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ON SOUND EXTINCTION BY BIOLOGICAL TARGETS

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To address the importance of sound extinction by densely aggregated biological entities, a systematic theoretical study of this problem is presented. The physical insight into the extinction phenomenon is given. The agreement between theoretical and experimental results is discussed.

INTRODUCTION

Sound extinction by biological scatterers, fish and zooplankton, is important for studying sound propagation in the ocean and should be carefully evaluated [6]. Moreover, in fisheries and zooplankton acoustics, the influence of sound extinction by biological targets on abundance and/or biomass estimation can be significant and has been discussed [6, 13]. Such an influence should be taken into account in interpreting the acoustical measurements, especially when a densely aggregated or an extended population is involved [3, 9, 12, 28, 30].

To obtain the physical insight of sound extinction, the sound absorption and scattering by biological scatterers have been studied theoretically and experimentally.

Various methods of measuring extinction cross section of biological individuals have been developed and can be generally categorised into three methods. The first one is the direct method, which is based on direct measurements of sound attenuation by biological targets [5, 6, 11, 12, 18, 20, 21]. The second is the indirect method, which includes analysing collected echosounder data using the parameter fitting method [8, 13]. The third method, the reference target method, is widely employed now and is based on the linearity of the measured area backscattering coefficients for the reference target and fish. Flat sea bed below the fish aggregation [10, 34], or a standard metal sphere suspended beneath the aggregation [1, 25], or both [24] have been used as reference targets.

By employing the developed methods, the extinction measurements have been made for various fish species and within a wide acoustic frequency band. The results of the measurements at high frequencies 20 – 420 kHz are described in the papers [1, 3, 5, 8, 10, 13, 18, 20, 21, 24, 29, 34], while the results for low frequencies, 0.3 – 5 kHz, are reviewed in [6].

Unfortunately, data involving sound extinction measurements for zooplankton are not readily available.

Extinction cross section, σ_{ext}, can be presented by the following two ways [22]. Firstly, it can be expressed through the total scattering cross section, which is defined by the scattering amplitude of target, $f(\vec{i},\vec{k})$, and describes the scattering in all directions:

$$\sigma_{ext} = \sigma_a + \sigma_s . \qquad (1)$$

Secondly, the forward scattering theorem can be applied:

$$\sigma_{ext} = (4\pi / \kappa)\,\mathrm{Im}\, f(\vec{i},\vec{i}) , \qquad (2)$$

$f(\vec{i},\vec{k})$ describes the scattering from $\vec{i}$ to $\vec{k}$ directions, $\vec{i}$ and $\vec{k}$ are unit vectors for the incident and scattered waves, respectively, $\vec{i} = \vec{k}$ for forward scattering and $\vec{i} = -\vec{k}$ for backscattering. Here σ_a denotes the absorption cross section, *Im* means the imaginary part of, κ describes sound wave number, $\kappa = 2\pi f / c$, where *c* is the sound speed in sea water.

The bistatic scattering amplitude, $f(\vec{i},\vec{k})$, is important in both these approaches. It is this characteristic that should be studied to obtain the solutions for the extinction cross section. Both analytical and numerical methods have been developed to study the bistatic scattering.

Analytical methods enable us to obtain the exact and approximate solutions. The exact solutions that are based on the method of variable separation have been used only for limited class of scatterer geometries and types of scatterer surfaces. A review of these methods is presented in [26]. Approximate methods, on the other hand, can be used to a much wider class of scatterer geometries and surface boundary conditions. Many approximate methods are based on the Kirchhoff integral theorem [2, 14, 33, 36, 37]. These methods differ in ways of the theorem simplification. The approximation solutions for scattering by finite slender bodies of revolution have been developed [23, 33, 36, 37]. Since these solutions are all based on the modal series representation, they can be referred to as Mode Based Deformed Cylinder Model (MB–DCM). Other approximate methods include the Kirchhoff Approximate Method (KAM) [14], the Geometrical Theory of Diffraction (GTD) [2], and the Phase Compensated Distorted Wave Born Approximation (PC-DWBA) [4]. However, these approximate methods all have their intrinsic limitations. The MB–DCM is more appropriate for elongated axisymmetric shapes of individual targets and near broadside incidence. The KAM and GTD are applicable only at high frequencies, while the PC–DWBA is reasonably accurate for weakly scattering, fluid-like scatterers only.

