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Quantitative evaluation for fluctuation of sound reflected from sea surface

海面反射波の変動特性に関する定量的検討

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1. Introduction

In sound wave propagation in water, it is important to evaluate characteristics of sound reflection on sea surface. Because of the changing sea surface with waves, amplitude and phase of reflected sound wave also fluctuates. In this study, we evaluated variability characteristics of reflected sound waves on sea surface using acoustic simulation with the FDTD method and water-tank test, based on Bretshneider-Mitsuyasu spectrum observed in deep offshore coast of Japan.

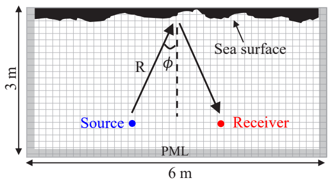
2. Acoustic simulation with the FDTD method

In order to simulate actual sea surface, we used a single summation method and Bretshneider-Mitsuyasu wave spectrum[1] shown in **Eq. (1).**

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

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 and parameters in the calculation. In this simulation, the sound source transmits tone burst waves. 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 $T_{1/3}$ condition. By quadrature demodulation of reflected sound observed at receiving point, we calculated amplitude and phase.



Frequency	5,10,15 kHz
Tone Burst	0.6 ms
Density	1000 kg/m^2
Sound speed	1475 m/s
Spatial, Time step	5 mm, 1.7 μs
R, ϕ	2~2.5 m, 0 deg
$H_{1/3}$	25~150 cm
$T_{1/3}$	0.5~2.0 s

Fig. 1 2D-FDTD simulation model and parameters

3. Water tank experiment

Figure 2 shows the configuration of the acoustic devices in water tank experiment. We controlled the hydraulic drive plunger and generated surface wave according to Eq. (1) spectrum. ITC1001 for the transmitter and B&K8103 hydrophone for the receiver are set at depth of 2m. In water tank test, the sound source transmitted tone burst wave every 0.3 seconds and measured amplitude and phase variability of reflected sound.

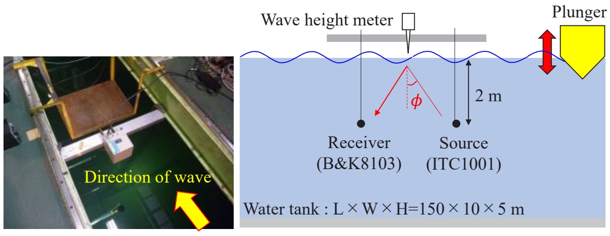


Fig. 2 Configutation of the water tank experiment

4. Comparison of FDTD and water tank test

In the previous paper[2] , we showed the PDF of amplitude variability of reflected sound from sea surface changes from Gaussian to Rayleigh, namely Rice distribution as the wave height increases. The PDF of Rice distribution is given by

$$p(x) = x(1+\gamma)\times 2\exp\left(-\left((1+\gamma)x^2+\gamma\right)\right)I_0\left(2x\sqrt{\gamma(1+\gamma)}\right) \ , \qquad (2)$$

where p , x and I_0 are probability density, amplitude and modified Bessel function, respectively. γ is the energy ratio of the coherent and the incoherent component. In this report, we evaluate value of γ for the amplitude variability using the maximum likelihood method.

Figure 3 shows relationship between $2k\sigma_z$ and γ. Here, $2k\sigma_z$ is an index representing the phase difference between the reflection from the average water level and the reflection from crests and troughs of sea surface wave when the sound wave is vertically incident. σ_z is the effective value of water level and Λ is the average of wavelength of surface wave. A comparison of the FDTD result with the tank test result shows good agreement. From these results, we found that γ tends to be smaller at lower frequencies under same $2k\sigma_z$ condition. Under a constant $2k\sigma_z$ condition, σ_z becomes larger at lower frequency, which means that reflection points

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along height direction increase. We considered the roughness of sea surface based on Bretshneider-Mitsuyasu spectrum is not sufficiently random in limited range, and evaluated influence of wavelength of sea surface, Λ.

5. Quantitative evaluation by FDTD method

In the simulation, we evaluate the relationship between Λ and γ under the same condition of $2k\sigma_z$ with R and ϕ, that are fixed at 2.5 m and 0 deg, respectively. In **Fig. 4**, it is shown that γ varies depending on the difference of Λ even under the same $2k\sigma_z$. When Λ is very large, phase fluctuation is observed due to vertical movement of smooth sea surface with a phase of $2k\sigma_z$. In this case, since the surface can be regarded as a mirror boundary, the amplitude fluctuation does not occur.

