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Variability characteristics of reflected sound waves from sea surface using effective roughness of sea surface
海面の実効粗さを用いた海面反射波の変動特性の検討

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1. Introduction

In sound wave propagation in the sea, it is important to evaluate characteristics of sound reflection from sea surface. Because of the changing sea surface with waves, amplitude and phase of the reflected sound wave also fluctuate. In this study, we evaluated variability characteristics of the reflected sound waves from sea surface using acoustic simulation with the FDTD method. We newly introduced the concept of effective roughness of the sea surface and evaluated variability characteristics of reflected sound waves from sea surface.

2. Acoustic simulation with the FDTD method

In order to simulate actual sea surface, we used a single summation method and Bretschneider-Mitsuyasu wave spectrum[1] observed in deep offshore coast of Japan shown in **Eq. (1)**.

$$S(F) = 0.257H_{1/3}^2 T_{1/3}\left(T_{1/3}F\right)^{-5} \exp[-1.03\left(T_{1/3}F\right)^{-4}] \quad (1)$$

F is frequency, $H_{1/3}$ is the significant wave height, and $T_{1/3}$ is the significant wave period.

Figure 1 shows 2D-FDTD simulation model in the calculation. In this simulation, the sound source transmits Gaussian pulse. Surface boundary with zero pressure is generated by Eq. (1). Other boundaries are set PML absorption layer. In the calculation of the FDTD, the sea surface is treated as a stationary boundary with no temporal variation. In order to evaluate the statistical properties of fluctuation of reflected sound, we generated 250 surface boundaries with same $H_{1/3}$ and $T_{1/3}$ conditions. By quadrature demodulation of reflected sound waves observed at receiving point, we calculated amplitude and phase.

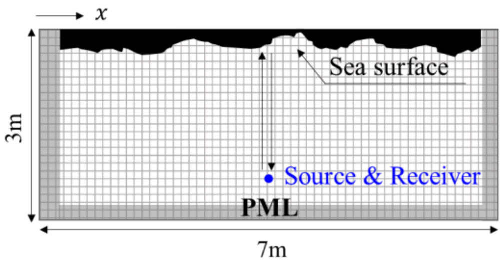

Fig. 1 Sea surface model for 2D-FDTD

3. Evaluation of variability characteristics

3.1 Definition of effective roughness of sea surface

Previous studies[2] have stated that the variability characteristics of the reflected sound waves from sea surface can be described using the Rayleigh parameter $2k\sigma_z$. Here, k is the wavenumber of sound wave, and σ_z is the effective value of water level. However, our research[3][4] revealed that on a relatively smooth sea surface that is not a random rough surface, the variability characteristics vary depending on the wavelength of the sea surface waves Λ, even with the same Rayleigh parameter $2k\sigma_z$.

In this study, the range of sea surface that contributes to the variability characteristics is $2\Delta x$, and the effective roughness of that range is defined as σ_{z0} as shown in **Fig. 2**. σ_{z0} changes depending on surface wavelength Λ, and converges to σ_z under the condition that Λ is small and sea surface approaches rough surface.

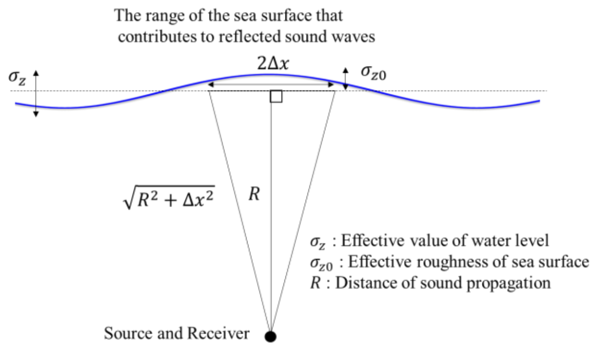

Fig. 2 Definition of effective roughness σ_{z0}

3.2 Rician distribution[5]

When the sea surface is a random rough surface, the variability characteristics of reflected sound waves can be described by Rayleigh parameter $2k\sigma_z$ and Rician distribution shown in **Eq. (3)**. Here, r and I_0 are amplitude of sound waves and modified Bessel function, respectively. γ is the energy ratio of the coherent and the incoherent component.

$$pdf(r) = 2r(1+\gamma)\exp[-\{(1+\gamma)r^2+\gamma\}]\, I_0\{2r\sqrt{\gamma(1+\gamma)}\} \quad (3)$$

In this study, we define a new Rayleigh parameter $2k\sigma_{z0}$ using the effective roughness σ_{z0} of sea surface. Here, it is assumed that the amplitude variability characteristics follow the Rician distribution, and the energy ratio γ can be described using a new Rayleigh parameter $2k\sigma_{z0}$ as shown in **Fig. 3**.

