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On Sound Extinction by Zooplankton

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Theoretical investigation of sound extinction cross section of zooplankton individual is made on the basis of optical theorem. To find general properties of this characteristic, analytical model, describing the scattering at krill individual, is used. The extinction cross section is evaluated for various krill species.

The dependence of the extinction cross section on the sound frequency is obtained. The paper presents the influence of the acoustical properties of the biological tissue and geometrical form of individual on the extinction cross section. The role of sound absorption in krill tissue is discussed.

1. Introduction

The knowledge of sound attenuation by biological objects is essential as in evaluation of sound long-range transmission losses, as in acoustical measurements of concentration of biological populations [7].

Attenuation of sound energy by fish aggregations has attracted much attention. The measurements of this characteristic have been carried out at various sound frequencies and for various fish species [2, 4, 7, 9, 15, 18]. The theoretical analyses has aided these measurements [5, 7, 19, 20]. The analytical expressions for fish extinction cross section have been derived.

Sound attenuation by zooplankton populations has been studied much less [1, 7, 10]. The algorithm for determining the extinction cross section of biological individual, proposed in the article [7], is applicable for zooplankton. It has been demonstrated in the papers [1, 10], that shadowing effect can be significant for dense and extended krill aggregation. However these articles suffer from the two limitations. The first problem is the employment of inaccurate models for description of scattering cross section of krill individual instead of the verified models [16, 17]. The second limitation is, that the calculations did not include the absorption.

This work presents theoretical studies of sound attenuation by zooplankton individuals. The analytical expression for krill extinction cross section is obtained. I use the verified model of bent cylinder [16] to describe the scattering by krill individual. The evaluation of the extinction cross section is made for various krill species. The dependence of the extinction cross section on the sound frequency is analysed. The paper demonstrates the sensitivity of this characteristic to contrasts parameters and absorption of krill tissue and to individual geometrical shape.

2. Model Description

The sound attenuation due to the scattering and the absorption by zooplankton aggregation is described by the attenuation coefficient α, which is related to the extinction cross section as follows (see, for example, [20]):

$$\alpha = 1/2 n \sigma_e \quad (1)$$

where n denotes the concentration of zooplankton population. The extinction cross section is the sum of the absorption cross section (σ_a) and the scattering cross section (σ_s):

$$\sigma_e = \sigma_a + \sigma_s \quad (2)$$

According to the optical theorem [11] extinction cross section σ_e can be calculated from the forward scattering amplitude and can be expressed as:

$$\sigma_e = (4\pi / \kappa)\,\mathrm{Im}\, f(\bar{i},\bar{i}) \quad (3)$$

where *Im* means taking the imaginary part, κ describes sound wave number, $\kappa = 2\pi f / c$, c is sea water sound speed. Here $f(\bar{i},\bar{i})$ and $\bar{i}$ denote respectively the forward scattering amplitude of target and the directional unit vector for the incidence wave.

To describe analytically σ_e for krill, I employ the model of bent cylinder [16, 17]. This model represents the recognised verified description of sound scattering by krill individual. On the basis of the formula for scattering amplitude for uniformly bent cylinder of constant radius of axis curvature (ρ_c), constant cross-sectional radius (a) and constant composition profile [16] the forward scattering amplitude $f(\bar{i},\bar{i})$ can be derived as:

$$f(\bar{i},\bar{i}) = -\frac{i}{\pi}\frac{l}{\gamma_{\max}}\int_0^{\gamma_{\max}} d\gamma \sum_{m=0}^{\infty} b_m \quad (4)$$

where $\gamma_{\max} = l / 2\rho_c$, l is total arc length of bent cylinder and coefficients b_m can be written in the following form:

$$b_m = -\frac{\varepsilon_m}{1 + iC_m} \quad (5)$$

where the Neumann factor $\varepsilon_m = 1$ for $m=0$, $\varepsilon_m = 2$ for $m>0$ and coefficients C_m can be expressed as:

$$C_m = \frac{[J_m'(k'a)N_m(ka)]/[J_m(k'a)J_m'(ka)] - gh[N_m'(ka)/J_m'(ka)]}{[J_m'(k'a)J_m(ka)]/[J_m(k'a)J_m'(ka)] - gh} \quad (6)$$

where $k = \kappa|\cos\gamma|$; $k' = k / h$, the functions $J_m(x)$, $N_m(x)$ denote the first kind Bessel functions and Neumann functions and $J_m'(x)$, $N_m'(x)$ are the first order derivatives of these functions over x. Here h and g describe sound speed and density contrast respectively.

The eqs. (4) - (6) are obtained under the following assumption: the angles of incidence and scattering cannot be too far off normal to the tangent of the cylinder axis [16]. These equations also do not consider the sound absorption in krill tissue (the employed Stanton's model does not take it into account). The problem of the absorption will be discussed below in last part of Section 3.

3. Calculations and Discussion

In this section we applied the above analytical expressions to calculate the extinction cross section of krill individual.

