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TARGET STRENGTH AND THE TILT ANGLE DISTRIBUTION OF CAGED FISH

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INTRODUCTION

The target strength (TS) of an individual fish can vary over a wide range of values. It can change with the physiological condition of the animal, notably the state of the swimbladder in those species which possess one. The TS also depends upon the orientation of the target relative to the acoustic beam, especially the tilt angle of the fish body with respect to the acoustic axis of the insonifying transducer. The orientation depends upon the behaviour of the fish and how it reacts to stimuli such as the disturbance created by ships and fishing gear.

Nakken and Olsen [1] have described experiments in which inert fish are rotated in a sound field to determine changes in TS with orientation. Subsequently, Foote and Nakken [2] have tabulated the experimental TS data for tilt angles in the range -45° to +45°, for several species including herring and mackerel, and two frequencies, 38 and 120 kHz.

More recent experimental work has used live targets which should be more representative of free-swimming fish in the sea. However, it is difficult to make simultaneous measurements of the tilt angle and the TS of one fish within a shoal. Such measurements may be done on solitary fish using split-beam or dual-beam sonar and stereo photography, but the solitary animal might not behave in the same way as fish in contact with neighbours inside a shoal, see Pitcher [3] for example. What can be done is to measure the echo from a group of fish held captive in a cage. The echo energy may then be compared with statistics of the tilt angle distribution or other behavioural factors (MacLennan and Forbes, [4]; Edwards and Armstrong, [5]). MacLennan et al. [6] have shown that diurnal changes in TS correlated more significantly with tilt angles than with other behavioural measures such as the nearest-neighbour distance.

The swimbladder is the dominant sound-reflecting organ in those fish which have one. Foote [7] has computed the sound field backscattered by real swimbladders, using three-dimensional geometric measurements of frozen bladders taken from gadoid fishes. He was able to reproduce the same qualitative features of the empirical Nakken and Olsen [1] TS functions, namely a series of minima and maxima over the range of tilt angles examined. However, it is not yet possible to predict the TS function of fish with no swimbladder, such as the Atlantic mackerel Scomber scombrus L., from morphometry and theoretical considerations alone. These fish produce a relatively weak echo from the liver, the bones and fatty tissues, organs which do not have a density much different from that of water.

MATERIALS AND METHODS

The fish were contained in a netting cage mounted in the assembly shown in Figure 1. The transducer was on a triangular frame above the fish cage. Calibration was performed using a 38.1 mm tungsten carbide sphere suspended below the transducer, by the method of Foote et al. [8]. Stereo cameras were located below the cage together with a TV camera to monitor the captive fish in real time.

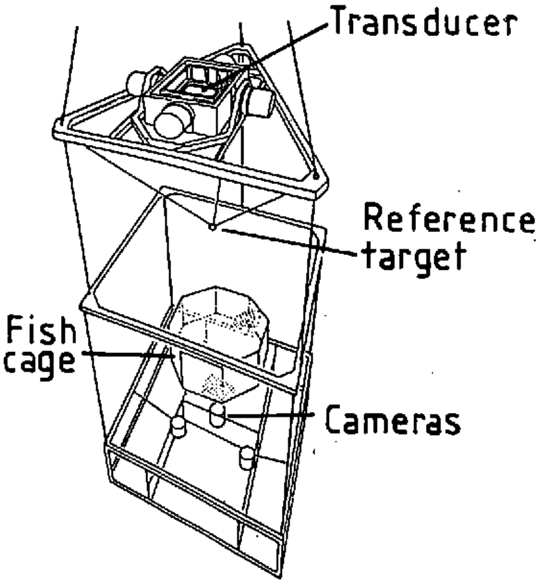

Fig. 1 Transducer, fish cage and camera assembly.

The fish were transferred to the netting cage at the sea surface, then the assembly was lowered to a depth of 20 m below a raft moored in a West of Scotland sea loch. Acoustic measurements were recorded throughout each experiment, but the stereo cameras were operated only during four hours at night (2200-0200) and four hours by day (1000-1400), to make the best use of the limited film capacity of the cameras. At six minute intervals, a flash gun was fired to expose a pair of stereo photographs. The fish exhibited a startle response each time the flash occurred, but they resumed apparently normal behaviour well within the six minute interval.