When Λ becomes smaller, sea surface becomes to be rough surface from smooth surface, and reflection points of sound wave on the sea surface is increasing. The acoustic interference from the increased reflection points determines the amplitude of reflected sound wave. Because the reflection points fluctuate randomly on sea surface, it is considered that amplitude fluctuation becomes larger.

In **Fig. 5**, we evaluated the relationship between $2k\sigma_z$ and phase variability σ_θ. Regardless of Λ, σ_θ equals to $2k\sigma_z$ when $2k\sigma_z$ is small, and σ_θ approaches a constant value of $\pi/\sqrt{3}$ which equal to standard deviation of uniform distribution when $2k\sigma_z$ exceeds 2 rad. Since the vertical movement of sea surface can be expressed as a Gaussian distribution, phase variability of reflected sound is also expressed as a Gaussian distribution with a standard deviation of $2k\sigma_z$. Because the phase range is $(-\pi, \pi)$, PDF changes from a Gaussian to a uniform distribution as $2k\sigma_z$ increases. This tendency can also be confirmed from the results of water tank experiment (Fig. 5).

In the theory of Rice distribution, there is a certain relationship between γ and σ_θ[3]. From the relation of $\sigma_\theta = 2k\sigma_z$ in Fig. 5, the asymptotic value γ_0 of Rice distribution is estimated using $2k\sigma_z$. Estimated γ_0 is plotted by a dotted line in Fig. 4. At a constant $2k\sigma_z$, γ is not smaller than γ_0 even if Λ is very small. When Λ is shorter than the wavelength of sound wave, the sound wave cannot recognize the roughness of sea surface, so γ tends to increase.

6. Conclusion

Under the condition of sea surface with a long wavelength Λ, it was found that characteristics of amplitude variability are not uniquely determined by $2k\sigma_z$, and γ varies depending on Λ. The phase variability σ_θ was found to coincide with $2k\sigma_z$ at low wave height regardless of Λ, and converge to the standard deviation $\pi/\sqrt{3}$ of uniform distribution with increasing $2k\sigma_z$.

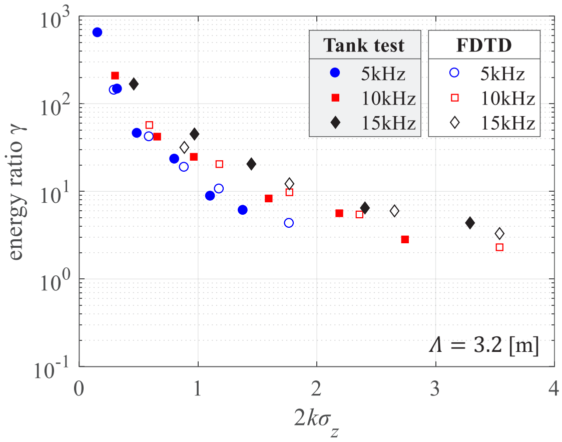

Fig. 3 Relationship of between $2k\sigma_z$ and γ

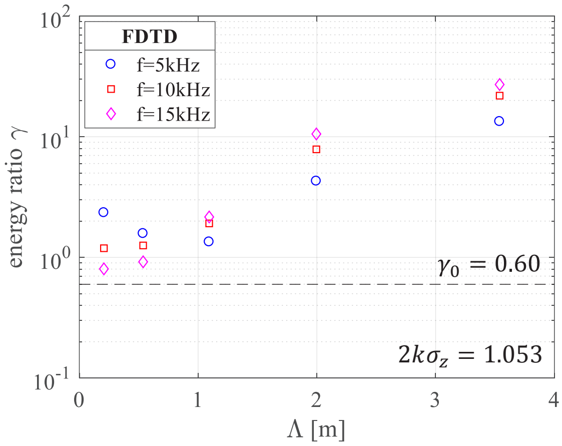

Fig. 4 Relationship of between Λ and γ

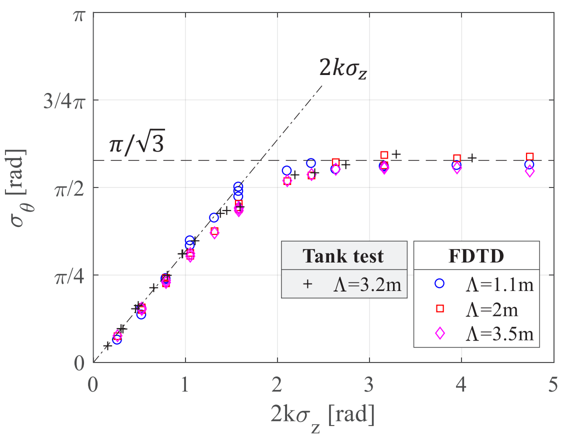

Fig. 5 Relationship of between $2k\sigma_z$ and σ_θ

References

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