3.1 Extinction Cross Section for Various Krill Species

Evaluations of the extinction cross section are carried out for *Thysanoessa sp.* (in the range of body length l : 10 ÷ 25 mm), *M. norvegica* (l : 20 - 50 mm) and *E. superba* (l : 30 - 70 mm) at the frequencies 30, 50, 120, 270 and 420 kHz, used in acoustical measurements of krill abundance. For *Thysanoessa sp.* and *M. norvegica*, I employ the dependencies of the contrast parameters g and h on the length l presented in article [13]. For *E. superba* the analysis is carried out at the minimum (g = 1.029, h = 1.026) observed contrasts [3, 6, 8]. The calculations are made for krill aspect ratio $e = 1 / 15$ and $\rho_c / l = 2 / 1$ [14, 16]. The results are presented in Figs. 1 - 3.

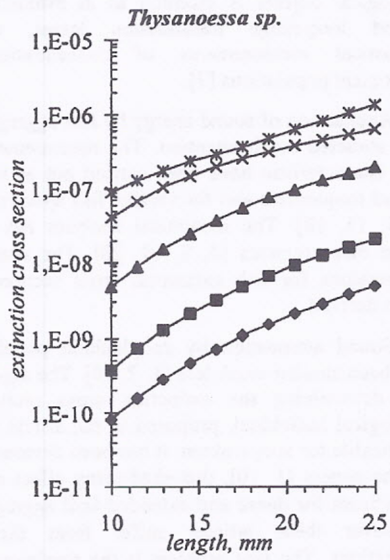

Fig. 1. Extinction cross section versus individual length for various frequencies (Thysanoessa sp.)

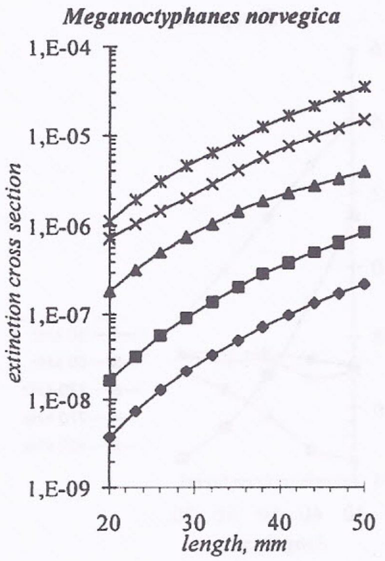

Fig. 2. Extinction cross section versus individual length for various frequencies (M. norvegica).

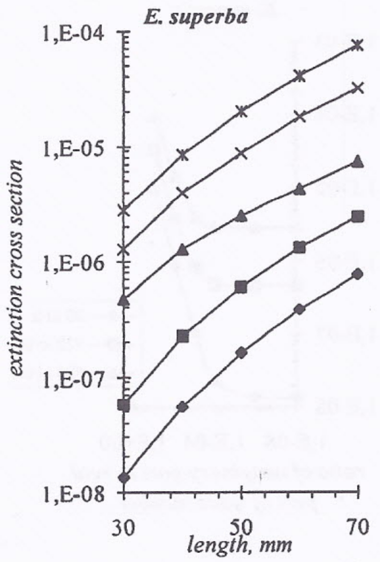

Fig. 3. Extinction cross section versus individual length for various frequencies (E. superba)

The parameter σ_e is presented in m^2 units. Five curves in the figures (from bottom to top) correspond to the frequencies 30, 50, 120, 270, 420 kHz. It is demonstrated that the extinction cross section increases for the longer krill individuals and larger sound frequencies.

3.2 Sensitivity Analysis on Krill Individual Parameters

The main problem, emphasised by many authors investigating sound scattering by krill, is lack of full information concerning characteristics of krill individuals. For example, information about the dependence of the contrast parameters g and h on the individual length l is available only for *Thysanoessa sp.* (in the range of body length l : 10 - 25 mm) and *M. norvegica* (l : 20 ÷ 50 mm) [12, 13]. However for *E. superba* only the dispersion of the contrasts for the limited length range is known [3, 6, 8]. The characteristics, important for scattering model, as the aspect ratio ($e = a / l$) and the ratio of radius of curvature of the cylinder axis to the arc length of the cylinder (ρ_c / l) are measured only for particular krill species [14]. The information about the absorption in zooplankton tissue is not readily available.

In this situation it is important to carry out the sensitivity analysis on the parameters that are less likely to be measured or known for krill. Figs. 4 - 6 give the results of this analysis.

Fig. 4 shows the relative difference of the extinction cross section for the maximum (g = 1.042, h = 1.030) and the minimum (g = 1.029, h = 1.026) observed contrasts for *E. superba* [3, 6, 8]. The contrast parameter changes, equalling to 1.26% for g and 0.4% for h, result in the 30 ÷ 60% variations of the extinction cross section. The extinction cross section variation is greater for smaller krill individuals and smaller sound frequencies.

Fig. 5 demonstrates the effect of changing the ratio of radius of curvature of the cylinder axis to the arc length of the cylinder (ρ_c / l) over the range from 2 / 1 to 0.5 / 1. This significant change of the ratio results in the 20 - 40% - variations of the extinction cross section. The variation depends on the sound frequency and individual body length.