Digitised two-dimensional coordinates of the matched fish images on the stereo-pair were used to compute the three-dimensional coordinates of the head and tail of each fish identified on the photographs. These reference points could be located to an accuracy of better than ± 1 cm. The tilt angle (ie the acute vertical angle between the horizontal plane and the line joining the fish head and tail fork) is immediately derived from the measured coordinates, given the direction of the vertical relative to the camera frame. Tilt angles were obtained for about 95% of the images. The other fish were obscured by neighbours or for other reasons failed to give clear indications of the head and tail positions.

RESULTS

Two experiments are reported here, one with herring (Clupea harengus L.) and one with mackerel (Scomber scombrus L.). Details of the fish are shown in Table I.

TABLE I

Species	No of Fish	Length (cm) Mean	Length (cm) st. dev.	Weight (gm) Mean	Weight (gm) st. dev.
Herring	74	21.2	5.8	69.3	13.0
Mackerel	62	31.6	2.1	253	52

The herring experiment ran for three nights and two days, and the mackerel experiment for one night and one day.

Mean tilt angles were computed for each hour of observation, making use of the data from 10 stereo-pair photographs. The echo energy is proportional to the acoustic cross-section of the fish. It is plotted against the tilt angle in Figure 2, each point representing an hourly mean. A monotonic relationship is evident from both the regression lines, with the echo energy reducing as the fish tilt away from the horizontal, but there is considerable residual scatter in the observations.

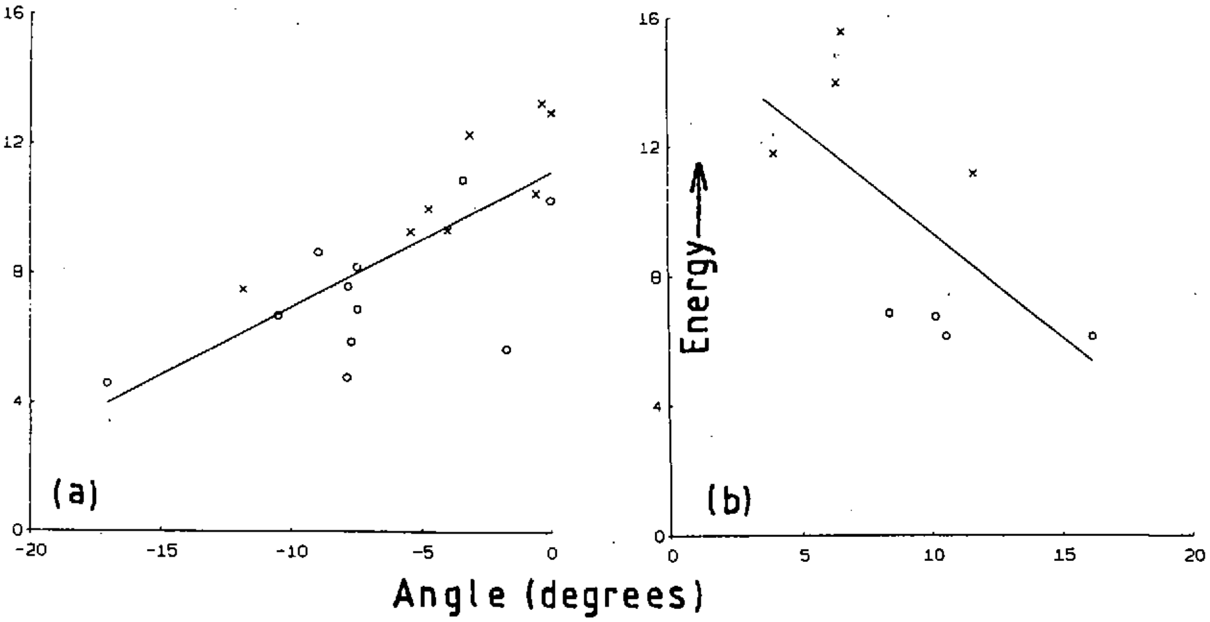

Fig. 2 Echo energy vs tilt angle for (a) herring and (b) mackerel. Vertical scale is arbitrary. x day; o night; ---- linear regression lines (a) r = -0.72; (b) r = -0.64.

Summary statistics of the tilt angle distributions are shown in Table II. N is the number of observations. Histograms of the tilt angle data for each species by night and by day are shown in Figure 3.

