International Council for the Exploration of the Sea

C.M. 1997/FF:7
Theme Session on Fisheries Technology

ON THE DEPTH DEPENDENCE OF FISH TARGET STRENGTH

by

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ABSTRACT

Data on the depth dependence of the target strength of live kokanee (*Oncorhynchus nerka*), a physostome, at 50 kHz (Mukai, T., and Iida, K., ICES J. mar. Sci., 53: 245-248 (1996)) have been reexamined. In the cited study, data collected over a range of depths on a total of 50 tethered, anesthetized specimens were averaged at each depth, mainly at 5, 10, 20, and 40 m, then fit with a model consistent with Boyle's law. Here the data are analyzed for each individual fish, and a variety of models are used to fit the respective data set. The goodness of fit is gauged by the standard error of the regression. The applicability of Boyle's law, or that giving the inverse pressure-volume relationship of a constant mass of gas under isothermal conditions, is examined in the light of the several fits and is seen to be confirmed. In a speculative application, the depth dependence for kokanee is assumed also to describe that for herring. Incorporation of this into the standard target strength equation for Norwegian spring-spawning herring yields the following expression: $TS=20 \log \ell - 67.3 -6.7 \log (1+z/10)$, where TS is the target strength in decibels, ℓ is the mean fish length in centimeters, and z is the depth in meters.

INTRODUCTION

An outstanding problem in fisheries acoustics is the depth dependence of target strength of swimbladder-bearing fish. It has long been recognized as an important problem (Edwards 1975, Dunn 1979, Midttun 1984), and it has stimulated a variety of investigations. Fundamental physiological studies by Ona (1984, 1990), performed on herring and gadoids, respectively, argue for a substantial effect.

More direct evidence for the acoustic effect of depth change has been acquired through measurement of *in situ* target strength, especially with dual- or split-beam echo sounders. This has been very suggestive in the case of oceanic redfish (Sebastes mentella) (Reynisson 1992, Reynisson and Sigurdsson 1996), but unresolved or ambiguous in the cases of walleye pollock (Theragra chalcogramma) in daytime (Traynor and Williamson 1983) and cod (Gadus morhua) (Rose and Porter 1996), both physoclists, hence with closed swimbladders. In the case of Icelandic summer-spawning herring (Clupea harengus), a physostome with open swimbladder, no dependence on depth has been found by Reynisson (1993), notwithstanding statement of a pressure dependence for the same species by Halldorsson (1983). In a study on Pacific herring (Clupea harengus pallasi) (Kautsky et al. 1991), the large target strength values were attributed to, among other factors, the mostly shallow depths where the fish were measured.

There may be a simple reason for the ambiguous nature of some in situ measurements: these may depend on the precise circumstances of the measurement. Several acknowledged factors are behaviour as expressed through the tilt angle distribution, including possible induced avoidance reactions if the measurement is performed from a moving ship (Halldorsson and Reynisson 1983, Olsen et al. 1983, Olsen and Ahlquist 1989) or changes associated with changes in the ambient light level (Edwards and Armstrong 1983); biological state, as defined by, inter alia, fat content, degree of stomach filling, and possible presence of reproduction products (Ona 1990); and depth, including history of depth excursion.

Such considerations have spawned a raft of auxiliary studies, for example, on the orientation distribution of fish (Olsen 1971, Foote and Ona 1987, Huse and Ona 1996) and on the influence of fat content on swimbladder volume (Ona 1990).

Given the evident inseparability of the several influences, especially those of depth and behaviour (Blaxter and Batty 1990), Olsen 1990, Freon et al. 1993), controlled laboratory-type measurements are very attractive. The validity of such measurements on tethered anesthetized, stunned, or freshly killed specimens, for example, of the kinds reported by Midttun and Hoff (1962), Nakken and Olsen (1977), Foote (1983), and Miyanohana et al. (1990), may be considered established (Foote 1983). The general agreement of computations of target strength based on measured target strength functions of tilt angle and assumption of an orientation distribution, is also encouraging (Foote 1983, Foote and Traynor 1988).