In order to solve the problem over a wider range of target parameters, numerical techniques have been developed. A review on the numerical methods, such as T-matrix method, Volume Integral Method, Matched Asymptotic Expansions Method, Boundary Integral Method and Conformal Mapping Approach, can be found in [7, 26]. However, these methods can suffer from computational difficulties.

To describe low frequency scattering by fish, the approximate and numerical approaches have been developed. A wide review can be found in [6]. The developed methods correctly consider the coupling effects in case of fish schools.

The MB–DCM method is a very versatile method. It has been used in a wide range of acoustic scattering applications including sound extinction by fish [35] and zooplankton [15-17]. There are a few reasons for the success of this method. Firstly, this method is relatively simple and computationally efficient. Secondly, it may be applied to any axisymmetric body of any material composition. Thirdly, results obtained from this method has been compared with those obtained from the exact solutions. The comparison has been done for the backscattering by rigid prolate spheroid [33] and for the backscattering and forward scattering by a fluid-like prolate spheroid [16, 17]. Good agreement has been achieved. Moreover, the range of off-broadside orientations, within which the MB–DCM is still accurate, has been defined based on a careful study of the model over a wide range of shapes and material properties of the scattering targets [26, 36]. It is also important that this method allows to describe sound scattering by fish at both high ($ka > 1$, where a is scatterer characteristic transverse size) and low frequencies ($ka < 1$). However, it is necessary to be careful in application of the approach near the resonance.The mentioned versatility of the MB–DCM is the reason why in this paper we choose this approach to describe the sound extinction by aggregated fish at high and low frequencies and by densely aggregated weakly scattering zooplankton.

The paper is organised as follows: in *Section I*, the general parameterised averaged solutions for extinction cross section are presented for fish and zooplankton. They take into account the differentiation of scatterers in the geometric characteristics, target geometrical shape and orientation, and in bioacoustic parameters such as density and sound speed contrasts of scatterer material. It is important to note that in the previous studies, the averaging has been made for zooplankton only [16]. Moreover, only the non-averaged extinction cross section of individual fish has been considered earlier [35]. The different approaches to the extinction problem are discussed in this section. In *Section II*, the dependence of the averaged extinction cross section on various parameters are analysed. The results of the previous sensitivity analysis are also discussed. In this section the comparison with results obtained from the PC–DWBA approach is made for weakly scattering zooplankton. The comparison with experimental data is presented in Section III.

1. MB-DCM APPROACH AND ECHO AVERAGES: GENERAL FORMULAE.

In this section we present the MB-DCM approach to study acoustical scattering by fish and zooplankton.

One of the important questions in modelling sound scattering by objects is how to describe their complicated geometrical shapes. Prolate spheroids have been widely used to model the shapes of elongated scatterers - fish and zooplankton [4, 16, 17, 33, 35, 37] since the exact modal series solution of the scattering by a prolate spheroid is available [4, 16, 17, 33, 37]. These exact solutions can be used to verify any approximate analytical models. Moreover, there is a good agreement between the model predictions and the measurement data [35]. In the modelling work presented in this paper, fish body and its swimbladder are described by fluid-like and gas filled prolate spheroids. The fluid-like prolate spheroid is also used for describing the shape of the weakly scattering zooplankton.

In case of aggregated biological targets, it is important to take into account their differentiation in geometrical and acoustical properties. We introduce a parameter array $\vec{\alpha} = \{\alpha_i\}$ $[i = 1, 2 \ldots 5]$ to describe the properties of ith target. The parameters α_1, α_2, α_3, α_4 and α_5 denote respectively the semi-minor or major axis lengths of the prolate spheroid (a or l), target aspect ratio ($e = l / a$), scatterer orientation (θ), and the contrast parameters of target material, h and g. The sound speed and density contrasts are defined respectively as $h = c_t / c$ and $g = \rho_t / \rho$, respectively, where ρ_t and c_t are density and sound speed inside the scattering target, and the parameters ρ and c refer to quantities of the surrounding water.

