Laboratory measurements of forward and bistatic scattering of fish at multiple frequencies

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Forward and bistatic scattering of sound by individual fish at frequencies of 120 and 200 kHz have recently been measured in the laboratory following an earlier experiment conducted at acoustic frequency of 38 kHz by Ding [J. Acoust. Soc. Am. **101**, 3398–3404 (1997)]. The results of forward-scattering strength obtained here, combined with those obtained in Ding, provide an empirical dependence of forward-scattering strength on acoustic frequency. It is observed that the forward-scattering strength increases rapidly with frequency and is much stronger than the backscattering strength. Scattering patterns, or scattering strength as a function of receiving angle, have also been measured for the first time in this new experiment. These results are currently being examined using theoretical models taking appropriate account of effects of both fish flesh and swimbladder. © *1998 Acoustical Society of America.* [S0001-4966(98)05405-8]

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INTRODUCTION

Forward scattering of fish has drawn significant attention since it was demonstrated that migrating salmon in the Fraser river of B.C., Canada could be discerned with an acoustic scintillation flowmeter (based on forward scattering by inhomogeneities in the water) deployed across the river (Curran *et al.*, 1994; Ye *et al.*, 1996). While effective techniques based on the forward-scattering principle are still yet to be developed for practical application in estimating fish population, fundamental knowledge of more general scattering characteristics of fish is essential for such a development. Ding (1997) carried out a novel laboratory experiment to measure directly forward scattering (at 38 kHz) by single fish with simultaneous measurements of backscattering, and it was found that the forward scattering is much stronger and varies with the angle of incidence less significantly, than the backscattering. In the meantime, Ding and Ye (1997) used a sound scattering model developed in Ye *et al.* (1997) to model the data of Ding (1997), and found that the fish body tends to be a more important factor than the swimbladder in determining forward-scattering strength. The results support an earlier model study by Ye and Farmer (1996).

Given the interesting results obtained in the first experiment, we carried out a second experiment at higher frequencies (120 and 200 kHz). Of more general interest, measurements of scattering patterns of fish (i.e., scattering strength versus scattering angle) have also been obtained. This paper describes the second experiment and reports the results, while a more careful analysis of the data will be the subject of subsequent papers.

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I. LABORATORY EXPERIMENTS

Both the first and second experiments were carried out in the water tank (15 m long, 10 m wide, and 10 m deep, filled with fresh water) of the National Research Institute of Fisheries Engineering (NRIFE) of Japan. The primary purpose of the first experiment was to measure the dependence of forward scattering of individual fish on the incident angle of sound. Details and results of the experiment are referred to Ding (1997). The second experiment was aimed at measuring bistatic scattering of fish at much higher frequencies (120 and 200 kHz), and will be described here in detail.

A. Setup

In this experiment, the transducers were mounted on a steel plate which can be moved by a motor to a desired position (Fig. 1). They were placed near one end-wall of the tank and in the middle of the water body, looking horizontally towards the other end-wall (with sound absorbers) near which hydrophones were placed. As pointed out by Ding (1997), it is essential to keep the positions of the hydrophones stable relative to the transducers. Therefore three broadband hydrophones were suspended within thin steel-string frames connected to rigid bars, and positioned to the same depth as the transducers. A target was then positioned between the transducers and the hydrophones at the same depth, and near the center of the tank.

A fourth broadband hydrophone was also mounted on the plate very close to the 200-kHz transducer for measurement of backscattering, as we intended to use a simple receiving system for multiple frequencies. This setup resulted in more noise in the backscattered signal since the hydrophone is nearly omnidirectional. We found that the measurements were 1 to 2 dB higher than the theoretical value for a