The recent appearance of a new data set (Mukai and Iida 1996) has raised the possibility of isolating the physical effect of depth change from behavioural and other biological effects. This data set consists of controlled measurements of target strength as a function of tilt angle for the physostomous kokanee salmon (Oncorhynchus nerka) over the depth range from 5 to 40 m. Under the relatively rapid depth changes imposed on the anesthetized specimens, the swimbladder may be viewed as enclosing a constant mass of gas whose volume varies inversely with the ambient pressure, a statement of Boyle's law (Sears 1953). At the measurement frequency, 50 kHz, the wavelength is less than the swimbladder length, and the acoustic backscattering cross section is very roughly proportional to the animal's geometric cross section, at least in some average sense. If the swimbladder volume changes with maintenance of the relative swimbladder dimensions, then the cross section σ will vary thus: $\sigma \propto V^{2/3} \propto P^{-2/3}$, where V is the swimbladder volume and P is the ambient pressure. While Mukai and Iida have already shown that this relationship holds when the data from all fifty specimens are pooled together, it may be wondered to what degree the relationship actually applies to individual specimens? It is to answer this question, that the data in the cited study are reexamined.

In a concluding, speculative application, the established depth dependence for kokanee, which follows Boyle's law, is assumed to be valid for herring. It is incorporated in the standard target strength - fish length relationship for Norwegian spring-spawning herring.

MATERIALS

The materials have been described briefly in Mukai and Iida (1996). They are described here with additional details for the sake of completeness. Processed data in the form of maximum and average values of target strength functions, which provide the raw ingredients for the modelling computations reported in the Methods section, are also considered as basic materials here.

The subject fish, kokanee salmon, is dominant in Lake Kuttara, Hokkaido, Japan (42°30'N,141°11'E). This was caught by gillnet or set-net, and held in a surface pen. In turn, each specimen was anesthetized with MS222 and tethered to an apparatus allowing automatic tilting over the range from -50 to 50 deg with respect to the horizontal position at 0 deg, with simultaneous pinging, as in Nakken and Olsen (1977) and Foote (1983) but with a downwards facing narrowband transducer. The transducer frequency was 50 kHz, and the ping rate gave an angular resolution in target strength function of 0.5 deg. The entire apparatus, including fish-tilting suspension system, motor, and transducer, could be lowered in the water column. The transducer was connected to a Kaijo echo sounder model KMC-101 by coaxial cable. Calibration was performed by the standard-target method (Foote et al. 1987) using a 38-mm-diameter high-carbon-steel sphere. This was maintained in fixed position below the suspended fish.

Measurements were made of target strength as a function of tilt angle over the specified tilt angle range. The measurement was repeated at each of four depths, usually 5, 10, 20, and 40 m, but sometimes at 30 or 35 m instead of 40 m. A total of fifty specimens were measured. Thus the total quantity of data consisted of 200 target strength functions of tilt angle.

These data were further reduced by each of two operations. The first was extraction of the maximum value of each target strength function. The second was averaging of the backscattering cross section σ, which is defined in terms of the target strength TS,

$$TS = 10 \log \frac{\sigma}{4\pi r_o^2} \quad , \qquad (1)$$

where r_o=1 m. The averaging was performed with respect to a normal distribution of tilt angle with mean -5 deg and standard deviation (s.d.) 15 deg, truncated at the third s.d.

METHODS

The basic datum is the backscattering cross section σ. This may be either the maximum dorsal aspect value σ_{max} or the averaged value σ_{avg} described in the Materials section. Two subscripts are attached to the respective value σ_{ij} to denote specimen number i and depth j.