The extinction cross section, averaged over α, should be used when aggregated biological scatterers are involved. The averaged extinction cross section can be expressed as

$$< \sigma_{ext} >_{\alpha} = \iint d\alpha \; W_{\alpha}(\alpha) \sigma_{ext} \,, \tag{3}$$

where the function $W_{\alpha}(\alpha)$ represents a multi-dimensional probability density function (PDF) of α. For simplicity, a Gaussian PDF is used for each parameter α_i and the statistical independence of the different parameters is assumed. Therefore, the multi-dimensional PDF, $W_{\alpha}(\alpha)$, can be expressed as:

$$W_{\alpha}(\alpha) = \prod_{i=1}^{5} \left(\frac{1}{(2\pi)^{1/2} S_{\alpha_i}} \exp\left[-(\alpha_i - \bar{\alpha}_i)^2 / (2 S_{\alpha_i}{}^2) \right] \right) . \tag{4}$$

Here and in what it follows $\bar{\alpha}_i$ and S_{α_i} represent the mean or averaged values and the standard deviations of the respective distributions. Using Eqs. (3), (4), the forward scattering theorem, Eq. (2), and the MB–DCM solution for the forward scattering amplitude [33], we obtain the solutions for the averaged extinction cross section of fish and fluid-like zooplankton.

1.1. SCATTERING BY FISH

It has been shown that both fish body and swimbladder can be important in sound extinction by fish [35]. If we assume that the scattering amplitudes from the fish body and swimbladder are added incoherently, the averaged total extinction cross section normalised by the square of the mean fish length $\bar{l}_b$, can be expressed as

$$\frac{\left\langle \overset{t}{\sigma}_{ext} \right\rangle}{\bar{l}_b^{\,2}} = \frac{\left\langle \overset{sw}{\sigma}_{ext} \right\rangle}{\bar{l}_b^{\,2}} + \frac{\left\langle \overset{b}{\sigma}_{ext} \right\rangle}{\bar{l}_b^{\,2}} \,, \tag{5}$$

where the brackets $\langle \; \rangle$ means averaging over the semi-minor axis length of fish body a_b, fish body aspect ratio $e_b = l_b / a_b$, fish orientation θ_b, and the contrast parameters g_b and h_b. The extinction cross sections of fish body, $\left\langle \overset{b}{\sigma}_{ext} \right\rangle$, and swimbladder, $\left\langle \overset{sw}{\sigma}_{ext} \right\rangle$, can be described as

$$\frac{\left\langle \overset{b,sw}{\sigma}_{ext} \right\rangle}{\bar{l}_b} = -\frac{2 R_l}{\pi S_{ka_b} S_{\theta_b} \bar{e}_b (k\bar{a}_b)^2} \int d\theta_b \exp\left[-\frac{(\theta_b - \bar{\theta}_b)^2}{2 S_{\theta_b}^2} \right] \int d(ka_b)(ka_b) \exp\left[-\frac{(ka_b - k\bar{a}_b)^2}{2 S_{ka_b}^2} \right] *$$

$$* \,\mathrm{Re}\left\{ \int_0^1 du \sum_{m=0}^{\infty} b_m(u, \theta_b, (ka_b R_a), g, h) \right\} , \tag{6}$$

where $S_{ka_b} = k S_{a_b}$. For fish body, $R_l = R_a = 1$. For fish swimbladder, $R_l = \bar{l}_{sb} / \bar{l}_b$ is the ratio of the mean major axis length of the swimbladder to that of the fish body, while $R_a = \bar{a}_{sb} / \bar{a}_b$ is the ratio of the mean semi-minor axis length of the swimbladder to that of the fish body. The parameters $g = \bar{g}_b$ and $h = \bar{h}_b$ are for fish body and $g = g_{sb}$ and $h = h_{sb}$ for swimbladder.

The explicit form of the modal coefficient b_m is given in [16, 17, 33]. The integration variable u denotes the co-ordinate along the major axis of the prolate spheroid, normalised by the half of its length.

In Eq. (6), the averaging over the aspect ratio has been performed analytically and it is exact. The averaging over the contrast parameters has been done by the approximate Method of Steepest Descend (MSD). The integrals over the fish orientation and body semi-minor axis (over ka_b) can be calculated numerically. In the previous study [35], only the extinction cross section of individual fish has been considered. Here we present the parameterised solutions for the extinction cross section averaged over fish geometric and bioacoustic parameters. These solutions enable the further analysis of the parametric dependencies of the averaged extinction cross section and make the computations less intensive.

