Proceedings of the Institute of Acoustics

FURTHER OBSERVATIONS ON THE ATTENUATION OF SOUND BY AGGREGATIONS OF FISH

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1. INTRODUCTION

The strength of backscattering by fish is expected to be proportional to the incident intensity of the transmitted pulse. This is the linearity assumption which is central to the echo-integration technique for estimating the abundance of fish[1,2]. When the fish occur in dense concentrations, however, simple linearity may no longer apply because of second or higher order scattering within the concentration which removes energy from both the transmitted pulse and the returning echo[3]. Second-order scattering is known as shadowing. This effect has been observed in experiments with caged fish[4-6].

Foote[1] has shown that shadowing may be taken into account by modifying the linearity equation to include the extinction cross-section of the fish. Higher-order (multiple) scattering may also occur in very dense concentrations, especially of bladder fish which are strong scatterers[7,8]. However, multiple scattering does not have a large effect on the total scattered energy. For the purposes of echo-integration, therefore, what we require is an understanding of the shadow effect and empirical values of the extinction cross-section.

In this paper, we discuss the theory of shadowing, with particular reference to the effect on echo-integration. Experimental methods for the study of acoustic extinction are discussed. Published data are scarce, but the available evidence is reviewed and compared in terms of the ratio of the extinction and backscattering cross-sections.

2. THEORY

Consider an acoustic wave which is propagating vertically through a layer of fish. I_0 is the intensity of the wave as it enters the layer, at $z = 0$. $I(z)$ is the intensity at depth z into the layer, corrected for the non-biological losses ie beam-spreading and energy absorption by the water. Thus $I(z)/I_0$ is a measure of the extra absorption (shadowing) due to the fish.

The transmitted intensity is expected to decrease exponentially with distance. In the case of two-way transmission, suppose I_1 is the received echo-intensity (corrected for beam-spreading), and h is the thickness of the aggregation. The extinction losses occur both on the outward and return paths, so

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$$I_1 = I_0 \exp(-2 h \rho \sigma_e) \tag{1}$$

Where σ_e is the extinction cross-section per fish and ρ is the average number of fish per unit volume. Sometimes it is convenient to use the area-density η which is the number of fish per unit area ahead of the wavefront, as viewed in the direction of propagation. In the case of a layer whose boundaries are obvious, if the fish were concentrated at particular depths with empty water above and below, $\eta = h \rho$ and

$$I_1 = I_0 \exp(-2 \eta \sigma_e) \tag{2}$$

which contains no explicit reference to the layer thickness. An important practical question is the effect of shadowing on fish densities estimated by echo-integration. If E is the echo-integral of the depth-channel z_1 to $(z_1 + h)$, then at low densities when shadowing is negligible

$$E = k \sigma_b \eta = k \sigma_b \rho h \tag{3}$$

where k is a constant and σ_b is the expected value of the backscattering cross-section. To incorporate shadowing in the model when ρ is constant over the depth-channel, equation (3) is replaced by

$$E = k \sigma_b (1 - \exp(-2 \eta \sigma_e))/(2 \sigma_e) \tag{4}$$

However, the assumption of constant fish density is unrealistic. Suppose $\rho(z)$ is the density at depth z, not necessarily constant, and $\rho_a(z)$ is the apparent density obtained from equation (3) and the observed echo-integral. The density is underestimated because of shadowing, so $\rho_a(z) < \rho(z)$. By applying (4) to successive small intervals of depth, an integral equation is derived which relates the apparent and true densities[2].

$$\rho(z) = 2 \sigma_e \rho_a(z) \int_0^z \rho(r)\, dr / [1 - \exp\{-2 \sigma_e \int_0^z \rho(r)\, dr\}] \tag{5}$$

The origin $z = 0$ is at or above the top of the fish concentration, so there is no shadowing for $z<0$. The true density may be determined by the numerical solution of (5), evaluating ρ from the top downwards[2,3].

