HoRNE

Rapp. P.-v. Réun. Cons. int. Explor. Mer, 184: 25–33. 1984.

# Fish and other organisms as acoustic targets

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## Introduction

Knowledge of fish and other organisms as acoustic objects is essential both for their identification or classification as well as their sizing and abundance estimation. During nearly 50 years of acoustics in fisheries, a considerable amount of activity has been concentrated on the study of target strength of fish and to some extent also of other marine organisms. The present paper intends to review our state of knowledge on the subject. Since there is as yet no acoustic theory which can fully describe the process of scattering from complex targets such as fish and other marine organisms, several practical approaches and techniques have been applied to obtain wanted information on target strength for applications. David Cushing (1973), himself a pioneer in the field, has written a historic review on the detection of fish, with a comprehensive list of references covering progress up to around 1970. Since then a number of conferences have been held to consider the state of development of our knowledge on target-strength matters.

The situation by the end of 1972 is reflected in the report from the last Bergen Symposium (Margetts, 1977).

The FAO/ACMRR Working Party on Fish Target Strength met in Aberdeen in 1977 "– with the view of assessing the state of and gaps in, current knowledge on the subject and to specifying future research needs and priorities –" and reported accordingly (Anon., 1978).

In June 1979 another meeting was held, this time in Cambridge, Massachusetts, USA. Among the topics were acoustic scattering characteristics of single and aggregated fish, equipment calibration, and verification of results. A critical review from this conference seems to me a bit too pessimistic to reflect the true state of the art (Suomala, 1981).

## Fish as acoustic targets

### Theoretical considerations

Although no acoustic theory has been fully formulated to describe the scattering process from fish in the sea, because of the complexity in shape and acoustic properties of their component bones, tissue, and bladder, theoretical considerations are of importance both for the design of experimental work and for the interpretation of results. Recently a new text book has been published by Clay and Medwin (1977) dealing with principles of acoustic reflection from targets including processes affecting the scattering characteristics of marine life.

In some approaches fish or their swimbladders have been treated as simple geometric shapes (Haslett, 1970). Yudanov and Kalikhman (1981) and Mitson (Anon., 1978) have also reported some results along this line. So far the method has given only a first approximation to the solution.

## Measurements of target strength

The philosophy behind the measurements can be regarded as twofold:

1) To obtain knowledge of scattering from fish with respect to the acoustic wavelength, fish species, size, orientation, swimbladder condition, and generally with respect to all variables affecting the target strength. This type of measurement requires carefully controlled conditions where the variables can also be observed or recorded together with the reflected signal. The results can then be used in models and applied to field conditions at sea.

2) For practical reasons, *in situ* observations on wild fish have the advantage of being a direct way to measure fish in their natural habitat. Such measurements can be used for calibration purposes, but also for verification of results obtained otherwise. Some disadvantages and associated problems are related to the transducer directivity and lack of control over the target being measured. Combined with underwater photography or fishing the method can be considerably improved.

A great number of experimental exercises have been performed to measure the target strengths of fish. They can be grouped into three methods.

*Measurements on tethered fish*

Such work has been conducted, among other places, in Japan by Hashimoto and Maniwa (1956) and Shibata (1971), in Norway by Midttun and Hoff (1962), Nakken and Olsen (1977), and Dalen *et al.* (1976), in the UK by Harden Jones and Pearce (1958), Cushing *et al.* (1963), and Haslett (1970), in the USA by Smith (1954), Diercks and Goldsberry (1970), Volberg (1963), and Love (1969, 1971, 1977), and in the USSR by Yudanov, Gaukov, and Shatoba (Yudanov, 1977) and Shishkova (1964). Measurements are also reported by Johannesson and Losse (1977). These series of observations have usually been made with stunned or dead fish over a wide range of frequencies, species, and sizes of fish.

The experiments were different, both in their performance and their data analysis. A more detailed discussion will be made later in this paper. However, it can already be concluded that target strengths of fish vary with size, orientation, species or group of species, and frequency of sound. The validity of the results has been questioned since they are derived from dead or stunned fish (Anon., 1978).