1.2. SCATTERING BY FLUID-LIKE ZOOPLANKTON

The following general formula for the averaged extinction cross section, normalized by the square of the individual mean length ($\bar{l}$), has been obtained in [16]:

$$\langle\sigma_{ext}\rangle/\bar{l}^{2}=-2(\pi(k\bar{a})^{2}S_{ka}S_{h}\bar{e})^{-1}\iint d(ka)\;dh\;\exp\left[-\frac{(ka-k\bar{a})^{2}}{2S_{ka}^{2}}\right]\exp\left[\frac{-(h-\bar{h})^{2}}{2S_{h}^{2}}\right]$$

$$\cdot\,\mathrm{Re}\left[\int_{0}^{1}du\sum_{0}^{\infty}b_{m}(ka,h,\bar{g})\right]\quad,\qquad(7)$$

where averaging over the aspect ratio has been made exactly; averaging over the density contrast and orientation has been done using the MSD; the extinction cross section can be averaged numerically over the sound speed contrast and semi-minor axis length (over ka).

For zooplankton, the averaged analytical solution has been obtained also on the basis of the PC–DWBA model [16]. The comparison [16] of the PC–DWBA with the MB–DCM averaged solutions has demonstrated that the former is much simpler and much more efficient computationally. In addition, the PC–DWBA provides deeper physical insight into the extinction problem.

It should be noted that Ye has developed an improved model to describe the scattering by a slender body [36, 37] and has shown that the MB–DCM presented in this paper is a special case of the improved model [36]. It can be demonstrated that for our current analysis the difference between the two methods is small for the forward scattering by fluid-like and gas filled bodies for near broadside incidence (not shown). Therefore, both methods should give the same results for the extinction cross sections of fish and zooplankton.

2. MAIN FEATURES OF SOUND EXTINCTION BY DENSELY AGGREGATED FISH AND ZOOPLANKTON.

In this section, based on the solutions presented above, we investigate the dependence of the averaged extinction cross section on various parameters by presenting a systematic sensitivity analysis. Such an analysis is important to understand the fundamentals of sound extinction phenomenon.

2.1 DEPENDENCE ON $k\bar{a}$ PARAMETER.

The dependence of the reduced target strength, ($10\log(<\sigma_{ext}>/\bar{l}^2)$) on dimensionless parameter $k\bar{a}_b$ for fish body, swimbladder and whole fish is presented in Fig. 1. The computations are made, using Eqs. (2), (5), and (6), with the following computation parameters: for swimbladder – the sound speed and density contrasts are respectively 0.23 and 0.00129, and for fish body – the mean contrasts are both equal to 1.04. Fish body mean aspect ratio is 32, the ratio of mean length of the swimbladder to that of the fish body, R_l=0.3, and the ratio of their mean width, R_a=0.5. For the orientation distribution - the mean incident angle of 0^0 and the standard deviation of 5^0 are used. For the distribution over a_b, $S_{a_b} = 0.1\bar{a}_b$.

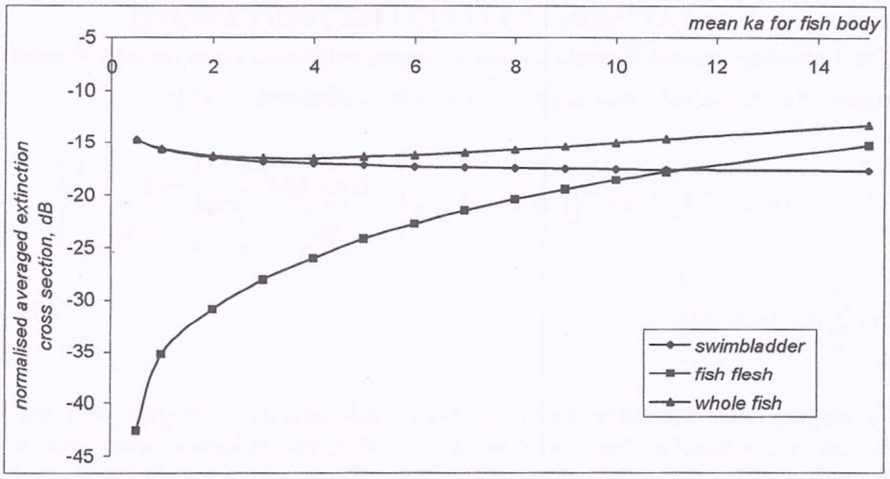

Fig. 1. Dependence of reduced target strength on parameter $k\bar{a}_b$ for fish.

