ICES Journal of Marine Science, 53: 249–252. 1996

Acoustic scattering by fish in the forward direction

Zhen Ye and David M. Farmer

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

This article is a study of the scattering of sound by fish in the forward direction. It is shown that in contrast to the situation with backscattering, the fish body rather than the swimbladder is primarily responsible for forward-scattering at high frequencies. In addition, the forward-scattering function of fish has a simple structure compared with the backscattered signal. Since the shape of a fish body is relatively easy to obtain, models for which the fish body is the major target are expected to be superior to those based on the swimbladder. More experimental work on the forward-scatter of sound by fish would seem worth while. Comparisons are made with the acoustic back-scattering by fish.

Key words: acoustics, modeling, scattering theory.

Z. Ye and D. M. Farmer: Institute of Ocean Sciences, PO Box 6000, 9860 West Sannich Road, Sidney, British Columbia, Canada V8L 4B2. Correspondence to Ye.

Introduction

In the traditional acoustic survey of fish stocks, echo-sounding systems have been commonly used, which rely heavily on the information of the sound scattered back from fish. However, an alternative method for fish counting, the scintillation technique, has been reported by Curran *et al.* (1994). This technique is analogous to certain atmospheric and astronomical studies using electromagnetic radiation, and also with turbulence studies discussed in detail by Farmer *et al.* (1985).

The underlying physics of fish detection by the scintillation technique (Ye *et al.*, 1996) is the forward-sound-scattering principle. A simple description of the method is as follows. Very short bursts of sound from acoustic projectors are successively transmitted in parallel across a river, roughly perpendicular to the flow, to hydrophones on the opposite bank. The pattern of amplitude and phase variation between the receivers can be analyzed to derive information on the flow and passing fish. In actual measurements, this technique has shown promising results (Curran *et al.*, 1994).

We are therefore concerned about the nature of the forward-sound-scattering process. Research on the forward-scattering of sound by fish is relatively scarce. Ye (unpublished data) recently used a forward-scattering theorem to investigate sound extinction by fish. It was shown that, in contrast to backscatter, the fish body could be the main acoustic target in the forward-scatter. This suggests several advantages for the scintillation technique compared to the traditional backscatter method. A prominent one is that it will ease the modeling of sound-scattering by fish. If the swimbladder is the main target, the accurate shape of the swimbladder will be essential to modeling, at least at high frequencies. Given the present methods, such as X-ray and plaster cast, this is often difficult to achieve. The shape of a fish swimbladder may also change from time to time and the shape will likely be altered when the fish is caught or killed. However, the fish body has rather consistent physical parameters and is expected to be much more stable than the swimbladder. All these factors may be advantageous in using the scintillation technique for fish detection, especially in riverine environments.

In the next section, we formulate the problem of sound-scattering by fish in general. The forward-scattering function will be calculated in the section ‘‘Acoustic scattering by fish’’, based upon a simple scattering model. The paper concludes with a brief summary and discussion.

Model of sound-scattering by fish

Many models have been proposed in the literature for studies of sound-scattering by fish, especially by fish with swimbladders (Foote, 1985; Furusawa, 1988; Ye and Farmer, 1994; Ye and Furusawa, 1995). Of all these models, the elongated deformed cylinder model (Junger, 1982; Stanton, 1988) seems appropriate for the present study, because most fish and their swimbladders are more or less elongated. Therefore, in this paper, we use the deformed cylinder model.

1054–3139/96/020249+04 $18.00/0

According to Junger (1982) and Stanton (1988), the scattering amplitude for an elongated scatterer can be expressed as a summation of the scattering from differential elements along the longitudinal axis, assuming the elements are within an infinitely long cylinder, and can be written as:

$$f(\hat{\imath},\hat{s}) = \frac{-i}{\pi}\int dz \sum_{m=0}^{\infty} B_m(a(z))(-i)^m \cos(m\phi(z)) e^{i(\vec{k}_i-\vec{k}_s)\cdot\vec{z}}, \quad (1)$$

where $\hat{\imath}$, $\hat{s}$ refer to the directions of incidence and scattering, and k_i, k_s refer to the incidence and scattering wave vectors, respectively. A geometry for Equation (1) can be referred to in Figure 1a of Stanton (1988). In the above the integration is performed along the longitudinal axis of the scatterer, φ is the azimuthal angle that sweeps through the plane perpendicular to the longitudinal cylinder axis at z, and the coefficients B_m are defined as:

$$B_m(a) = -\varepsilon_m i^m/[1+iC_m(a,K,K')], \quad (2)$$

with ε_m being the Neumann factor and

$$C_m(a,K,K') \equiv \frac{[J'_m(K'a)N_m(Ka)]/[J_m(K'a)J'_m(Ka)] - gh[N'_m(Ka)/J'_m(Ka)]}{[J'_m(K'a)J_m(Ka)]/[J_m(K'a)J'_m(Ka)] - gh}, \quad (3)$$

and

$$g = \rho_g/\rho_w,\ h = c_g/c_w,\ K' = K/h,\ K = k\cos\theta. \quad (4)$$

In the above, $J_m(x)$ and $N_m(x)$ are, respectively, the first kind Bessel functions and Neumann functions, a is the radius of the cylinder element concerned, ρ_g (ρ_w) and c_g (c_w) are the mass density and sound speed inside (outside) the scatterer, θ is the incidence angle relative to the axis perpendicular to the longitudinal axis, and $J'_m(x)$ and $N'_m(x)$ represent $\partial J_m(x)/\partial x$ and $\partial N_m(x)/\partial x$ respectively.

Equation (1) can be used to calculate the scattering amplitude of either fish body or fish swimbladder. In the past, this equation has been mainly used to study acoustic backscatter. In this article we use this formula to study the forward-scattering of sound. In order to focus on specific examples we choose the physical parameters in the range of that from Table 7.1.1 in Clay and Medwin (1977) and Clay and Horne (1994), and list them in Table 1. The physical parameters for the swimbladder gas are from A6.1.1 in Clay and Medwin (1977). Furthermore, without losing generality, we model the fish body and swimbladder as prolate spheroids (Furusawa, 1988). In principle, exact solutions are available for the spheroids. However, the solutions involve complicated spheroidal wave functions and computations are often tedious and time consuming. It is therefore advantageous to resort to approximate methods. We model the prolate spheroids as deformed cylinders to which the approximation in Equation (1) is to be applied. According to Furusawa (1988), in the absence of detailed information about fish morphology, a general spheroidal model is appropriate: the fish body and swimbladder are modeled as fluid and gas prolate spheroids, the ratio between the bladder length and body length is about 0.34, and the ratio between the minor and major radii ranges from 0.1 to 0.2. In this paper, we take the ratio between the minor and major radii as 0.1 for the fish body and 0.15 for the fish swimbladder.

Taking these physical and morphological parameters, we therefore study sound-scattering by a canonical fish, incorporating the scatter introduced by fish body and swimbladder.

Acoustic scattering by fish

In actual practice, a forward-scatter acoustical scintillation system is set up such that transmitters and receivers are facing each other. Thus, the problem is one of line of sight propagation (Ishimaru, 1978). In addition, the beamwidths are narrow. This allows us to assume that the incidence angle equals the scattering angle. Thus, we need only to calculate the forward-scattering amplitude, i.e. $f(\hat{\imath},\hat{\imath})$.

In this section we consider sound-scattering by a single fish. Two examples are studied: fish length L = 30 cm and 70 cm. Function $f(\hat{\imath},\hat{\imath})$ depends explicitly on the fish orientation, with respect to the wave propagation path. For simplicity and brevity, we assume that the fish moves perpendicularly to the acoustic path, which corresponds to the normal incidence.

The forward differential scattering cross-section is defined as:

$$\sigma = |f(\hat{\imath},\hat{\imath})|^2. \quad (5)$$

In Figure 1, we plot the forward differential cross-section vs frequency, calculated from Equation (1) with the parameters given in Table 1, for the two examples. Since we are concerned with high frequencies, the resonance region of swimbladders is neglected. To isolate scattering by the fish body from that of the fish swimbladder, we plot the differential cross-sections individually. In Figure 1, the solid lines denote the forward differential scattering cross-section of the fish body and the dashed lines refer to that of the fish swimbladder. The results show that (1) the fish swimbladder dominates acoustic scattering at low frequencies; (2) the scattering from the fish body becomes progressively more important than that of the swimbladders at increasing frequency; at high frequencies, greater than 60 kHz for the fish of 30 cm in length and frequencies greater than about 26 kHz for the fish of 72 cm in