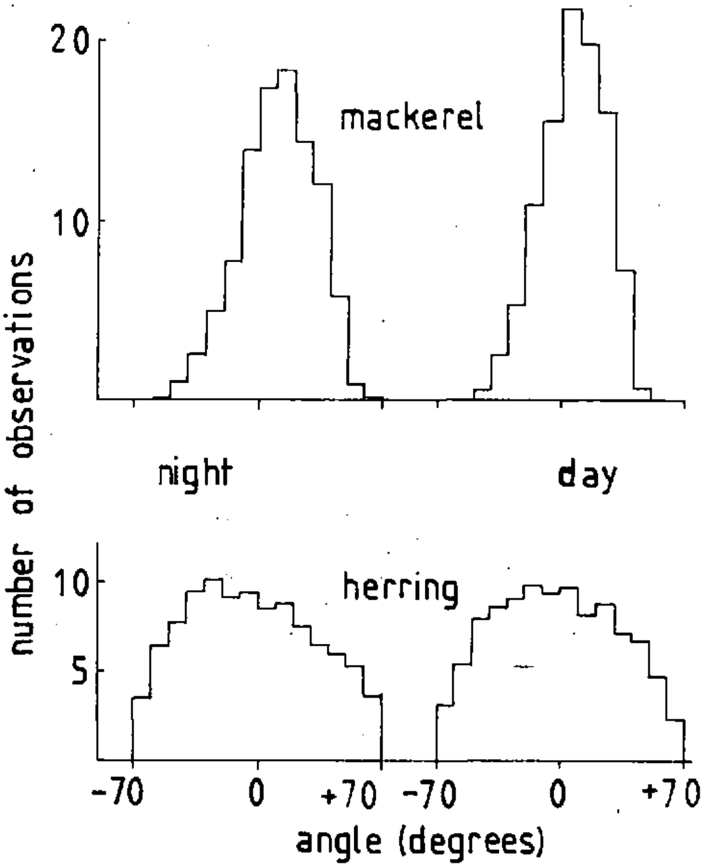

Fig. 3 Distribution of observed tilt angles for mackerel (upper), herring (lower), by night (left) and by day (right).

TABLE II

Statistics of the tilt angle distribution

	No of Measurements	Tilt Angle (degrees) Mean	Standard Deviation	Median	Inter-quartile Range
a) Herring					
night 1	1939	-2.0	34.9	-3.9	-29.4, +25.1
day 1	2584	-0.5	35.3	-1.1	-28.5, +27.4
night 2	2219	-3.4	37.3	-7.1	-34.4, +27.7
day 2	2485	-3.0	33.7	-4.5	-30.7, +24.0
night 3	2322	-4.1	33.6	-5.3	-31.0, +20.6
all nights	6480	-3.2	35.3	-5.5	-31.6, +24.5
all days	5069	-1.7	34.5	-2.8	-29.6, +25.7
b) Mackerel					
night 1	2140	10.3	20.8	11.3	-3.7, +25.9
day 1	2050	6.1	17.8	7.2	-6.1, +19.5

Calculations with TS Functions

Foote and Nakken [2] have published empirical TS functions for many individual fish. In order to test the significance of the tilt angle in explaining observed TS variations, we computed average TS functions using the Foote and Nakken [2] data for all fish within ± 1 standard deviation of the mean length of our fish. If X (n,θ) is the target strength in dB of the n'th fish at tilt angle θ, then the appropriate average over N fish is:-

$$\overline{X}(n) = 10\ \mathrm{Log}_{10}\ [\sum_{n=1}^{N} 10^{(X(n,\theta)/10)}/N] \quad ..... \qquad (1)$$

The resulting TS functions are shown in linear form, as acoustic cross-sections in Figure 4. These functions have been applied to the observed tilt angles to estimate the expected echo energy from the fish aggregation. This is essentially the technique described by Foote [9], except that his TS functions were derived from the same fish as the acoustic measurements. The expected and observed echo energies are compared in Figure 5.