Each of three models was fit to σ_{ij}:

Type I. Linear model

$$\sigma = \sigma_o + az \quad , \tag{2}$$

Type II. Quadratic model

$$\sigma = \sigma_o + az + bz^2 \quad , \tag{3}$$

Type III. Pressure-power model

$$\sigma = \sigma_o (1 + z/10)^{\delta} \quad . \tag{4}$$

The number of free parameters to be determined for each model is two, three, and two, respectively.

In fitting the models, regression analysis was employed directly with σ, that is, the respective σ_{max} or σ_{avg}, in both the linear and quadratic models. In fitting the third model, the data were first logarithmically transformed, then fit to the following model:

$$TS = TS_o + 10\,\delta \log (1 + z/10) \quad . \tag{5}$$

The value σ_o in equation (4) is derived from the regression coefficient TS_o by the simple inversion,

$$\sigma_o = 4\,\pi\,10^{TS_o/10} \quad . \tag{6}$$

When investigating the exact Boyle's-law model, the exponent δ in equation (4) was assigned the value -2/3, TS_o was derived from equation (5) by averaging, and σ_o was subsequently determined from equation (6).

Two series of computations were performed. In the first, all 200 derived data were used, resulting in separate model fits for σ_{max} and σ_{avg} for each of the three generic model types. In the second series, only Type-III models were considered, namely the general model with arbitrary δ and the special case δ=-2/3. Each of these was applied individually to each set of values of σ for the same fish, hence σ_{ij} for constant i for all four values of j. The quantity σ_{ij} was then normalized to the corresponding value at depth 0 m, namely $\sigma_{o,i}$. The normalized quantity $\sigma_{ij}/\sigma_{o,i}$ was fit by the general model, determining two coefficients, and by the particular Boyle's-law model, with δ=-2/3.

To judge the goodness of fit of the various models, the standard error se was computed in the following way:

$$se = \left| \frac{1}{n-f} \sum_{i,j} (\sigma_{ij} - \hat{\sigma}_{ij})^2 \right|^{\frac{1}{2}} \quad , \qquad (7)$$

where n denotes the number of data, f is the number of degrees of freedom, and $\hat{\sigma}_{ij}$ is the estimated value for σ based on the fitted model. The number of degrees of freedom is considered to be two, three, and two for the respective model type, and one for the special case of Boyle's law.

RESULTS AND DISCUSSION

The results of fitting the three models to all of the data pooled equally are presented in Fig. 1. There are no significant differences in the goodness of fit, which may be visually apparent but which is also supported by the respective values of se.

Interestingly, perhaps, is the comparison of magnitudes of se in the two cases of σ_{max} and σ_{avg}. These are roughly 27.4 and 7.5. The logarithm of the ratio, 10 log (27.4/7.5), is 5.63 dB. This compares favorably with the nominal figure of 7.1 dB given for the difference between maximum and average values of dorsal aspect target strengths (Foote 1997). The present comparison is possible because the standard error scales as the magnitude of σ.

Because of the closeness of the three corresponding fits for both σ_{max} and σ_{avg}, only the pressure-power model was examined in the next set of computations. Performance of the normalization is described in the Methods section; the results of fitting σ/σ_o are shown in Fig. 2 for the general model and in Fig. 3 for the exact Boyle's-law dependence. The differences in the respective regression curves favor the exact Boyle's-law dependence used in Fig. 3.

Deviations from Boyle's law in the case of individual fish specimens are evident in Figs. 2 and 3. This is explained by the display of 50 regression curves in each part of Fig. 4. Each curve shows the general Type-III model for the data as distinguished by individual specimen.

The monotonically increasing curves in Fig. 4 show vivid departures from Boyle's law. In the case of the intermediate example with increasing depth dependence for σ_{avg}/σ_o in Fig. 4, the basis data for the identified specimen, fish no. 37, are presented in Fig. 5. The average values at 20 and 40 m can be imagined to exceed that at 5 m, while that at 10 m is the least. In fact, detailed computation indicates that the respective values of σ_{avg}/σ_o are 1.97, 0.59, 2.19, and 2.05 arranged in order of increasing depth. For the present statistical sample size of 50, however, Boyle's law is indeed observed to be upheld.

