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Broadband bistatic scattering from an array of regulary spaced cylinders

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ABSTRACT

Acoustic scattering by an array of regularly spaced cylinders in water tank has been investigated both theoretically and experimentally in order to evaluate the interference of scattered field. We carried out broadband bistatic scattering measurement for various pulse length over the frequency range 0.6 < ka < 2.7 including Rayleigh and Geometrical scattering region and the azimuthal angle (0~360°). Target strength(TS) for a group of cylinder is calculated based upon the infinite cylinder scattering model [1] which uses scattering directivity and phase difference and it includes interference of scattered field between cylinders. Measured TS were capable of describing fluctuations of calculated TS in azimuthal angles and frequencies that the usual incoherent summation never produces such fluctuations. Also, the scattering patterns corresponding to azimuthal angles and frequencies reflect the Bragg scattering. In particular, the fact that regular patterns appeared in side-scattering (90°) is very much correlated with scatterer spacing suggest that an inverse estimation of scatter spacing may be possible by measuring the bistatic scattered field.

INTRODUCTION

There are various objects that cause acoustic scattering in the ocean such as air bubbles, sea surface roughness, suspended particles, plankton, schools of fish, bottom roughness, ripples, and volume in-homogeneity. The ocean scatterer can be classified into air-filled, fluid-filled, and rigid depending on the surrounded medium and the sound speed and density contrast inside the object.

The objects in the sea are all different sizes and shapes, but many researchs have been performed in spherical and cylindrical shapes to numerically calculation and interpret the acoustic scattering. For example, air bubbles that are made when waves break are considered to be spherical shapes filled with air, and copepods, which are dominant species of zooplankton, are considered as a cylindrical shapes filled with fluid that have a similar density to the sea, also the swimbladder is considered as a cylindrical shape filled with air while mines or submarines are considered as rigid cylinder that are emptied [2-6].

Scattering pressure from such underwater objects is calculated in the target strength, which is the ratio between incident waves and scattering waves, and the target strength of an object is defined with the function of transmit frequency, incident angle, and the azimuthal angle; moreover, when the objects that cause scattering exist in a group within the insonified volume, the target strength increases along with the number of objects in the insonified volume. Therefore, the studies to measure the target strength of a single object in order to estimate the number of scatter causing objects in the target strength of a group have been conducted. However, most ocean scatterers are continuously distributed in groups instead of as single objects, and there are not enough studies to evaluate the target strength from such distribution. Furthermore, it is required to study the variation of the target strength from the interference of scattered field between such objects when they are closely spaced in the insonified volume.

The studies on acoustic scattering of a single cylinder is majorly on the bent and fluid filled cylinder (zooplankton) which described these objects realistically, air-filled and tilted cylinders (swimbladders), hollow cylinders (submarine) where the internal rings are distributed regularly measuring the backscattering from the frequency and incident angle as well as the bi-static scattering from the frequency, incident angle, and azimuthal angle of the rigid and finite cylinder (mine). For the acoustic scattering of the cylinder arrangement, the scattering function of two parallel cylinders was firstly suggested by Twersky [7], after which Young and Bertrand [8] calculated and measured the target strength upon the incident angle of the two paralleled cylinders. Although there are many studies on calculating the scattering pressure from more than two cylinder arrangements [9], there are not enough experimental studies on measuring the variation of the scattering pressure upon the frequency, incident angle, azimuthal angle, and spacing of the cylinder arrangement.

In order to identify the interference effect between each scatter causing object and scattering pressure for the case when these objects are grouped, it is required to experimentally verify the variation of the scattering pressure numerically upon the frequency, azimuthal angle, and pulse length. Therefore, in this study, the broadband bi-static scattering is measured from the spacing of the cylindrical objects when cylinders of the same size are arranged regularly. When the waves with various frequency and pulse lengths are entered, the directivity and the variation of the target strength from the azimuthal angle are measured to compare with the model with cylinder arrangement. Understanding the variation of the target strength of the cylinder arrangement through measurement and calculation increases the accuracy of identifying, classifying and estimating the number of such objects from the acoustic signals that continuously exists in group, also will be able to suggest the distribution of these objects through the scattering signals.