If E_r is the echo-integral of the reference target, and noting that E is proportional to the intensity, equation (2) is rearranged to give

$$\log_e(E_r) = -2 (\eta \sigma_b)(\sigma_e/\sigma_b) + \text{constant} \tag{6}$$

The quantity $(\eta\ \sigma_b)$ is the area-scattering coefficient which is obtained from the fish echo-integral, corrected for shadowing as necessary. (σ_e/σ_b) is estimated from the regression of $\log_e (E_r)$ on $(\eta\ \sigma_b)$, which may be refined by iteration.

3. EXPERIMENTAL METHODS

The same general principle has been applied in most of the published studies of acoustic extinction by fish. A reference target which has constant scattering properties is observed on the far side of the fish concentration (Fig. 1). The signals from the reference target and the fish are recorded. This is done over a range of fish densities, as wide as can be arranged in practice, and preferably including measurements with no fish present. The reference signal is expected to reduce as the fish-density increases, if shadowing is significant. The rate of change of the reference echo-integral is an indication of the relative magnitudes of extinction and backscattering, ie the ratio σ_e/σ_b.

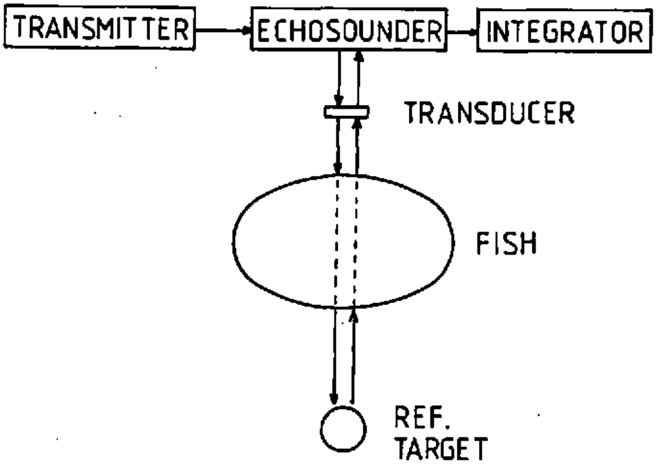

Figure 1 Reference target technique for measuring the acoustic extinction

The reference target is commonly a metal sphere suspended at a fixed distance below the transducer[5,8]. Another possibility is to integrate the echo from the seabed[8]. When a metal sphere is used, the seabed echo may be measured at the same time, providing additional data from the one experiment.

Controlled experiments may be conducted using fish in a cage[4,6]. The density is adjusted by changing the number of captive fish. This technique has the advantage that the precise size-distribution of the observed fish can be determined. However, it is possible to conduct similar experiments in-situ, on wild fish. Olsen[3] has developed a floating rig for this purpose. The reference target (a steel sphere) is suspended 40 m below the transducer, and the rig is deployed in an area where dense fish aggregations are frequently encountered. This technique has the advantage of observing the fish in their natural environment, but it is difficult to collect representative samples to determine the size-distribution.

Another method for the study of wild fish, is to observe the seabed echo with an echosounder on a survey vessel as the ship crosses the edge of fish aggregations. Again, the seabed signal may be compared against the fish echo-integral. Of course, the seabed signal will be variable, depending on differences in the hardness of the bottom from one place to another. If it is assumed that there is no consistent difference in the type of bottom below fish aggregations, as compared to locations with no fish, then if sufficient data are collected, useful results can be obtained from the average trend of the seabed signal against that from the fish.

There is one technique which does not require a reference target. Rottingen studied the echo-integral of caged fish over a wide range of densities[4]. He found that the echo-integral is proportional to the fish density up to a certain limit, after which it continues to rise but at a slower rate. This non-linearity is primarily caused by shadowing, although Foote has pointed out that changes in fish behaviour with density, notably in the tilt-angle distribution, could explain some of the non-linearity[5].

4. RESULTS

4.1 Caged Fish

Further experiments have been conducted at Loch Duich in 1989, following up the work reported in ref [6], on three species of fish - mackerel, cod and herring. Details of weights and lengths of the observed fish are given in Table 1.