For purposes of comparison with other data, the normalizing values $\sigma_{max,o}$ and $\sigma_{avg,o}$ are expressed as target strengths, which are regressed on the logarithm of fish length ℓ in centimeters according to each of two models, the general model,

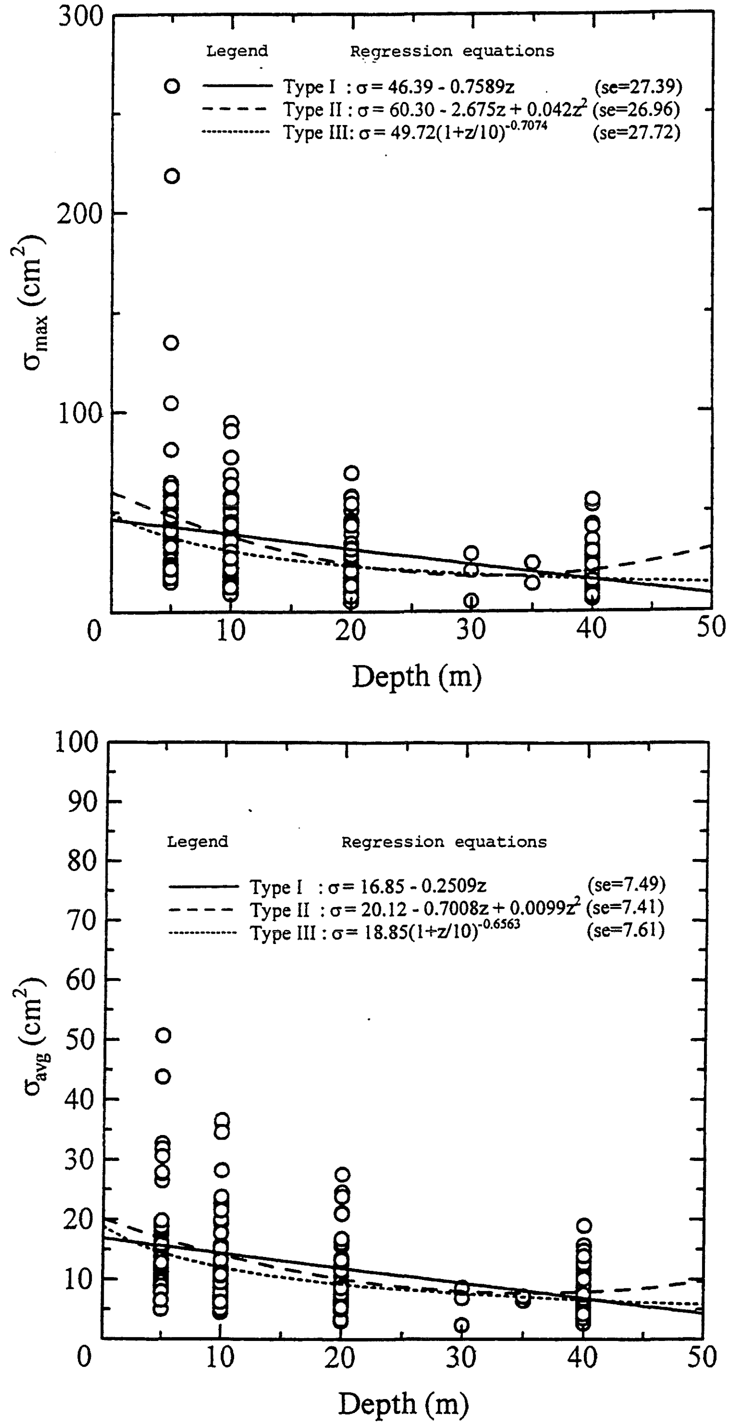

Fig. 1. Pooled data for σ_{max} and σ_{avg} together with fitted regression curves to each of the three models described in equations 2-4.