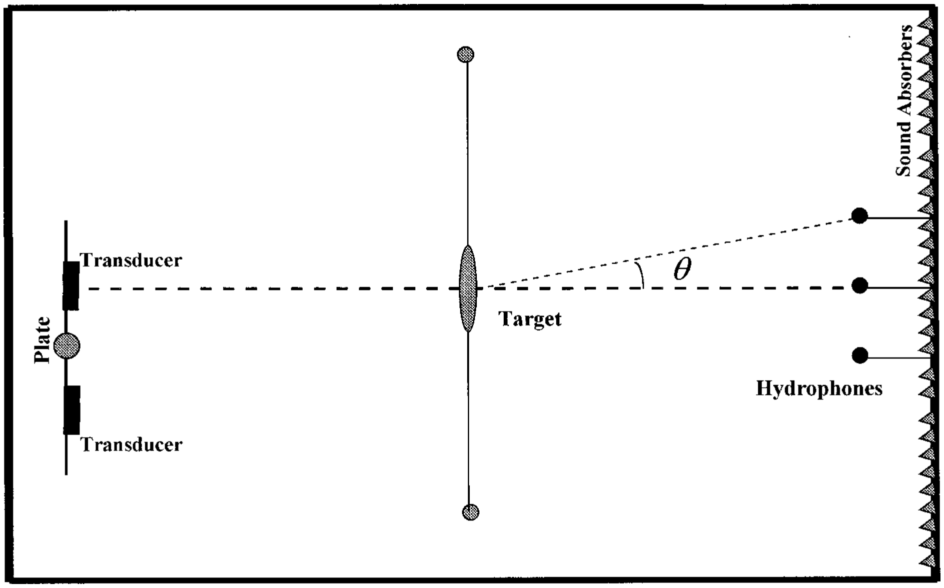

FIG. 1. Experimental setup.

copper sphere of 60-mm diameter. However, the measured backscatter merely served as a reference for forward scatter, rather than for a precise measurement.

Signal transmission was through a function generator and a power amplifier. The function generator produces a prescribed pulse length and carrier frequency; pulsed sinusoidal signals were sent to the power amplifier and applied to the transducers. The pulse repetition rate was controlled by a trigger signal generator, which was also used to synchronize the transmission and reception.

B. Procedure

For each measurement, the transducers were positioned so that the target was located on the beam axis. The hydrophones were positioned in such a way that desired scattering angles relative to the target (θ in Fig. 1) were formed. For measurement of forward scattering (i.e., scattering angle equal to the incident angle), special care was taken to align one of the hydrophones and the target on a common axis of the transmitted beam. For each measurement, received signals were recorded first in the absence of the target (reference direct-path signal) and then with the target in place. The difference of the received signals thus obtained is the scattered signal (Ding, 1997). After each measurement, the hydrophones were moved to new positions and the same procedure was repeated. Note that in this experiment, the incidence of sound was always normal and only the scattering angle is changed by moving the hydrophones.

Let P_d and P_s be the received amplitude of direct-path waves and scattered waves. Following Ding (1997), the amplitude of the scattering function at the scattering angle θ (Fig. 1), is given by

$$|F|=\frac{P_s}{P_d}\frac{r_i r_s}{r_d}, \tag{1}$$

where r_i and r_d are the distance from the transmitter to the target and to the receiver at $\theta=0$, respectively. The distance from the target to the receiver at $\theta=0$ is given by $r_s=r_f/\cos\theta$, where $r_f=r_d-r_i$.

C. The first Fresnel zone

When a target is large relative to the wavelength, and close to the transmitter, the Fresnel (phase) zones have to be considered. The radius of the first Fresnel zone in the case of forward scattering can be expressed as [extended from Clay and Medwin (1977)]

$$a_1=\sqrt{\lambda r_i r_f/r_d}, \tag{2}$$

where λ is the wavelength. If a target is not entirely within the first Fresnel zone, the scattered waves from the first and second zone tend to interfere destructively. In this experiment, $r_i=5.23$ m, $r_f=6.36$ m, and $r_d=r_i+r_f=11.60$ m. Thus $a_1=19$ cm at frequency 120 kHz, and 15 cm at 200 kHz. The fish length ranges from 31 to 35 cm. That is, at 120 kHz the fish are entirely within the first Fresnel zone, whereas at 200 kHz the main body of the fish is still in the zone with only 0.5–2.5 cm of the head and tail outside the zone.