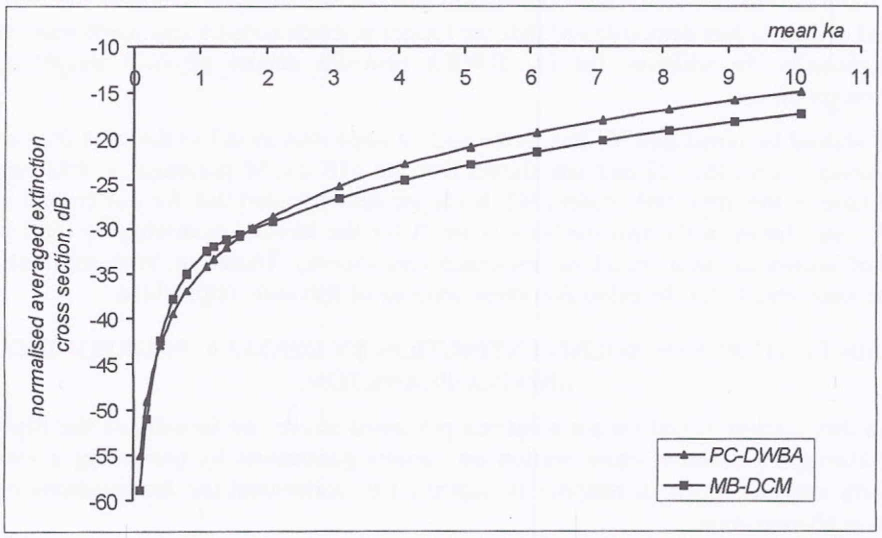

Fig. 2. Dependence of reduced target strength on parameter $k\bar{a}$ for zooplankton.

Three lines in each plot correspond to the swimbladder, fish flesh and the whole fish. The results indicate that an increase in fish length and acoustic frequency (increase of $k\bar{a}_b$ parameter) causes a decrease in the extinction cross section due to swimbladder. In contrast, the extinction cross section of fish body (over the entire $k\bar{a}_b$ range) and whole fish (for $k\bar{a}_b > 4$) increases with $k\bar{a}_b$. The relative contribution of fish flesh to the total extinction cross section increases with $k\bar{a}_b$ and achieves 64% at $k\bar{a}_b = 15$.

The numerical results for the averaged extinction cross section for weakly scattering zooplankton are illustrated in Fig. 2 [16]. The dependence of $10\log(<\sigma_e>/\bar{l}^2)$ on dimensionless parameter $k\bar{a}$ is presented for two approaches, MB–DCM and PC-DWBA. The figure is obtained based on Eqs. (2), (7) for MB-DCM and the equation given in [16] for PC–DWBA. The computation parameters are $S_a = 0.2\,\bar{a}$, $\bar{e} = 32$, $S_e = 0.2\,\bar{e}$, $\bar{h} = 1.0279$ and $S_h = 0.25(\bar{h} - 1)$. Two curves in the figure refer to the different models as indicated. The comparison demonstrates that the difference between the two solutions increases with growth of $k\bar{a}_b$. The discrepancy is about 2.5 dB at $k\bar{a} = 10$.

2.2. SENSITIVITY ANALYSIS.

To illustrate the influence of the bioacoustic properties of fish flesh on the extinction, we, using Eqs. (2), (5) and (6), compute the normalised averaged extinction cross section over the entire possible range of the contrast parameters $\bar{g}_b$ and $\bar{h}_b$. Results for small $k\bar{a}_b = 0.3$ and large $k\bar{a}_b = 10$ are presented in Fig. 3 and Figs. 4a-b, respectively. Figures 4a and 4b correspond respectively to fish body and whole fish. The computation parameters are the same as those when obtaining Fig. 1.