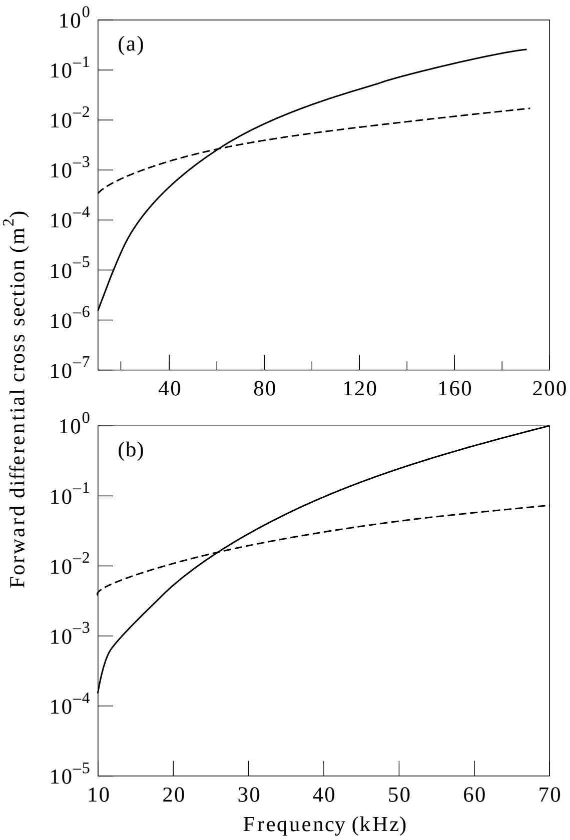

Figure 1. The plots of the forward-scattering differential cross-sections versus frequencies for fish length L = 30, 72 cm. The solid lines refer to the scattering by the fish body and the dashed lines are for the scattering by the fish swimbladder: (a) Scattering by a fish with length 30 cm; (b) scattering by a fish of 72 cm in length.

Table 1. Physical parameters for sound scattering by fish.

	Water	Swimbladder gas	Fish body
Sound speed (m s^{-1})	1485	345	1560
Mass density (kg m^{-3})	1026	1.24	1056

length, the fish bodies become the major acoustic target; (3) the scattering functions from the fish body appear to take simple curves, which almost monotonically increase with the frequency. Further numerical computation shows that the similar qualitative features also exist for incidence scattering at a tilted angle (not shown here).

For comparison with the backscatter, in Figure 2 we plot the backscattering target strength of the fish body and swimbladder vs frequency for the fish L = 72 cm. In this figure, the solid line refers to the target strength of the body and the dashed line represents the fish

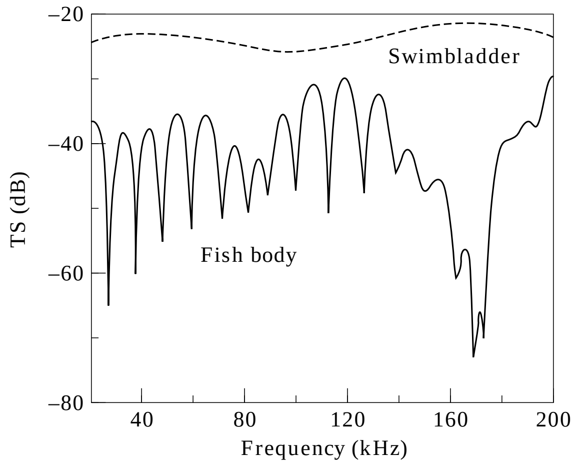

Figure 2. Backscattering target strength of the fish body and swimbladder for a fish of length 72 cm. The solid line is for the scattering by the fish body, and the dashed line refers to the scattering by the fish swimbladder.

swimbladder. Here we see that: (1) the target strength of the swimbladder is always greater than that of the fish body, confirming the previous measurements and theories (Furusawa, 1988); the smallest difference between the two target strengths is about 5 dB, indicating that the fish body may be ignored in backscatter models; and (2) comparing Figures 1 and 2, we also see that in the forward-scatter, the scattering functions lack the oscillatory features that exist in the back-scatter; this may facilitate experimental work in forward-scatter, since the results will be less sensitive to small changes in the relevant parameters. Numerical studies show that these features also apply to fish with other lengths.