*Measurements on live fish in controlled systems*

Buerkle and Sreedharan (1981) measured the target strength of live cod supported in the centre of the acoustic beam and rotated in varying combinations of pitch and roll. McCartney and Stubbs (1971) measured six gadoid species with four frequencies from 4 to 20 kHz. The fish could swim within a bag 1 m long and 40 cm in diameter. A hydrophone measured both the incident and the reflected signals of the same transmitted pulse so that calibration errors could be avoided. On the other hand, the fish could pitch by an unknown angle. The authors conclude "there is no guarantee that the absolute maximum value in the pitch plane has been recorded, especially at high $L/\lambda$". Because of variations in the scattered signals, the maximum value of eight pulses was used.

Several experiments have been performed with caged, but otherwise free-swimming fish. The method was introduced by Johannesson and Losse (1977) in some FAO projects for calibration purposes. Groups of fish of known number were used. Volume backscattering strengths were measured and the average target strength of individuals calculated in addition to fulfilling the main purpose of integrator calibration. Results from target-strength measurements by this method are also reported by Aglen *et al.* (1981) and by Johannesson and Vilchez (1981) who sometimes improved the method with a TV camera monitoring the fish distribution from beneath the cage.

Goddard and Welsby (1975), using a 2 × 2 m and 1 m deep cage, observed individuals and groups of fish in dorsal and 22½ degrees aspect with TV-monitoring from beneath the cage. Similar experiments on caged groups of fish have been conducted in Scotland for several years and have been reported by Dunn (1978), Forbes *et al.* (1980), Edwards and Armstrong (1981), and MacLennan (1981). Some of these British experiments also include studies of adaptation effects on target strength.

The general drawback with this type of experiment on live caged fish is the lack of control, particularly over the tilt-angle distribution of the caged fish. This may explain the reason why the sometimes large variances in observed strength have seldom been explained. However, there is one experiment which, in this respect, may claim to be properly conducted since a television camera could observe and record the tilt-angle distribution (Foote, 1983). Foote's experiment also consisted of target-strength measurements of tethered, anesthetized individuals. The TS functions thus measured, together with behaviour information, constituted a basis for calculating the expected echo from the encaged fish. The direct echo measurements from the encaged fish were in excellent agreement with the calculated values. Among other things, this experiment concluded that observations on anesthetized fish are valid and representative for live, free-swimming fish.

*In situ measurements*

There are certain requirements involved in using this method of observing fish in their natural habitats. First, to ensure single-fish signals, the pulse lengths of echoes are normally tested and second, the transducer directivity must be removed from the received signals. Craig and Forbes (1969) have given one method which should be well known to everyone working in this field. Cushing (1968) regarded all the echoes as observed at a mean angle from the transducer axis. Midttun and Nakken (1971) observed fish traces, i.e., successive echoes from the same fish, and regarded the maximum echo in a trace as being observed on the transverse axis of the beam. They then calculated target strengths by reducing the maximum echoes according to the known transverse directivity pattern of the transducer. Ehrenberg (1972) introduced another signal-processing technique, but Ehrenberg and Lytle (1977) conclude that in many cases the reduction method does not work well, and suggest a dual-beam technique to be applied for *in situ* measurement of target strength. Some results are published by Traynor and Nelson (1981). Robinson (1976), in a preliminary experiment with a deep-towed transducer, measured the target strength of blue whiting. Blue whiting have also been measured by Monstad and Midttun (1981).

*In situ* observations have also been used as a direct method for integrator calibration. Dispersed concentrations are simultaneously integrated and counted on a paper recorder. According to this direct method, described by Nakken and Dommasnes (1975), inaccuracies involved in conventional calibrations of the echo-sounder system are circumvented.

## Consideration of results

The validity of the results obtained on stunned, freshly killed, or anesthetized fish can be trusted provided the experiments are properly conducted.