SCATTERING MODEL FOR AN ARRAY OF REGULALY SPACED CYLINDER

The geometry of cylinder array is as describes in figure 1. The scattering of cylinder array depends on the scattering angle ϕ, spacing d, the range from hydrophone to the center of the cylinders and the cylinder array is perpendicular to the z axis. Range between each cylinder and hydrophone h are calculated as a function of scattering angle ϕ, range R and spacing d using the second law of cosines. The total scattering pressure can be estimated to summation of scattering pressure of each cylinder. The phase difference of the scattering wave from each cylinder occurs only because of the range from the cylinder to hydrophone. Applying the range to equation and summing pressure, the total pressure field of the 9 cylinders was obtained. The limitation of the mode number is determined at the level of 95 % of total sound pressure. The mode limitation increases exponentially with *ka*, and mode number is 19.

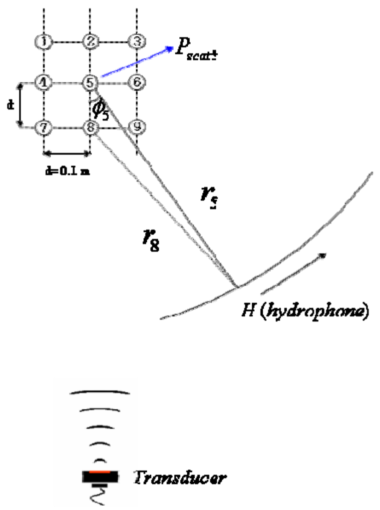

Figure 1. Geometry for formulating the problem of sound scattering from 9-infinite cylinders

$$P_{scat} \underset{kr>>1}{\rightarrow} P_{inc}\sqrt{\frac{2}{\pi kr}}e^{i(kr-\pi/4-wt)}\sum_{m=0}^{\infty}(-i)^m B_m \cos(m\phi)$$

$$B_m = \frac{-\varepsilon_m i^m}{(1+iC_m)} \qquad (1)$$

$$C_m \equiv \frac{J_m^{'}(k_1 a)N_m(ka) - ghJ_m(k_1 a)N_m^{'}(ka)}{J_m^{'}(k_1 a)J_m(ka) - ghJ_m(k_1 a)J_m^{'}(ka)}$$

$$g \equiv \frac{\rho_1}{\rho_0},\ h \equiv \frac{c_1}{c_0},\ and\ \ k_1 = \frac{k}{h}$$

$$P_{total} = \sum_{n=1}^{N} P_{scat_n} = P_{scat_1} + P_{scat_2} + \cdots + P_{scat_N} \qquad (2)$$

$$P_{total} = P_{inc}\sqrt{\frac{2}{\pi k}}e^{-i(\frac{\pi}{4}+wt)}\left(\frac{e^{ikr_1}}{\sqrt{r_1}} + \frac{e^{ikr_2}}{\sqrt{r_2}} + \cdots + \frac{e^{ikr_n}}{\sqrt{r_n}}\right) \qquad (3)$$

$$\times \sum_{m=0}^{\infty}(-i)^m B_m \cos(m\phi)$$

$$\phi_1 \approx \phi_2 \approx \cdots \approx \phi_N \quad , \quad r >> d$$

$$TS_{total} \equiv 10\log\frac{P_{total}}{P_{inc}} \qquad (4)$$

EXPERIMENTAL DESCRIPTION AND OBSERVATIONS

The target is an arrayed of regularly spaced cylinder (rigid, fixed target) made of stainless steel (density contrast g is 7.9 and sound speed contrast h is 3.73). The radius of cylinder a is equal to 5 mm and length is 1.3 m. 9-cylinders arrayed into three-row and three-column which has spacing *d* is 0.1 m. Transducer (Reson, TC2116) covered and overall bandwidth of 30-130 kHz (0.6 < ka < 2.7) which include Rayleigh scattering region (ka < 1) and geometrical scattering region (ka > 1) where k is the wave number in water and a is the radius of the cylinder. The ratio d/λ is ranged from 2 to 8.6 where *d* is the spacing of cylinder array and λ is the acoustical wavelength. The beamwidth of the transducer was 14.6° at 50 kHz.

The bistatic measurement used a fixed transducer and a hydrophone rotating about the target. The transducer was set at the middle depth of the water tank (5 m × 5 m × 5 m). A hydrophone (Reson, TC4014) was mounted at the same depth and rotate around cylinders at intervals of 1°. Continuous wave (CW) signals with 0.1, 0.2, 0.3-ms pulse length generated by a wave generator (Agilent 33120A) were transmitted and amplified by 30 dB with a Power amplifier (B&K 2713). The scattered signals were measured at 2 m distance form the target as a function of aspect angle, θ, in 1° increments over 360°(fig. 3). The signals were received by the hydrophone, amplified by 30 dB with a measuring amplifier (B&K 2610), and digitized at a 500 kHz sampling rate. At each frequency, 5 pings were recorded, at a rate of 1 ping per second. 5 pings signals were almost equal because target is fixed, rigid cylinders and source and receiver were stable. The average sound velocity in water tank measured with CTD was 1491 m/s, and water temperature was 23.6°.