Figures 4a, 4b demonstrate that the averaged extinction cross section is more sensitive to the sound speed contrast than to the density contrast at large $k\bar{a}_b$ for both fish body and whole fish. However, for small $k\bar{a}_b$ the results are presented only for fish flesh (Fig. 3). In this case the contribution of fish flesh to the total extinction cross section is too small (see Fig. 1) that the averaged extinction cross section of the whole fish is not sensitive to the fish flesh contrasts. Moreover, in contrast to the case of large $k\bar{a}_b$, the fish flesh extinction cross section is sensitive to both contrasts at small $k\bar{a}_b$.

It is interesting that both $\left\langle \sigma_{ext}^{b} \right\rangle / \bar{l}^2$ and $\left\langle \sigma_{ext}^{sw} \right\rangle / \bar{l}^2$ are inversely proportional to the mean aspect ratio of fish body, (Eq. (6)). In other words, an increase in fish swimbladder or fish body elongation causes a decrease in normalised averaged extinction cross section.

To analyse the sensitivity of the extinction cross section to the orientation, the orientation dependence of the *imaginary part* of the forward scattering amplitude should be studied (see Eq. (2)). For forward scattering only the dependence of the *modulus* of scattering amplitude has been analysed previously [36]. It has been demonstrated for fluid-like and gas-filled prolate spheroids that the sensitivity to the orientation is more significant at larger $k\,a$. Using the MB-DCM, we have analysed the dependence of the *imaginary part* of forward scattering amplitude over the narrow orientation range (including ±15 degree - deviations from the broadside incidence). The slight dependence has been demonstrated for fish body and fish swimbladder over the entire $k\,a_b$ - range (not included in this paper).

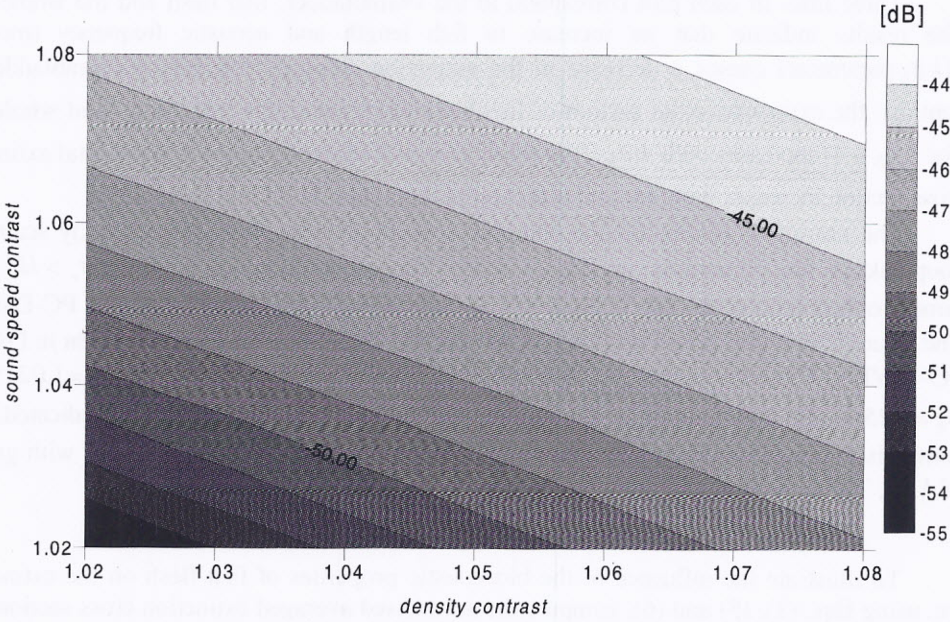

Fig. 3. Sensitivity of reduced target strength (dB) to contrast parameters at $k\bar{a}_b$ =0.3 for fish flesh.