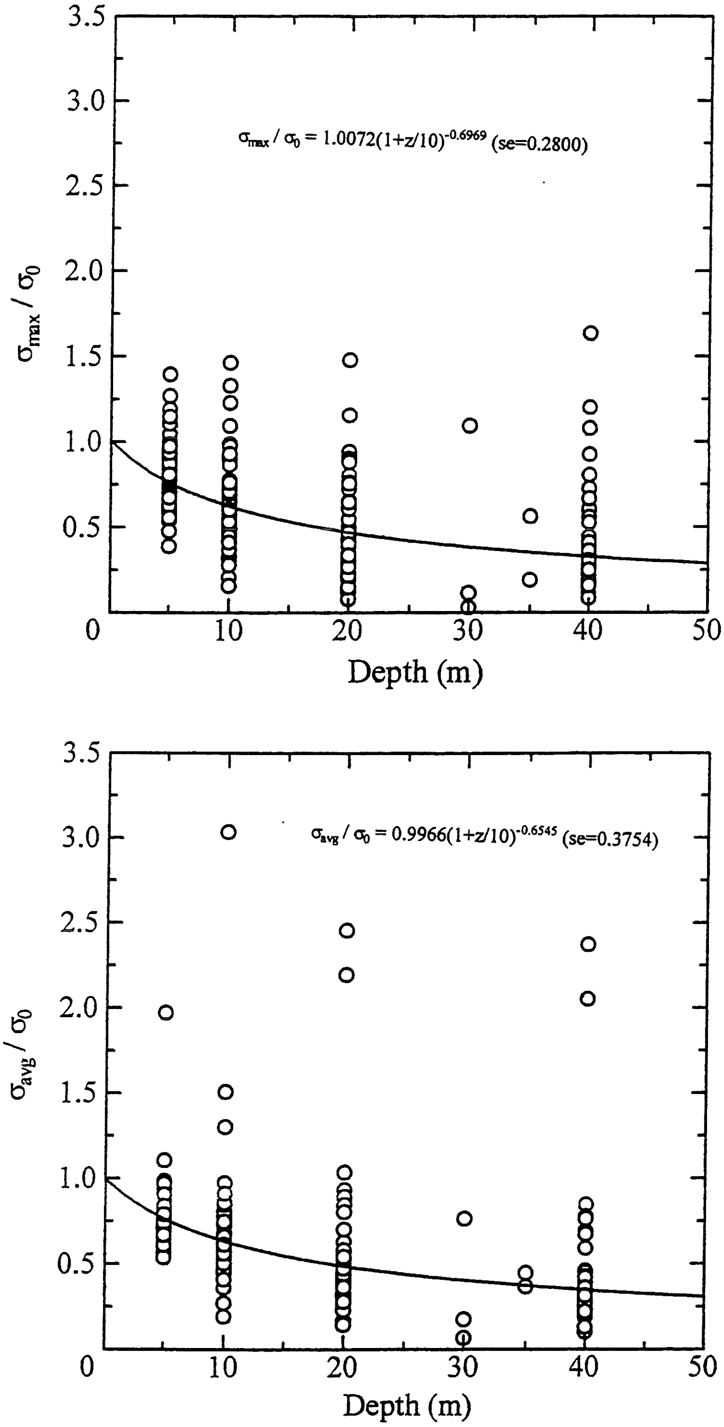

Fig. 2. Scatter diagrams of individual values σ_{ij} normalized to the respective $\sigma_{o,i}$, as determined by the Type-III model in equation 4 based on the four values σ_{ij} for j=1,2,3,4.

