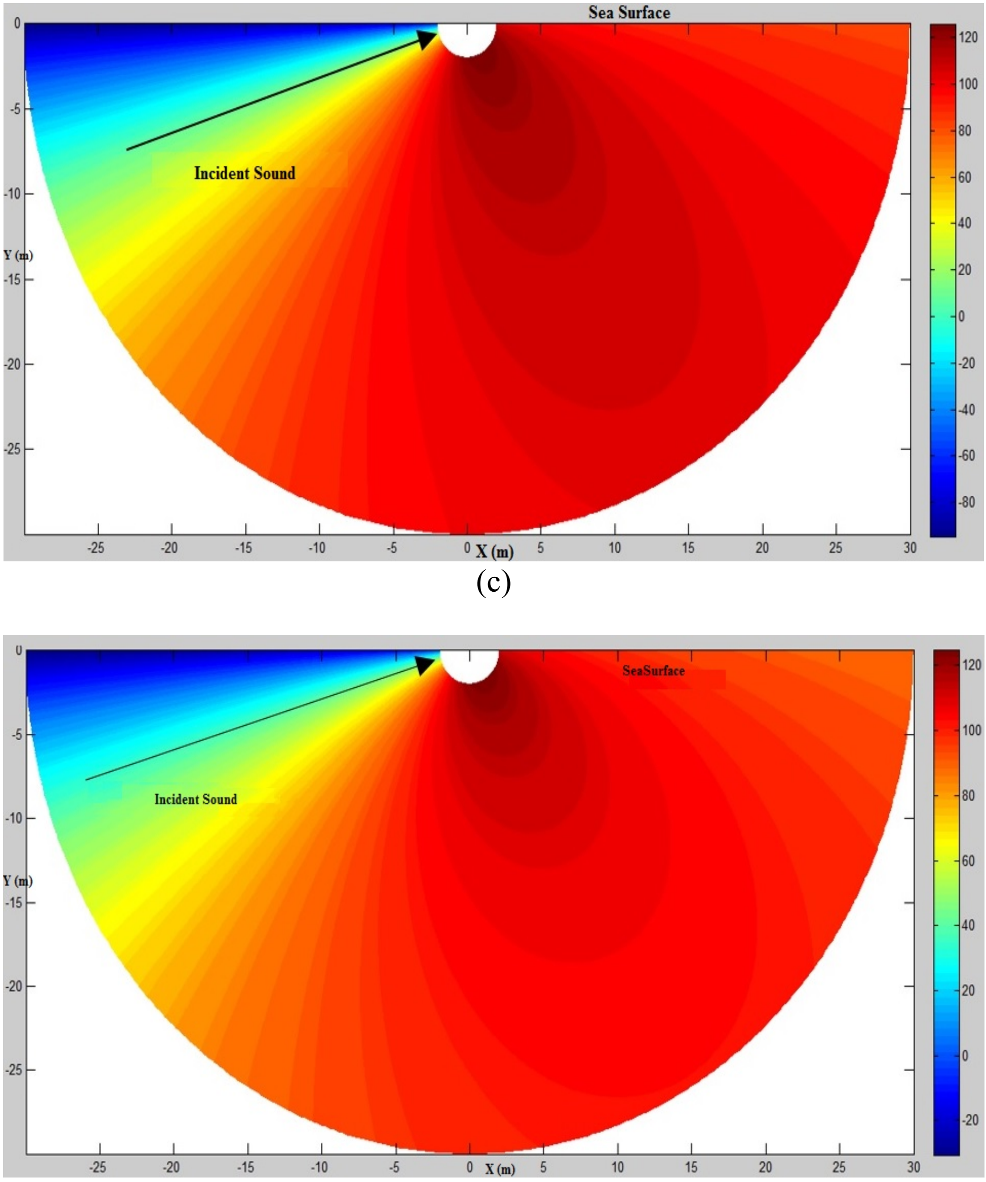

(c)

(d)

Fig. 6 Scattered intensity from the sea surface (w/m^2): (a) U=9.36 kn., θ=90 deg., (b) U=35 kn., θ=90 deg., (c) U=9.36 kn., θ=30 deg,, (d) U=35 kn., θ=30 deg.

4. Conclusions

Surface scattering coefficient, as an important parameter which includes important factors related to the sea surface, is used in the analyses of sound propagation and sonar equations. Various methods have been introduced to determine this coefficient with different accuracies, especially after the Second World War. In this paper, the most well-known frequency dependent and independent methods are applied in order to calculate the surface scattering strength. Therefore, frequency dependent methods of Perturbation Theory as well as Chapman-Harris and Ogden-Erskine empirical relations are discussed and utilized in order to compute surface scattering coefficients at different wind speeds, grazing angles, and frequencies. On the other hand, surface scattering coefficients are calculated by the frequency independent approach of Beckman-Spizzichinio. The Resulting surface scattering coefficients are used to determine the scattered intensity from the sea surface at different wind speeds and grazing angles. Based on the obtained results of the frequency dependent methods, absolute values of surface scattering strengths are found to decrease, when the frequency and grazing angle increase. The computed scattered intensities from the sea surface have the same trend as the surface scattering strengths, when the grazing angle increases, but due to the environmental noise effects, at higher wind speeds and frequencies, the scattered intensity increases. Contrary to the frequency dependent models, the frequency independent method which is discussed in this paper is capable of calculating the scattered intensity in different directions. Accordingly, the underwater scattered intensity fields are calculated at two different wind speeds and grazing angles. It is observed that the scattered intensity reduces as a result of an increase in the wind speed.

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