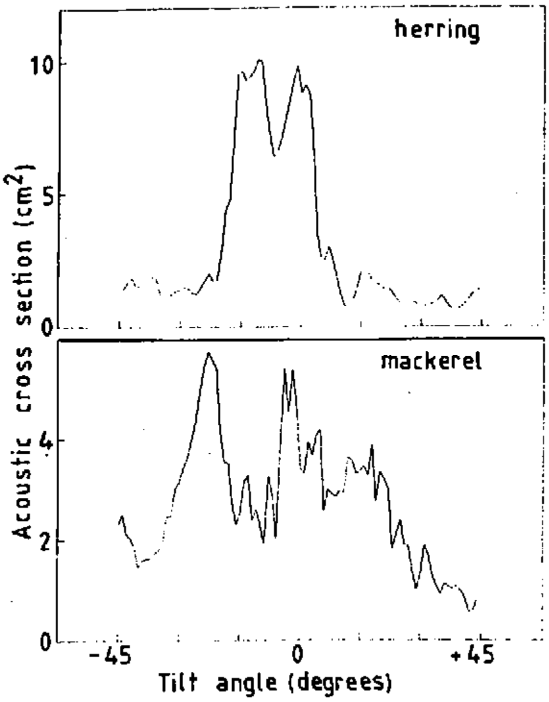

Fig. 4 Target strength functions for herring and mackerel. Averaged data from Foote and Nakken [2].

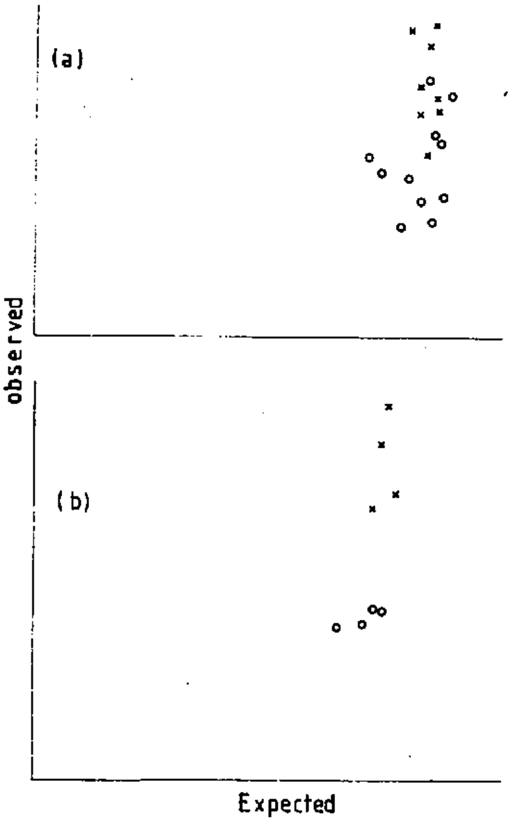

Fig. 5 Comparison of observed and expected echo energies for (a) herring and (b) mackerel. x day, o night.

DISCUSSION

The results in Table II(b) and Figure 3(b) indicate that the mackerel adopted a well-defined shoaling behaviour. The mean tilt angle is a few degrees higher by night than by day. On the assumption that the fish swim more slowly by night, this finding accords with the results of He and Wardle [10]. The standard deviation of the tilt angle distribution is around 17.8° by day and 3° more by night. One would expect shoaling fish to align more closely when nearest neighbours are able to see each other, and this hypothesis is supported by our results for mackerel.

The mackerel tilt angle distributions are slightly skewed as evidenced by the consistent difference of about 1° between the median and the mean tilt angles. In the past, it has generally been assumed that fish tilt angles follow a normal distribution, see for example Foote [9]. While normality may be a reasonable assumption for many purposes, since the median-to-mean difference is small compared to the standard deviation, we note that in the case of our mackerel, a fitted normal curve would underestimate the number of fish in extreme head-down attitudes.

The results for herring show a much wider distribution of tilt angles, see Table II(a) and Figure 3(a). It is clear that the herring swam more randomly than the mackerel and they were more likely to adopt extreme tilt angles which could be anywhere from head down (-90°) to head up (+90°). We rejected any observations outside the range ± 70° when the accuracy of the upward-looking stereo measurement would be in doubt, but the rejected data amounted to no more than 1% of the total.

The mean tilt angle of the herring is closer to the horizontal by day than by night, although the diurnal variation is superimposed on a steady decline over the three days of the experiment. The echo energy also reduced with time. Both these effects may be associated with the gradual loss of gas by diffusion from the swimbladder. If this association is true, the apparent link between the mean tilt angle and the echo energy may not be one of direct cause-and-effect. The tilt angle could change with the swimbladder volume because of the effect on buoyancy.