### *Swimbladder contribution*

The swimbladder is the major cause of scattering from bladder-bearing fish (McCartney and Stubbs, 1971). Foote (1980 a), in comparing target strengths from mackerel with those from three gadoids of the same size range, shows that the bladders contribute 90 to 95 % of the total echo. Goddard and Welsby (1975) found that dogfish give echoes some 13 dB lower than those from gadoids. Midttun and Hoff (1962) observed maximum dorsal echoes when the fish were tilted sufficiently to render their swimbladder horizontal. They suggested that the difference in directivity pattern between cod and saithe is caused by differences in the bladder form. Observations on wild fish at sea have verified that suggestion (Midttun and Nakken, 1971). The Scottish experiments, for example Edwards (1980), show the effect of changing depth on the target strength, but lack of control over the fish behaviour, i.e., changing tilt-angle distribution, prevents too firm conclusions from being drawn. It would have been of particular importance to observe the effect on mackerel of changing depth, but at least the reported target-strength values of mackerel are again shown to be considerably lower than those of herring and gadoids (Edwards and Armstrong, 1981).

To obtain deeper understanding of the nature of the scattering process from bladder fish, attention should be called to studies on the bladder itself, its form and deformations by varying pressure changes, and to comparisons of the acoustic wavelength with dimensions of the swimbladder. Valuable contributions in this respect could perhaps be expected from physiologists, as for example, Hawkins (1981) and Blaxter (1981).

### *Aspect-angle dependence*

The experiments on tethered fish show that target strength changes with aspect angle. The dorsal reflectivity patterns measured by Nakken and Olsen (1977) on six species of varying size at two sound frequencies (38 kHz and 120 kHz) have been published by Foote and Nakken (1978). The consequence of the observed directivity in the reflection from fish is that the target strength of wild fish will vary with fish behaviour, i.e., with aspect-angle distribution. Olsen (1971) observed the orientation distribution of cod in Lofoten, and Nakken and Olsen (1977) have prepared a model for calculating the expected mean target strength of cod with the observed orientation distribution. Midttun and Nakken (1971) measured an average target strength of Lofoten cod of mean length 80 cm to be −28·3 dB, which is in good agreement with the model. Foote (1980 b) has prepared another model for averaging with respect to different orientation distributions and beamshapes of the transducer. Footes's model gives higher values compared with those of Nakken and Olsen, especially for medium-sized fish (20–60 cm) and a clarification would be appreciated.

In Figure 1 the consequence of behaviour on target strength is shown for two behaviour patterns and it is also compared with the maximum values of target strength, based on the values published by Foote and Nakken (1978) and computed from Foote's model.

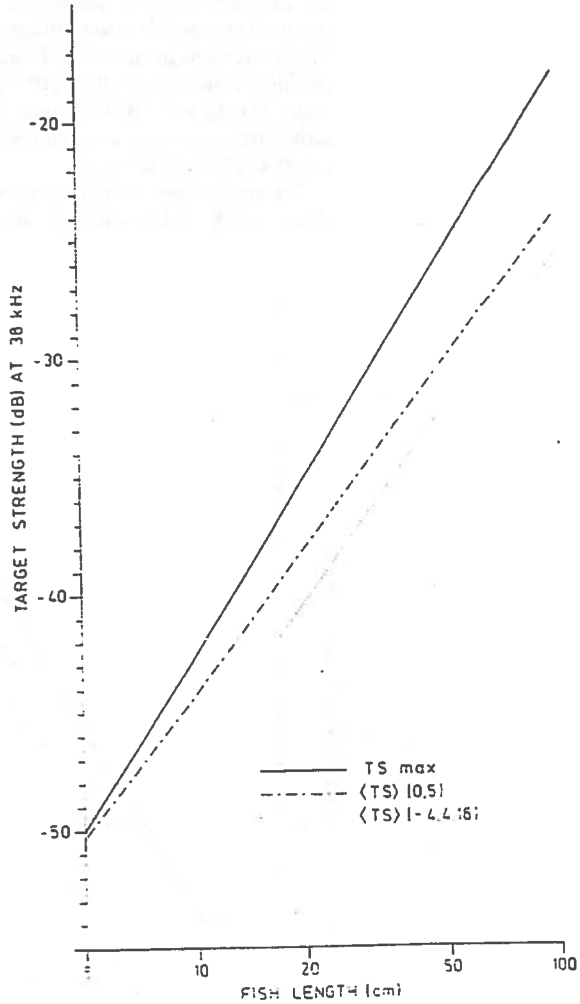


Figure 1. Target strength and behaviour. Target strength versus length for gadoids observed with the SIMRAD EK-38 echo sounder. Each regression is based on measurements of the dorsal-aspect target-strength function of 171 cod, saithe, and pollack (Nakken and Olsen, 1977; Foote and Nakken, 1978), calculated after Foote's model (Foote, 1980 b). Maximum values and values for two behaviour patterns are shown.