Two sets of scattered data were measured in order to obtain the target strength which covered an overall bandwidth of 50 – 120 kHz and 30-130 kHz, respectively. Bistatic scattering is examined over the dimensionless frequency range 1 < ka < 2.5 and 0.6 < ka < 2.7, respectively. Increments of frequency were 2 kHz in experiment 1 and 1 kHz in experiment 2. Increments of aspect angle were 1.5° in experiment 1 and 1° in experiment 2. Incident acoustic pressure at each frequency measured using integral intensity method when transducer aligns with hydrophone and target in order. The incident pressures were measured at 1 m from the transducer when hydrophone positioned at 180° (backscattering). Scattered signals overlapped with direct path between source to hydrophone at forward scattering (0 – 40°, 320 – 360°).

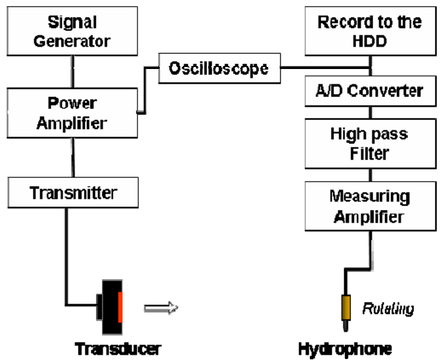

Figure 2. System block diagram

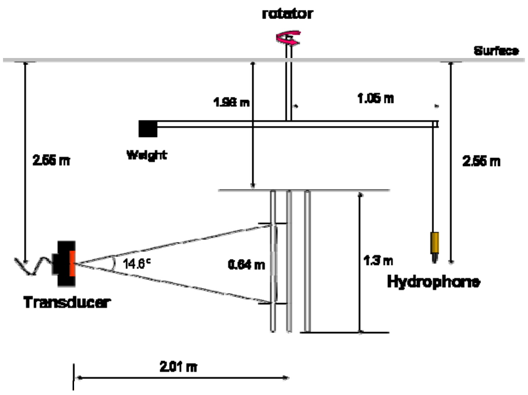

Figure 3. Geometry for measurement of 9-cylinders scattering. The ARRS(Auto Rotating and Receiving System) was used to measure the bistatic scattering automatically

MEASUREMENT RESULTS

The sonar equation to estimate the bistatic target strength as a function of frequency and azimuthal angle ϕ is given by [10]

$$TS(f,\phi) = RL - SL + TL_1 + TL_2$$

where $TS(f,\phi)$ is the integrated target strength in dB re 1 m, RL is the received level in dB re 1 μPa, and SL is the source level in dB re 1 μPa at 1 m. TL_1, TL_2 are the transmission loss in decibels from the source to center of cylinder group and from the reciever to center of cylinder group. Absorption loss can be negligible because the absorption coefficient predicted using the formula suggested by Francois and Garrison is ~3×10^{-3} dB/m for 100 kHz.

The experimental measurements with theoretical calculations for target strength are compared in the figure 4. Solid line represents the target strength of a single cylinder calculated using the infinite cylinder model. Dashed line shows the target strength for the group of 9-cylinders calculated by simply summing together the scattering cross sections for the individual cylinder and thereby neglecting phase difference effects. Dot-solid line shows the target strength calculated using the scattering model of group cylinder, and has fluctuations of TS appear due to constructive and destructive interference. The experimental data at azimuthal angle tends to be closer to the predictions obtained using infinite cylinder model. The measured TS are plotted versus ka for 0.1, 0.2 and 0.3 ms pulse length (fig. 5). For the azimuthal angle of 90°, the target strengths are approximately -23 to -10 dB, showing the periodicity of the peaks at interval of ka=0.34. And for the azimuthal angle of 180° (backscattering), the target strengths are approximately -23 to -10 dB, showing and increase with ka and occurs the periodicity of the peaks at interval of ka=0.17. As can be seen, there is a strong variation at 0.3 ms, which is <5 dB greater than 0.1 ms at equal ka. The comparison of calculated TS with measured TS shows a good agreement at all of ka for the prediction of highlight (fig. 6). In figure 6(b), predicted TS displays Bragg scattering which is due to scatterer spacing of cylinder array. We also observed Bragg scattering from measured TS in frequency and angle domain.