The difference in the standard deviations of the herring tilt angle distributions by night and by day is 0.8°; the standard error is 2.5°, so the difference is insignificant. Because of the width of the distributions, the assumption of normality would be even less appropriate than for mackerel. Moreover, there is again a significant difference between the mean and the median (1.8 ± 0.4°), but in herring the median is less than the mean. The tilt angle distributions are skewed in opposite directions for the two species.

It is not clear why this should be; perhaps some behavioural mechanism linked to the presence or absence of a swimbladder is responsible.

The TS function for herring (Fig. 4a) shows two peaks near to the dorsal aspect and a much reduced level at extreme tilt angles. It is possible that the minimum near to 5° is spurious "noise". The TS functions for the individual fish studied by Nakken and Olsen [1] contained several maxima and sharp minima, an effect characteristic of interference between the many sound scatterers in the fish body. It is reasonable to suppose that the true TS function, averaged over a large number of fish, would be unimodal.

The TS function for mackerel (Fig. 4b) is less satisfactory. It does not exhibit a clear maximum near to the dorsal aspect. It is possible that the Nakken and Olsen [1] results may have been affected by the very low target strength of mackerel, some 15 dB less than herring for fish of the same weight. Moreover, for several of the mackerel, the TS function has not been measured over the full ± 45° range. It is doubtful whether the average function shown in Figure 4b can be regarded as reliable.

The comparison of the expected and observed echo energies in Figure 5 suggest that most of the observed variation of the echo is due to factors other than the fish tilt angle. The small differences noted in the tilt angle distributions should cause relatively little change in the echo energy, according to the TS function shown in Figure 4. Of course, these functions were obtained on different fish which were dead or stunned, and their relevance to our free-swimming fish may be questioned.

We conclude that while there is an association between changes in the echo energy and the tilt angle distribution of caged fish, the observed TS is subject to variations much greater than can be explained by the tilt angle alone. It is not clear what causes these variations, but they are not too important in acoustic surveys, since it is the mean or expected value of the TS which is required for the interpretation of survey data.

REFERENCES

1 Nakken, O. and Olsen, K. 1977. Target strength measurements of fish. Rapp. P.-v. Reun. Cons. int. Explor. Mer, 170, 52-69.

2 Foote, K.G. and Nakken, O. 1978. Dorsal aspect target strength functions of six fishes at two ultrasonic frequencies. Fisken og Havet, Serie B, No. 3, 96pp. Fiskeridirektoratets Havforskningsinstitutt, Bergen.

3 Pitcher, T.J. 1986. The functions of shoaling behaviour. pp 294-337, Chapter 12 in "The Behaviour of Teleost Fishes", T.J. Pitcher (Ed.). Croom Helm, London.

4 MacLennan, D.N. and Forbes, S.T. 1987. Acoustic methods of fish stock estimation. In "Developments in fisheries research in Scotland", R.S. Bailey and B.B. Parrish eds, Fishing News Books, London (282pp).

5 Edwards, J.I. and Armstrong, F. 1983. Measurement of the target strength of live herring and mackerel. In "Symposium on fisheries acoustics, Bergen, Norway, 21-24 June 1982", O. Nakken and S.C. Venema eds, FAO Fish. Rep. 300, 69-77.

6 MacLennan, D.N., Magurran, A.E., Pitcher, T.J. and Hollingworth, C.E. (in press). Behavioural determinants of fish target strength. Proceedings of the International Symposium on Fisheries Acoustics, Seattle USA, 22-27 June 1987. (To be published in the ICES Rapports et Proces-verbaux).

7 Foote, K.G. 1985. Rather-high-frequency sound scattering by swimbladder fish. J. Acoust. Soc. Am. 78, 688-700.

8 Foote, K.G., Knudsen, H.P., Vestnes, G., MacLennan, D.N. and Simmonds, E.J. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. ICES Coop. Res. Rep. 144 (69pp).

9 Foote, K.G. 1983. Linearity of fisheries acoustics with addition theorems. J. Acoust. Soc. Am. 73, 1932-1940.

10 He, P. and Wardle, C.S. 1986. Tilting behaviour of the Atlantic mackerel, Scomber scombrus at low swimming speeds. J. Fish Biol. 29 (Supplement A), 223-232.