*Length and frequency dependence*

In order to study the length and frequency dependence the observations have been normalized by some of the investigators who compared L/λ with σ/λ² (Love, 1969, 1971, 1977; Shibata, 1971; McCartney and Stubbs, 1971; Goddard and Welsby, 1975). Haslett (1970) normalized L/λ by σ/L², but his values have also been transformed to a σ/λ² normalization by McCartney and Stubbs (1971). The attraction is that observations made over a wide range of sizes and frequencies can be compared. A disadvantage is that the frequency dependence may be biased since the length parameter evidently is the most important within the length and frequency spectrum in practical fisheries research. Foote (1979) has discussed the question of representation and concludes that merging of target strengths in species or frequency is generally unjustified. Nakken and Olsen (1977), in comparing values from 38 kHz and 120 kHz, note that the difference in target strengths seems to vary with the magnitude of target strength (fish length).

The dorsal-aspect target strength versus length dependence as reported by selected authors, mostly for cod, is shown in Figures 2 and 3. The values are referred to 38 kHz. Some of the regression lines represent maximum values; others are from caged fish and based on averaged values. The linear regression has been applied by all authors, probably because it is a simple way both for presentation and for later use in practical work. The coefficients are between 19 (Love, 1971) and 28 (Yudanov and Kalikhman, 1981; MacLennan, 1981), but lie mostly near 24 to 25 dB/decade. Foote's (1979) averaged values of cod are about 22 dB/decade.

The absolute values are dependent on the calibration accuracy except for those of McCartney and Stubbs, which are independent of calibration. On the other hand, these values should be expected to be somewhat below maximum, as mentioned earlier; they are also about 2 dB below those of Nakken and Olsen on cod, which correspond to Shibata's line (see Fig. 2). Data from Yudanov and Kalikhman also match fairly well. Love's line fits for small fish, but not for the larger. McCartney and Stubbs's line based on Haslett's data from many sources seems also to be generally low although the length dependence is in accordance with the majority. Goddard and

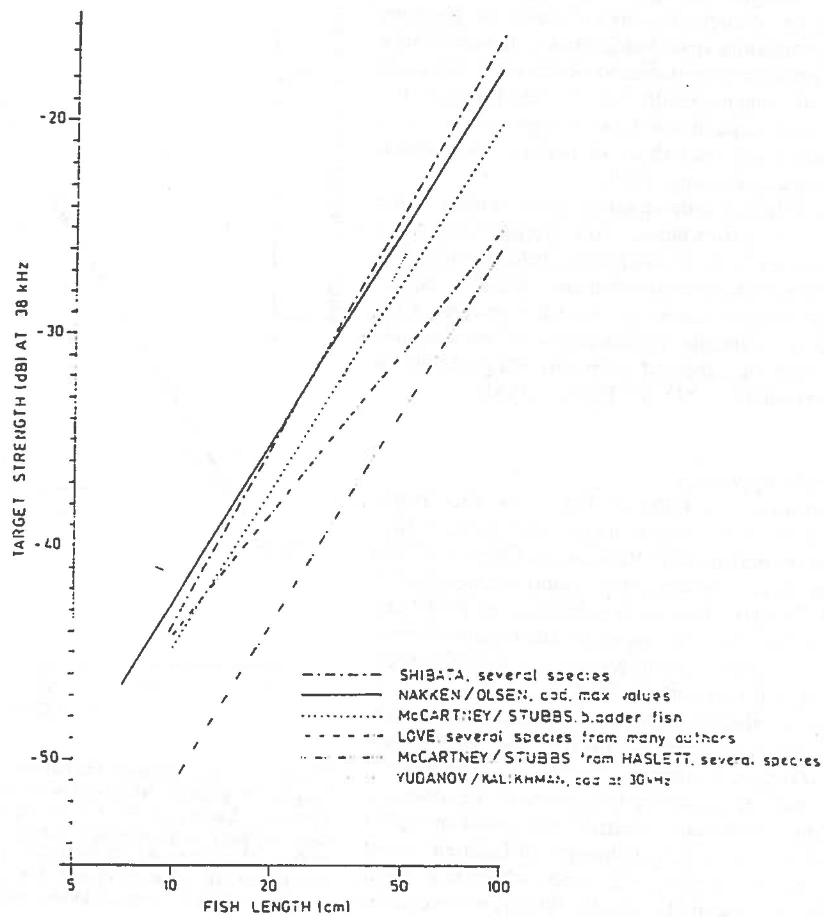


Figure 2. Dorsal-aspect target strength versus length at 38 kHz based on measurements from the authors indicated in the figure.