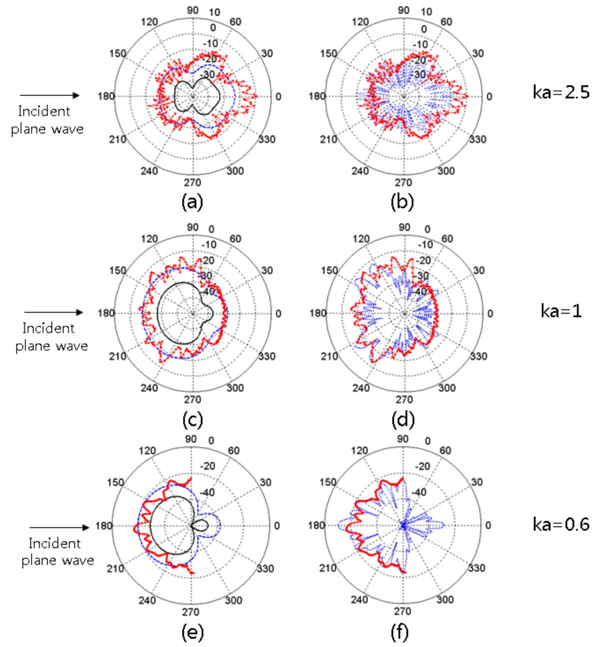

Figure 4. Comparisons of the calculated and measured target strengths from an array of cylinders. TS of a single cylinder calculated with infinite scattering model (solid line). TS of 9 cylinders, calculated by incoherent summation of the form function for the individual cylinder (dash line). Measured TS (dot-solid line) with ka=0.6, 1 and 2.5.

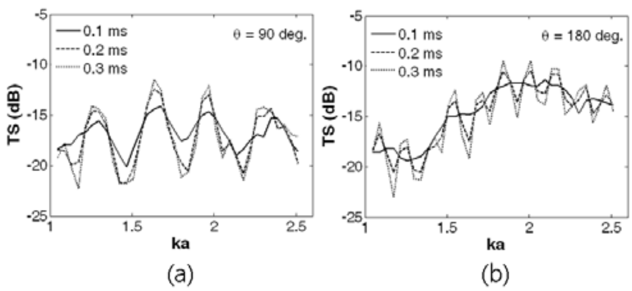

Figure 5: The measured TS versus ka for 0.1, 0.2 and 0.3 ms pulse length. Target strength variations at azimuthal angle 90° (a) and 180° (b).

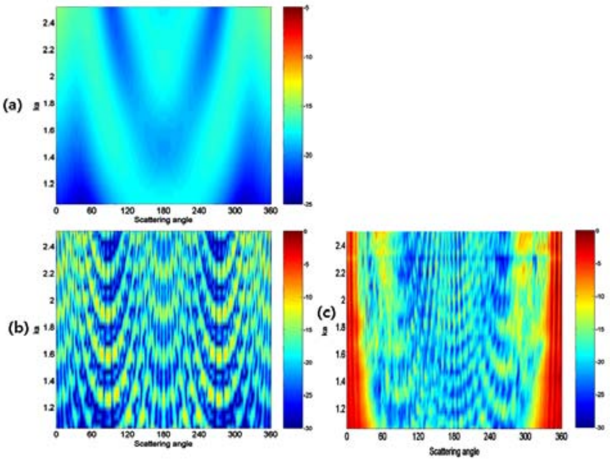

Figure 6: Comparison of the scattering patterns of a group of cylinders by the incoherent summation of one cylinder TS (a) and coherent summation (b) in scattering angle/ ka domain. TS by coherent summaion varies strongly with scattering angle and ka (dimensionless frequency) as a results of interference effects. Measured scattering patterns of an array of regularly spaced cylinders (c).

SUMMARY

We carried out broadband bistatic scattering measurement for various pulse length over the frequency range $0.6 < ka < 2.7$ including Rayleigh and Geometrical scattering region and the azimuthal angle (0~360°). Also, target strength for regularly spaced cylinders has been calculated and compared. It included interference of scattered field between the cylinders, and calculates the aggregate scattering field of the group by coherently summing the contributions from the individual cylinder. In azimuthal target strength, fluctuations of TS appear due to constructive and destructive interference.

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