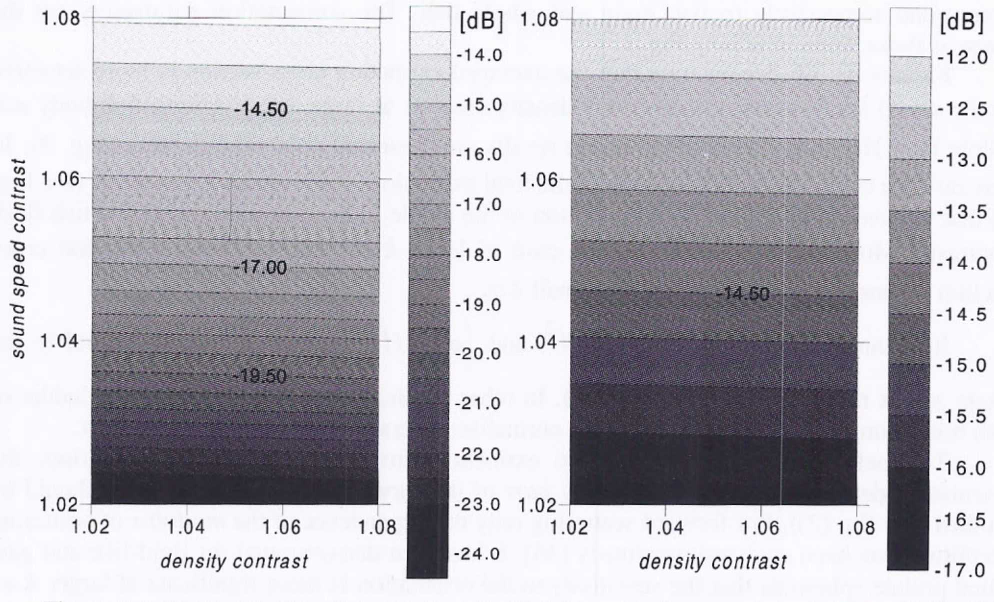

Fig. 4. Sensitivity of reduced target strength (dB) to contrast parameters at $k\bar{a}_b$ = 10 for fish flesh (a) and whole fish (b).

The sensitivity analysis for fluid-like zooplankton (for non-averaged quantities only) has been performed in [4, 16, 17]. It has been shown that the extinction cross section slightly depends on the geometrical shape of the individual scatterers. Moreover, the extinction cross section is more sensitive to the sound speed contrast than to the density contrast. Based on these results, it can be summarised that the averaged extinction cross section also slightly depends on the geometrical shape of the individual scatterers and is sensitive to the sound speed contrast. In addition, from Eq. (7), we can conclude that the normalised and averaged extinction cross section is inversely proportional to the mean aspect ratio $\overline{\varepsilon}$.

3. COMPARISON WITH MEASUREMENT EXTINCTION DATA.

The comparison between the theoretical results and the experimental data is required for verification and development of scattering models. Unfortunately, because of the lack of readily available field and laboratory experimental data, the comparison is not possible for zooplankton. However, as it has been indicated in the INTRODUCTION section, the measured data for fish are available. In Fig. 5 we compare the measured extinction cross section data with the numerical results obtained based on the MB–DCM. The data are presented from the scattering measurements involving *Northern anchovy* collected by Davies [5], *Saithe* by Foote [8], *Japanese anchovy* by Hashimoto [18], *Yellowtail* (72 cm), *Sea bream* (31 cm), and *Spotted mackerel* (29.2 cm) by Ishii et al. [20] and [21], and *Pacific herring* by Burczyński et al. [3].