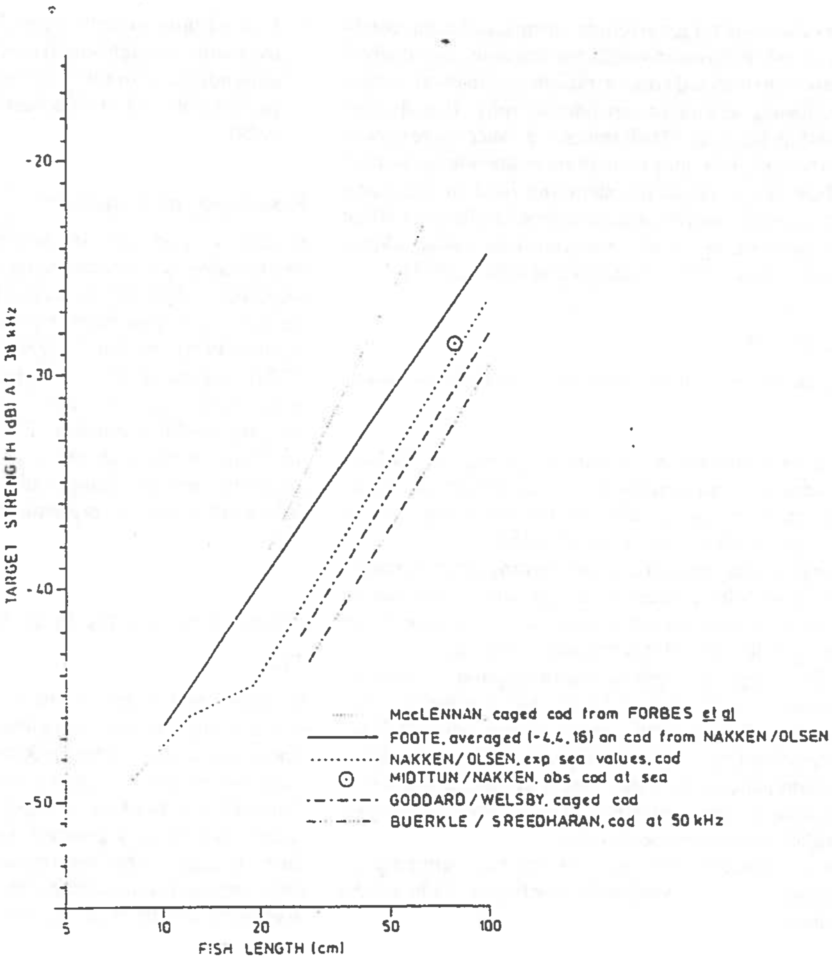


Figure 3. Target strength versus length of wild or caged fish (see text).

Welsby's data from caged individual cod show the same length dependence (Fig. 3). Their regression line is close to Nakken and Olsen's calculated values for "wild fish", although the aspect angles have not been observed by Goddard and Welsby. Foote's regression line for cod is seen to differ from Nakken and Olsen's calculations. Midttun and Nakken's observations in Lofoten are also seen in the diagram in Figure 3. Buerkle and Sreedharan's measurements on cod at 50 kHz are generally a bit low; it is questionable whether the fish were well enough acclimatized. Finally, the regression line from MacLennan's report based on Forbes *et al.* (1980) is reproduced. It is based on mean values of fish length and averaged target strength per individual from measurements on groups of cod in varying numbers from 7 to 56. The tilt-angle distributions were not observed and it is therefore difficult to verify these results by calculations from models. The length coefficient (28·4 dB/decade) is felt to be higher than expected from Foote's model. His model gave excellent agreement when used on caged herring as already mentioned above (Foote, 1983).