Table 1 Numbers, lengths (cm) and weights (gm) of the caged fish

	Herring		Mackerel			Cod		
Number	81	43	435	245	133	78	39	21
Mean L	26.31	26.35	30.70	30.50	30.61	29.17	28.22	27.57
Mean W	116.20	116.60	217.72	216.25	224.99	241.04	213.21	191.19

The experimental procedures were identical to those described in ref [6], except for the upper reference target which in 1988 was used to monitor the system performance continuously. During the most recent experiments, the upper target was removed for 23 out of each 24 hours, allowing regular calibration while eliminating the problems due to forward scatter by the upper target.

The mean backscattering strength of the fish, the lower sphere and the seabed echo are shown in Table 2, along with the observed target strength per fish. Empty-cage measurements were also made, but they gave anomalous results, possibly due to a calibration error.

4.2 Wild Fish

One of us (MacLennan) participated in a cruise of the Norwegian research vessel *Michael Sars* in December 1989, when dense aggregations of herring were observed using the Simrad EK500 split-beam echosounder. The seabed echo was integrated at the same time. The mean fish length (from trawl samples) was 33.1 cm.

Preliminary results from this work are presented here (Fig. 2). The slope of the regression line leads to the estimate $(\sigma_e/\sigma_b) = 1.4 \pm 0.3$. The standard error of this estimate is deduced from the residual scatter of the data about the regression line. Further analysis of the experimental data is in progress and the final results will be published later.

5. DISCUSSION

Several experimental investigations of shadowing have been reported[3-6]. The results have not always been presented in a directly comparable form. However, it is usually possible to estimate (σ_e/σ_b) from the reported data. In some cases, it is necessary to assume a value for σ_b. For experiments at 38 kHz this can be obtained from published TS-length relationships[9]. If L is the fish length in cm, and TS is the target-strength in dB, then $TS = 20 \text{ Log } L - b$ where $b = 72.0$ for clupeoids and 67.4 for gadoids.

The reported results are summarised in Table 3. In the case of the Dutch experiments, the 1988 and 1989 data have been combined to give the best estimate of extinction for each species and frequency. The quoted results are those for which the observed σ_e is significantly different from zero. For mackerel, there will be some shadowing but it is too small to be detected in our experiments. No useful results have yet been obtained at 200 kHz.

The results indicate that the ratio (σ_e/σ_b) is larger for clupeoids than for gadoids. Within each family, however, the estimates cover a wide range of values. That is perhaps not surprising. The target-strength is known to exhibit wide variation around the expected average value[9]. The degree of extinction is likely to be similarly stochastic in nature, depending on behavioural and physiological factors which are not evident to the remote observer. There is

Table 2 Results at 38, 120 and 200 kHz. Measurements of the mean backscattering strength of cage-plus-fish, the lower sphere and the seabed, all in dB. The density is the number of fish below 1 m^2.

F (kHz), Species	No. of Fish	Fish Density	Cage + Fish	Lower Target	Seabed	Effective TS/fish
38	435	138.5	-39.48	-46.16	-23.80	-60.89
Mackerel	245	78.0	-37.45	-47.45	-23.40	-56.37
	133	42.3	-37.10	-46.81	-23.32	-53.37
Herring	81	25.8	-31.35	-48.55	-24.15	-45.46
	43	13.7	-33.59	-48.16	-24.08	-44.95
Cod	78	24.8	-22.70	-48.56	-24.54	-36.65
	39	12.4	-27.53	-47.93	-24.35	-38.47
	21	6.7	-31.48	-47.88	-24.03	-39.73
200	435	138.5	-33.79	-39.55	-20.99	-55.20
Mackerel	245	78.0	-35.00	-41.81	-21.11	-53.92
	133	42.3	-36.04	-41.78	-20.94	-52.31
Herring	81	25.8	-32.68	-43.37	-21.19	-46.79
	43	13.7	-34.89	-42.81	-20.99	-46.25
120	78	24.8	-30.63	-50.21	-26.94	-44.58
Cod	39	12.4	-34.06	-50.03	-26.95	-45.00
	21	6.7	-37.83	-50.01		-46.08

Table 3 Collected experimental results. The extinction has been estimated by reference to (B) the bottom echo, (S) the lower sphere or (E) the non-linearity of the fish echo-integral. Ref [10] is this paper.