Moreover, we can plot the forward-scattering differential cross-section vs fish length at a given frequency to investigate how the fish length affects the scattering. In Figure 3 we present such a plot with acoustic frequency 200 kHz, which is used in the current forward-scatter system (Curran *et al.*, 1994). From this figure we see that scattering by the fish body dominates for the fish whose length is greater than 11 cm.

From the above discussion, we may draw the following conclusions for forward-scattering of sound by fish: (1) As the frequency increases, the fish body becomes progressively more important and dominates at high frequencies. (2) At a given frequency, the fish body is the dominant scatterer for larger fish.

Since the shape of a fish body is relatively easy to obtain, the above results may suggest use of forward-scatter systems for larger fish at high frequencies in those environments that are suitable for this kind of measurement. A particular example is the measurement of migrating salmon in the Fraser River, BC, Canada. In

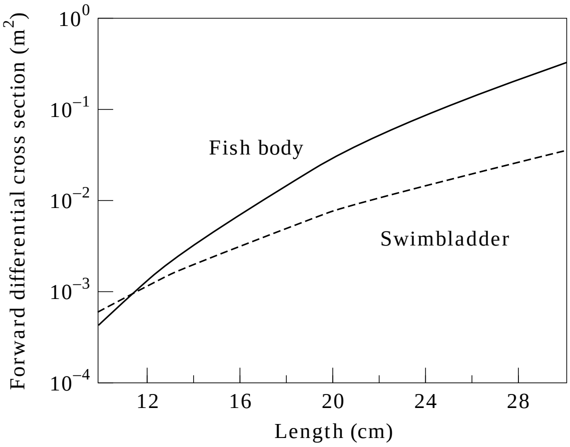

Figure 3. The forward-scattering cross-sections versus fish length at 200 kHz. The solid line is for the scattering by the fish body, and the dashed line refers to the scattering by the fish swimbladder.

this case, measurement is carried out at 200 kHz and the salmon are of the order of 60 cm in length. Given the above discussion, the forward-scatter system may be ideal for fish counting in this case.

Brief summary

In summary, we have studied the forward-scattering of sound by fish. The elongated deformed cylinder model was used for this purpose. Several possible advantages of forward-scatter were mentioned, with comparisons to the traditional backscatter approach. We suggest further experiments on the forward-scattering of sound by fish.

Acknowledgement

This work is supported by the Department of Fisheries and Oceans of Canada.

References

Clay, C. S. and Horne, J. K. 1994. Acoustic models of fish: the Atlantic cod (*Gadus morhua*). Journal of the Acoustical Society of America, 96: 1661–1668.

Clay, C. S. and Medwin, H. 1977. Acoustical Oceanography. John Wiley and Sons, New York. 544 pp.

Curran, T. A., Lemon, D., and Ye, Z. 1994. The acoustic scintillation flowmeter: application for a new environmental tool. Journal of the Canadian Hydrographic Association, 49: 25–29.

Farmer, D. M., Clifford, S. F., and Verall, J. A. 1985. Scintillation structure of a turbulent tidal flow. Journal of Geophysical Research, 92: 5368–5382.

Foote, K. 1985. Rather high frequency sound scattering by swimbladder fish. Journal of the Acoustical Society of America, 78: 688–700.

Furusawa, M. 1988. Prolate spheroidal models for predicting general trends of fish target strength. Journal of the Acoustical Society of Japan (E), 9: 13–24.

Ishimaru, A. 1978. Wave Propagation and Scattering in Random Media, pp. 126–143. Academic Press, New York.

Junger, M. C. 1982. Scattering by slender bodies of revolution. Journal of the Acoustical Society of America, 72: 1954–1956.

Stanton, T. K. 1988. Sound scattering by cylinders of finite length. I. Fluid cylinders. Journal of the Acoustical Society of America, 83: 55–63.

Ye, Z., Curran, T. A., and Lemon, D. 1996. Fish detection by the acoustic scintillation technique. ICES Journal of Marine Science, 53: 317–321.

Ye, Z., and Farmer, D. M. 1994. Acoustic scattering from swimbladder fish at low frequencies. Journal of the Acoustical Society of America, 96: 951–956.

Ye, Z., and Furusawa, M. 1995. Modeling of target strength of swimbladder fish at high frequencies. Journal of the Acoustical Society of Japan (E), 16: 371–379.