In the analysis above of present knowledge on target strengths of fish, most of the discussion has been concentrated on results obtained on gadoids, especially cod. But results of target-strength studies on other species have been reported in the literature, especially the work done in many FAO projects, mostly in tropical waters.

The FAO Working Party (Anon., 1978) concluded tentatively that all fish with swimbladders may be grouped together into one class with respect to target strength. A confirmation of this suggestion should be considered. In Figure I observed values – from Foote and Nakken (1978) – on three gadoids (cod, saithe, and pollack) at 38 kHz have been merged and analysed by Foote. The regression coefficients are 24·5 dB/decade for maximum values and 21 and 20 dB/decade for the two indicated behaviour patterns. This merging can be justified (Foote, 1979), but a further merging including all bladderfish needs to be investigated.

Concerning the observations at sea, the reported results are few, but they seem to agree fairly well when the tilt-angle distribution is taken into consideration. More observations of target strength during different conditions of fish behaviour would be valuable, especially if executed on unmixed concentrations and in combination with trawling or underwater photography. It is also believed that the study of fish traces, i.e., successive echoes from the same fish, may contribute to knowledge both of fish behaviour and of the sampling field of the transducer. Indeed, even information for identification of fish species may be gathered from echo-trace studies (Midttun and Nakken, 1971; Nakken and Olsen, 1977).

### Conclusions

From the considerations above my tentative conclusions are:

1. The swimbladder is the major scatterer in bladder-bearing fish and contributes at least 90 per cent of the reflected energy. Studies on the air bladder as an acoustic scatterer are recommended.
2. For practical applications the existing target-strength functions with respect to length and aspect can be used in models for calculation of the average target strength for different behaviour patterns.

   The target strength to length relation for gadoids increases at 25 dB per decade for maximum dorsal aspect and 20 to 22 dB per decade for wild fish at sea with a "normal" behaviour pattern. But more information is needed on fish aspect-angle distribution in relation to different types of behaviour. Behaviour studies should be encouraged.
3. Other bladder fish may be treated similarly to gadoids, but this should be confirmed from model studies.
4. Fish without swimbladders have not been observed over wide enough length ranges to indicate the length dependence, but for 35 cm mackerel a target strength per kilo of −45 dB has been recommended (Anon., 1978).

### Resonance measurements

Several workers have studied the possibility of estimating fish size by observations on the resonance frequency (Andreeva, 1964; Weston, 1967; Holliday, 1972). Experimental work has been reported by McCartney and Stubbs (1971), Holliday (1977), and Løvik and Hovem (1979). In general, the resonance frequencies were found to be higher than expected from the theory of free oscillating gas-filled bubbles. The method is still in an initial phase of research and requires sophisticated instrumentation and analysing equipment. Some results from field work at sea are presented by Løvik *et al.* (1982).

## Other organisms as acoustic targets

### Theory

Holliday and Pieper (1980) have divided biological sound scatterers into two groups, those with gas inclusions and those without. Scattering from the second class, which includes phytoplankton, zooplankton, and fishes without bladder, is largely specified by size, sound speed, and density contrast with the surrounding medium. In Figure 4 the theoretical acoustic signatures, i.e., target strength versus frequency, of some types of marine organisms common in the oceans are reproduced from