F (kHz)	Species	Fish Length (cm)	Method	σ_b (cm^2)	σ_e (cm^2)	(σ_e/σ_b)	Ref
38	Herring	35.0	S, in-situ	9.70	49.0	5.0	3
38	Herring	33.1	B, in-situ	8.70	12.2	1.4 ± 0.3	10
38	Herring	26.0	B+S, cage	4.50	15.1	3.3 ± 1.3	6
38	Herring	20.0	S, in-situ	3.20	12.0	3.8	3
38	Sprat	12.1	E, cage	1.16	0.97	0.8	4
38	Cod	28.3	B+S, cage	19.5	22.2	1.1 ± 0.3	10
120	Cod	28.3	B+S, cage	3.8	10.0	2.6 ± 0.8	10
38	Saithe	35.1	E, cage	28.2	21.8	0.77	4
120	Saithe	35.1	E, cage	-	19.4	-	4

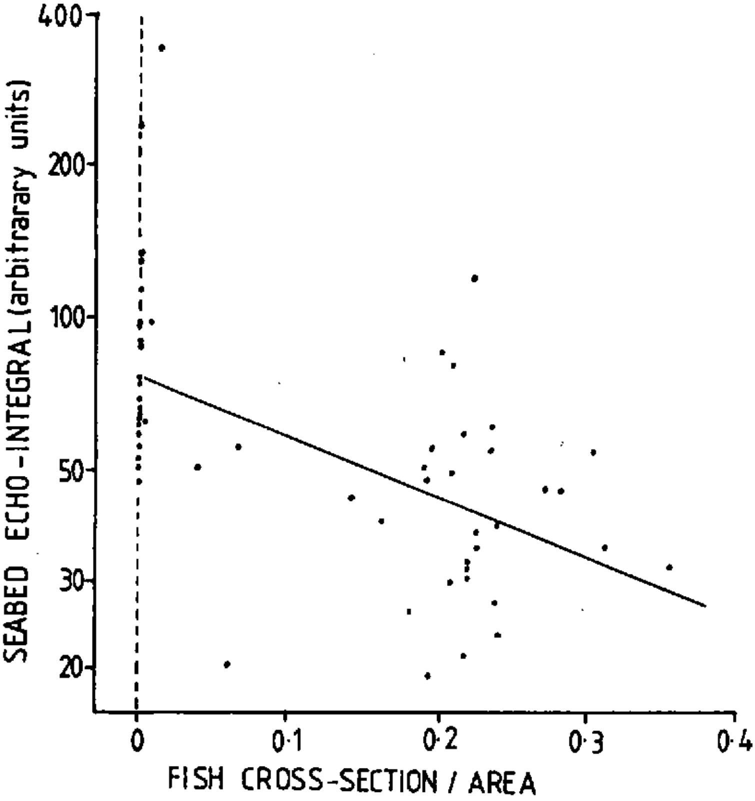

Figure 2 Comparison of echo-integrals from the seabed and intervening fish. The horizontal axis is $\eta\sigma_b$, the proportion of the area represented by the fish cross-section. The solid line is the best fit by least squares regression.

a factor of 6, equivalent to 8 dB, between the largest and smallest estimates of (σ_e/σ_b) for clupeoids. The average is not sufficiently precise to be used with confidence to correct echo-integrals for the effect of shadowing. Further work is necessary to relate the magnitude of the shadow effect to fish behaviour and physiological factors such as the state of the swimbladder.

It is suggested that the seabed-integral should be recorded routinely during acoustic surveys, to provide an indication of the significance of shadowing. This may not be possible with older equipment, but modern echosounders such as the EK500 have sufficient dynamic range for the purpose.

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