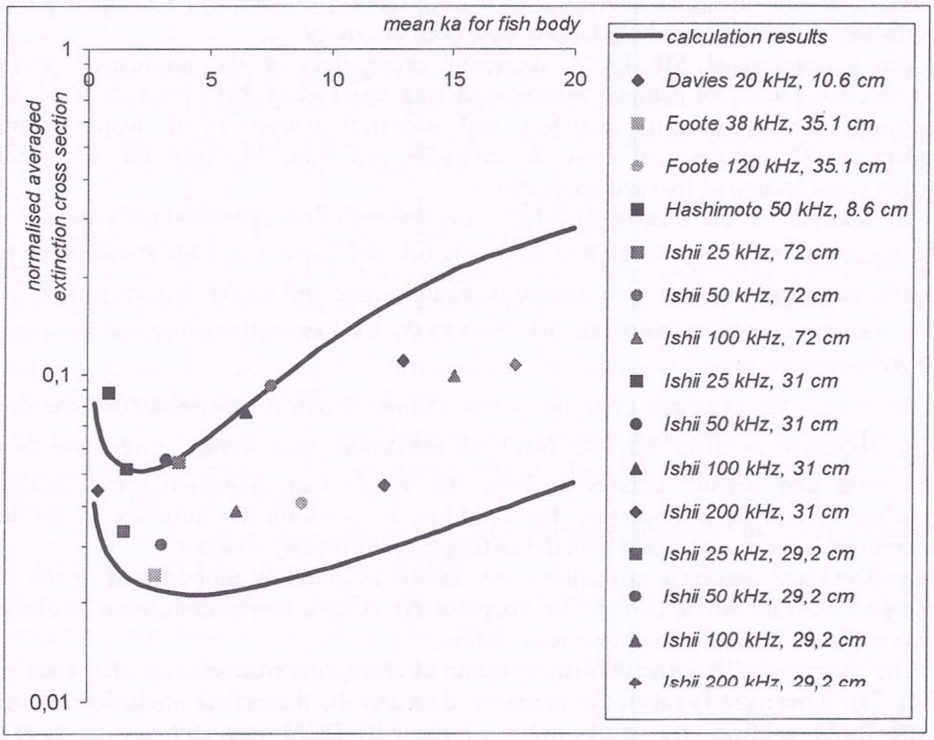

Fig. 5. Comparison of theoretical and measured results.

Because of the scattering experiment complexity, a direct comparison between the measured data and the model predictions with a set of controlled parameters is extremely hard, if it is not impossible. It is more realistic to evaluate theoretically the bounds of the variability of the extinction cross section in terms of the predictable and reasonable parameter limits.

Taking into account the fact that the normalised averaged extinction cross section increases with the density and sound speed contrasts, and decreases with the aspect ratio, we present two theoretical curves in Fig. 5. For the top curve, the mean sound speed and density contrasts of fish body both equal 1.08, and the mean aspect ratio of fish body is 16, while for the bottom curve these values are 1.03 and 32, respectively. These two curves can be considered as the theoretical bounds of the extinction cross section of fish. The other computation parameters are similar to those in obtaining Fig. 1. In calculating $k\bar{a}_b$ for the measurement data, we have assumed that the mean fish body aspect ratio equals 20. Fig. 5 demonstrates that all measured data except for one (Hashimoto, 50 kHz) fall into the domain bounded by the two theoretical curves. It can serve as a guide to the applications of the MB–DCM to the theoretical studies and interpretations of sound extinction by marine animals.

4. SUMMARY

A review of the theoretical and experimental studies of sound extinction by fish and zooplankton has been given. The MB–DCM has been applied to the extinction problem. Differences between this method and the other methods (PC–DWBA and Ye's approach [36]) including their advantages and limitations have been discussed.

The parameterised MB–DCM analytical expressions of the normalised averaged extinction cross section of fish and weakly scattering zooplankton have been obtained. These expressions are convenient for analytical and numerical analysis of the major parameter dependencies. The analysis of these dependencies has been presented for the averaged extinction cross section of fish and zooplankton.

The analysis has demonstrated the following features of the extinction phenomenon:

1. The extinction cross sections both of the whole fish (for larger $k\bar{a}_b$) and zooplankton (over the entire $k\bar{a}$ range) increase with growth of scatterer size and sound frequency ($k\bar{a}_b$). The relative scattering contribution of the fish flesh to the total extinction cross section increases with $k\bar{a}_b$.
2. At high $k\bar{a}_b$ the averaged extinction cross section of fish is independent of the density contrast. However, at small $k\bar{a}_b$ the fish flesh extinction cross section is sensitive to both sound speed and density contrasts, while the whole fish extinction cross section is independent of fish flesh properties. For fluid-like zooplankton the influence of the sound speed contrast is more significant than the influence of the density contrast.
3. Normalised and averaged extinction cross section is inversely proportional to the target mean aspect ratio for whole fish and for zooplankton. A reduction in elongation results in an increase in the normalised extinction cross section.

The comparison with the published results of absorption measurements has been made for fish. The agreement between the measured data and the theoretical predictions based on the MB–DCM confirms the applicability of the MB–DCM approach to the extinction problem.

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