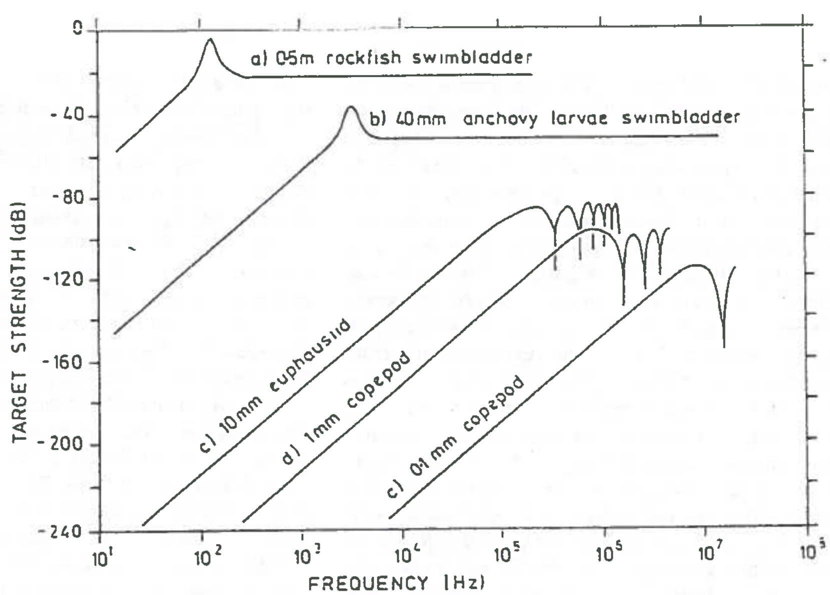


Figure 4. Theoretical acoustic signatures of several common types of marine organisms (after Holliday and Pieper, 1980).

the same authors. The signatures from a fish and a fish larva, both with swimbladder, are modified from the free-bubble theory whereas those from other zooplankton organisms are based on a model of scattering from fluid spheres by Anderson (1950). For both classes, the size of the scatterer determines both the scattering level and the frequency at which the transition from Rayleigh to geometric scattering occurs. The fluid sphere model leads to the conclusion that frequencies between 50 and 500 kHz should be useful for quantitative studies of zooplankton from 5 to 40 mm in size. Johnson (1977) has made a simpler fluid sphere model to be applied to euphausiids and copepods. These models are very sensitive to changes in sound speed and density contrasts and Johnson (1977) demonstrates that a one-per-cent variation in one of the contrasts caused a change in target strength of about 2 dB.

Greenlaw (1979) has suggested a method for estimating size distribution and abundance by means of a multi-frequency sonar system, provided the acoustic signatures with size are known. He is reporting encouraging results from measurements on euphausiids.

## Measurements

Beamish (1971) measured *in situ* target strength from a typical euphausiid at 102 kHz and found that four fifths of the scattering was caused by compressibility contrasts between target and medium and the remaining one fifth is attributed to the density contrast.

Greenlaw (1977) measured backscattering spectra for preserved specimens of three zooplankton (copepod, euphausiid, and sergestid shrimp). Compared with fluid sphere models the results did not fit well in the geometric zone. Both euphausiids and shrimps were found to be directional scatterers.

Dalen and Kristensen (1981) measured both fresh and preserved krill at 14 frequencies between 30 kHz and 1·0 MHz with results near those of Greenlaw (1977). They also measured variations with changing lateral aspect angles. The tilt-angle distribution of free-swimming krill during downward migration was observed with an underwater camera. They also noted that the bodies of krill almost always are kept in a stretched posture.

Some work has also been carried out by measuring *in situ* volume backscattering strength at one or more frequencies simultaneously with underwater photography and biological sampling with trawl or water pumps. Sameoto (1980) applied a 120 kHz sounder and towed opening and closing nets with a camera mounted on the frame. He studied the behaviour of euphausiids and some copepods and established empirical relationships between biomass and numbers from the samples and volume backscattering strength of the same layer. The method is dependent on quantitative biological sampling of the same layer as measured acoustically. Holliday and Pieper (1980) have used a four-frequency sonar system together with quantitative biological sampling with a water pump and found that changes in plankton composition could be explained from principal features of the observed acoustic profiles.

## Tentative conclusion

Studies on other organisms (than fish) as acoustic targets are in an initial phase and have so far been concentrated on model studies and on observations of a few plankton species mainly consisting of euphausiids. Valuable results have been achieved, showing among other things that scattering from krill (and shrimp) is directional within the used frequency band. This should favour a modification of the hitherto applied fluid sphere model for establishing the theoretical acoustic signatures of such animals.

Promising results have also been obtained at sea both with single-frequency and multi-frequency sonar systems in observing volume-scattering strength. More knowledge of target-strength variations with size of individuals is required together with behaviour studies.

## Final remarks

In this review much relevant and good work may not have been mentioned. This is partly caused by my limited capacity and because a growing number of people are now engaged in this field of fisheries research, people with backgrounds in applied mathematics, acoustics, and biology, including subjects in a science too large for a simple sailing oceanographer to cover. But if I should give any advice: "Don't forget to watch the paper recorder of the echo sounder at sea for further inspiration".

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