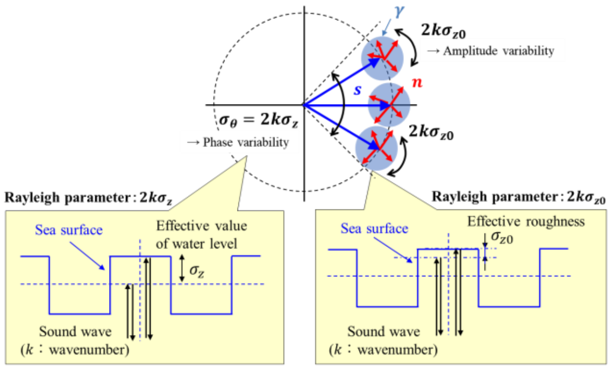

Fig. 3 Definition of Rayleigh parameter $2k\sigma_{z0}$

3.3 Results of simulation

In this simulation, surface wavelength and propagation distance are normalized by the frequency of sound waves as $k\Lambda$ and kR. We evaluated the variability characteristics under the condition that $k\Lambda$ and kR are fixed, that is, the geometric similarity between the shape of sea surface and the sound wave are satisfied. **Figure 4** shows the relationship between Rayleigh parameter $2k\sigma_z$, the energy ratio γ and the standard deviation of phase σ_θ obtained by simulation. When the sea surface is a random rough surface, γ is uniquely determined by $2k\sigma_z$, so that γ is displayed as γ_0 in **Fig. 4**. **Figure 4** shows that γ is uniquely determined by $2k\sigma_z$, γ takes a different value depending on $k\Lambda$. Regardless of $k\Lambda$, σ_θ equals to $2k\sigma_z$.

From using the assumption of effective roughness shown in **Fig. 3** and the simulation result of **Fig. 4**, the relationship between $2k\sigma_{z0}$ and $k\Lambda$ are calculated. As a result, it was found that the relationship between R and $2\Delta x$ converges to **Eq. (4)** under all $k\Lambda$ conditions.

$$2\Delta x \cong 0.204\, R \qquad (4)$$

We evaluate the variability characteristics using the effective roughness σ_{z0} obtained from **Eq. (4)**, the surface wavelength Λ, frequency f as parameters. **Figure 5** shows the simulation results when R is fixed at 2.5m. The energy ratio γ indicating the amplitude variability can be described uniformly by new Rayleigh parameter $2k\sigma_{z0}$ expressed by the effective roughness, and the value converges to energy ratio γ_0 of Rician distribution. The phase variability σ_θ can be described uniformly by Rayleigh parameter $2k\sigma_z$ expressed by the effective value of water level.

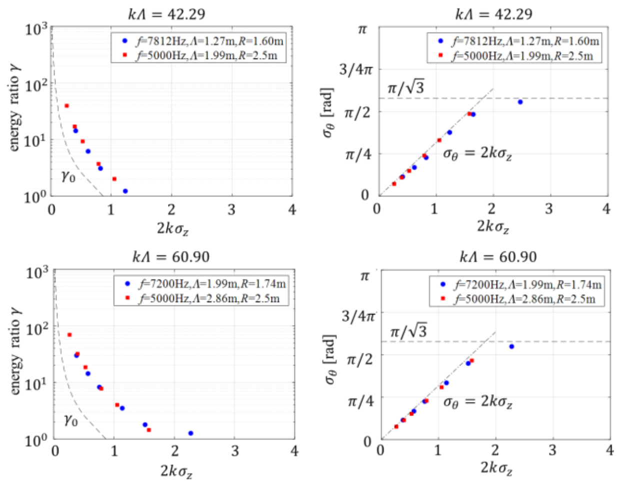

Fig. 4 Relationship between $2k\sigma_z$ and γ, σ_θ

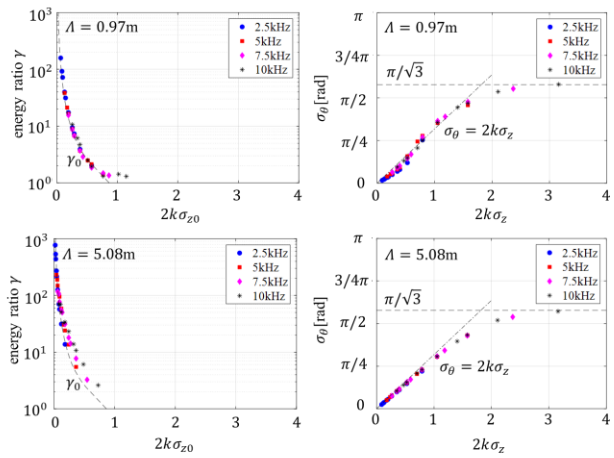

Fig. 5 Relationship between $2k\sigma_{z0}$ and γ, σ_θ

4. Conclusion

We have clarified that the energy ratio γ of amplitude variability and phase variability σ_θ can be uniformly described by Rayleigh parameter $2k\sigma_{z0}$ and $2k\sigma_z$, respectively.

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