II. RESULTS

In this experiment we have measured several immobile (dead) Japanese mackerel (*Scomber Japonicus*) in similar conditions (directly sent from a nearby fishing port). The fork lengths (fork length is defined as the distance from the tip of the snout to the end of the rays in the center of the caudal fin) of these fish ranged from 31.0 to 35.5 cm. Of particular interest here is the measured forward- and backscattering target strengths (TS) at normal incidence versus frequencies, which are shown in Fig. 2(a) for a number of Japanese mackerel [including those used in the earlier experiment (Ding, 1997)]. It is seen that the forward-scattering TS increases from about -19 dB at 38 kHz to about 4 dB at 200 kHz. The backscattering TS, however, varies within a much smaller range (from -36 to -31 dB), with one excep-

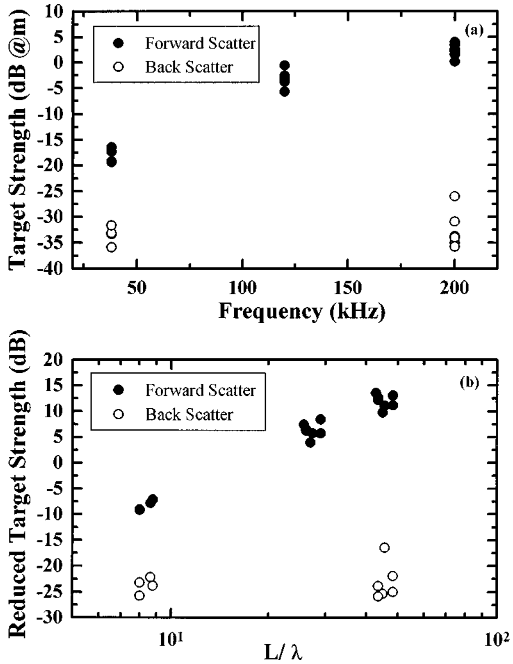

FIG. 2. Forward- and backscattering strength at three frequencies (38, 120, and 200 kHz). (a) Target strength, (b) reduced target strength. Backscattering at 120 kHz was not measured in the experiment.

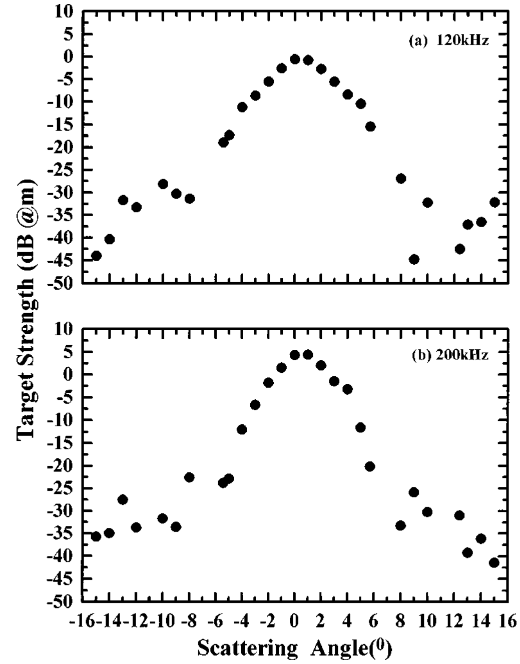

FIG. 3. Bistatic scattering pattern of a Japanese Mackerel, for a length of 35 cm and a weight of 546 g. (a) 120 kHz, (b) 200 kHz.

tional point near -25 dB due to a fish with an exceptionally large swimbladder. Note that the backscattering at 120 kHz was not measured in this experiment.