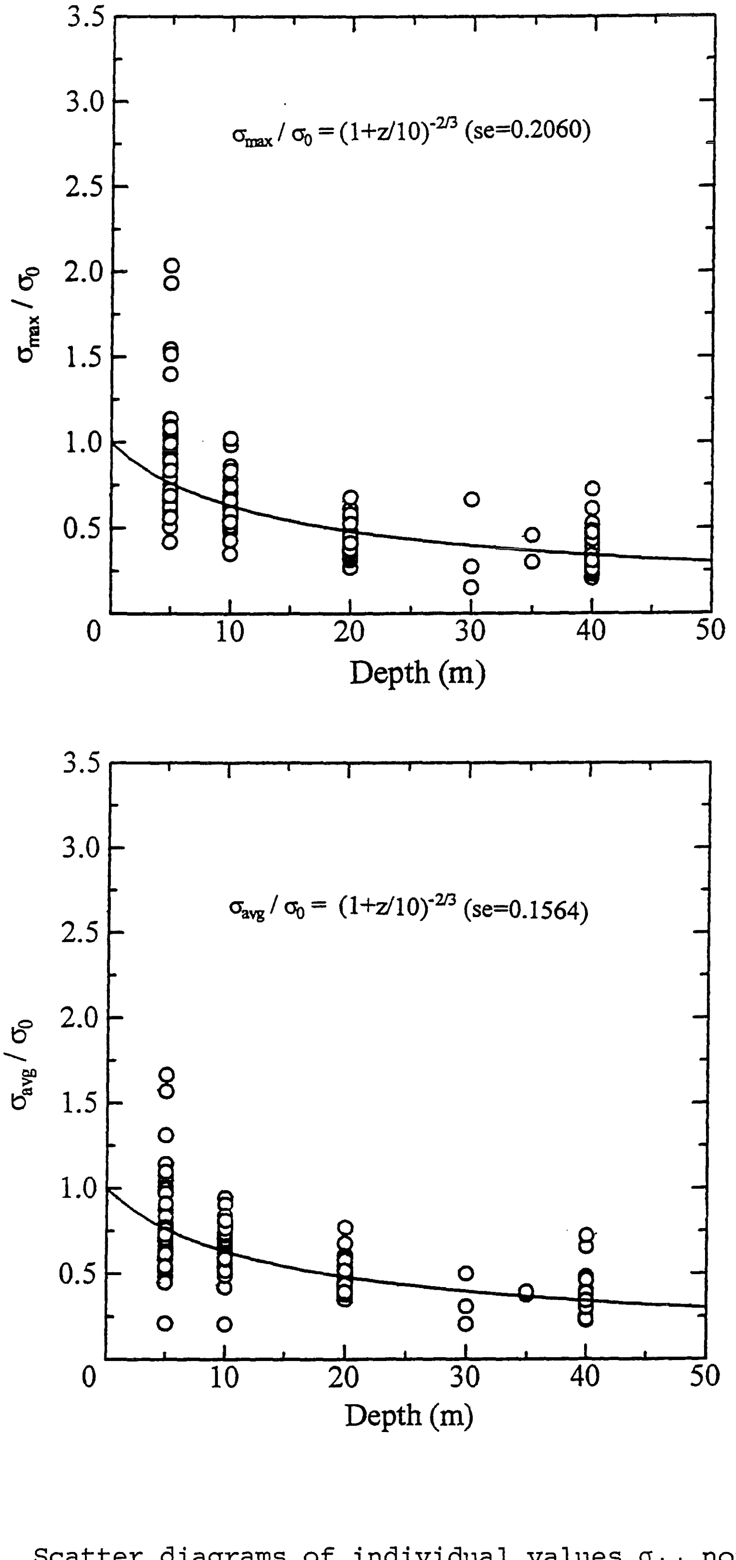

Fig. 3. Scatter diagrams of individual values σ_{ij} normalized to the respective $\sigma_{o,i}$, as determined by the Boyle's-law model, or Type-III model with $\delta=-2/3$, based on the four values σ_{ij} for j= 1,2,3,4.