As the data were collected for fish of various fork lengths, which also affect target strength, it is useful to choose dimensionless or normalized parameters. By a similarity analysis, it is reasonable to normalize scattering amplitude $|F|$ by fork length L, and investigate its dependence on L/λ, where λ is the wavelength. Therefore we define normalized, or reduced target strength, either forward or backscatter, as

$$\mathrm{TS}_n = 20 \log_{10}\left(\frac{|F|}{L}\right). \tag{3}$$

Figure 2(b) shows the reduced target strength for the data in Fig. 2(a). Two important features can be observed immediately from Fig. 2. First, the forward-scattering TS increases rapidly with frequency. This result qualitatively supports earlier theoretical modeling of forward scatter by Ye and Farmer (1996) who show that forward scatter of fish increases monotonically with frequency while backscatter oscillates with frequency. Second, the forward-scattering TS is much stronger than the backscattering TS, and the difference increases dramatically with frequency. For example, in Fig. 2(b), the forward scatter is 13 dB higher than the backscatter at 38 kHz and becomes 36 dB stronger at 200 kHz.

Another interesting aspect of the measured acoustic scattering by fish, never obtained before, is scattering pattern. Figure 3 shows the measured scattering pattern, i.e., target strength versus the scattering angle θ in Fig. 1, for a single fish with a fork length of 35.0 cm and a weight of 546 g. It was measured at frequencies of 120 and 200 kHz, and at scattering angles ranging from $-15°$ to $15°$. At $\theta=0$, the result corresponds to the forward-scattering strength. It is seen that with a 20-dB threshold, the scattering pattern at 120 kHz has a well-defined mainlobe between $-6°$ and $6°$. The mainlobe narrows to $\pm 5°$ at 200 kHz. Beyond the mainlobe, the scattering pattern fluctuates.

Preliminary analysis of the data using the model of Ye *et al.* (1997) indicates that the model overestimates the forward-scattering strength by a few dB. It is speculated that this may be due to lack of a coupling mechanism between fish body and swimbladder in the model (Ding and Ye, 1997). An improved model taking appropriate account of the coupling is under development.

Both forward and bistatic scatter could be used for the purpose of detecting fish. For example, consider a situation where a receiver is spatially separated from a transmitter as in Fig. 1. When fish pass across the acoustic beam, their forward-scattered signals can interfere strongly with the direct-path signal, thus inducing signal fluctuation. This can be analyzed using scintillation techniques to detect the passage of the fish (Ye *et al.*, 1996), if the contribution from the fish is well above the background signal variability. On the other hand, in the case of low fish density or strong background variability, bistatic scatter could be used. Figure 3 shows that for a single fish of 35 cm and at 200 kHz, the bistatic scattering strength at scattering angle $\pm 5°$ is still approximately 20 dB stronger than the backscattering strength. If the fish is still in the acoustic beam but the receiver is displaced far from the beam, then the bistatic scatter can be separated from the direct-path signal when a sufficiently short pulse is used. In both cases, the fish can be well within the first Fresnel zone as long as they are not too close to the transmitter or the receiver. Although practical techniques have yet to be developed, we believe that this laboratory study provides a more complete understanding of sound scattering by fish, and lays the foundations for future development of related technology.

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Clay, C. S., and Medwin, H. (**1977**). *Acoustical Oceanography* (Wiley, New York).

Curran, T., Lemon, D., and Ye, Z. (**1994**). ''The acoustic scintillation flowmeter: Applications for a new environmental tool,'' J. Association Canadian Hydrographic Service, Spring, 24–29.

Ding, L. (**1997**). ''Direct laboratory measurement of forward scattering by individual fish,'' J. Acoust. Soc. Am. **101**, 3398–3404.

Ding, L., and Ye, Z. (**1997**). ''A method for acoustic scattering by slender bodies. II. Comparison with laboratory measurements,'' J. Acoust. Soc. Am. **102**, 1977–1981.

Ye, Z., and Farmer, D. M. (**1996**). ''Acoustic scattering by fish in forward direction,'' ICES Journal of Marine Science **53**, 249–252.

Ye, Z., Curran, T., and Lemon, D. (**1996**). ''Fish detection by the acoustic scintillation technique,'' ICES Journal of Marine Science **53**, 317–321.

Ye, Z., Hoskinson, E., Dewey, R., Ding, L., and Farmer, D. M. (**1997**). ''A method for acoustic scattering by slender bodies. I. Theory and verification,'' J. Acoust. Soc. Am. **102**, 1964–1976.