In Fig. 6 I present the ratio of extinction cross section for e = 1 / 7.5 to the extinction cross section for e = 1 / 15. The extinction cross section of a wider target (ratio e = 1 / 7.5) is larger than that of a longer target with ratio e = 1 / 15.

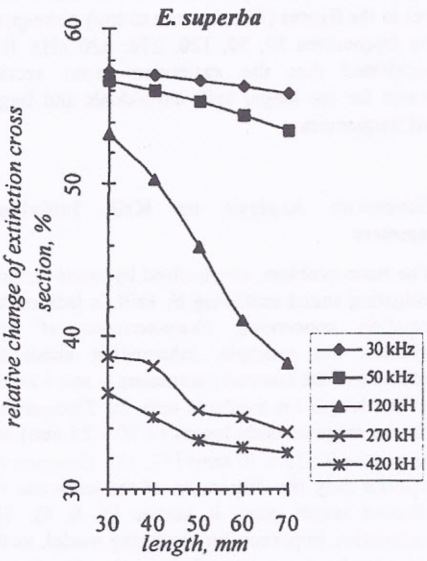

Fig. 4. Effect of changing sound speed and density contrasts on the extinction cross section for various sound frequencies (ρ_c / l = 2 / 1, e = 1 / 15).

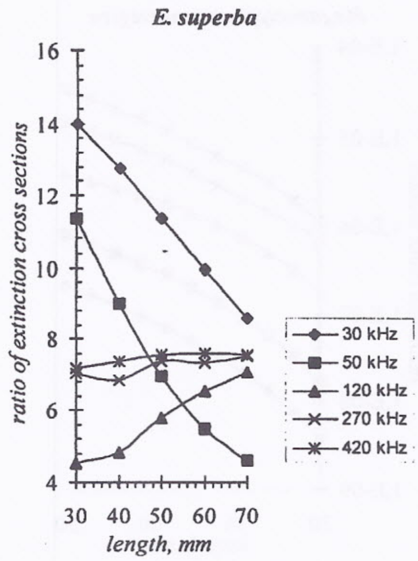

Fig. 6. Effect of changing aspect ratio on the extinction cross section (ρ_c / l = 2 / 1, minimum values of g and h for E. superba).

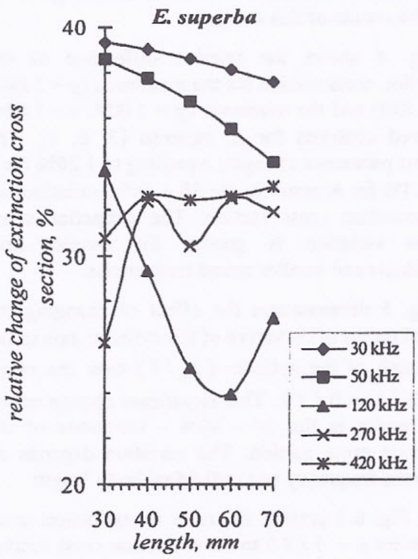

Fig. 5. Effect of changing the ratio ρ_c / l on the extinction cross section for various sound frequencies (e = 1 / 15, maximum values of g and h for E. superba).

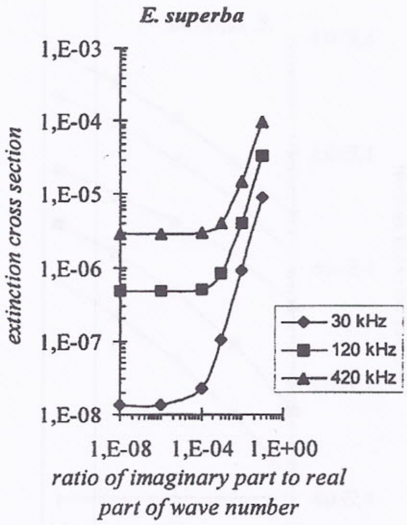

Fig. 7. Effect of absorption in krill tissue on the extinction cross section (m^2). 30 mm krill individual.

3.3 Influence of the Absorption on the Extinction Cross Section.

To evaluate the effect of sound absorption on the extinction cross section I replace the real wave numbers k' inside krill body (eq. (6)) by complex ones $k' = k'(1+i\varepsilon)$. Here ε describes the absorption in krill tissue. This replacement is applicable where the absorption is small and $\varepsilon \ll 1$. I think, that this inequality is satisfied for krill. Of course, the information on absorption in zooplankton tissue is not readily available and we do not know the accurate values of ε. However, following arguments prove that fluidlike animal can be considered as weakly absorbing:

(1) since acoustic properties of krill tissue and of ambient water are similar (g and h are close to 1), it can be presumed that their absorption is also similar. At considered frequencies the absorption in sea water is almost negligible;

(2) the observed strong regular pattern of backscattering target strength versus frequency [17] imply that fluidlike animal can be considered as weakly absorbing;

(3) Stanton's models for backscattering cross section for fluidlike zooplankton, neglecting the absorption, match the measured data [17].

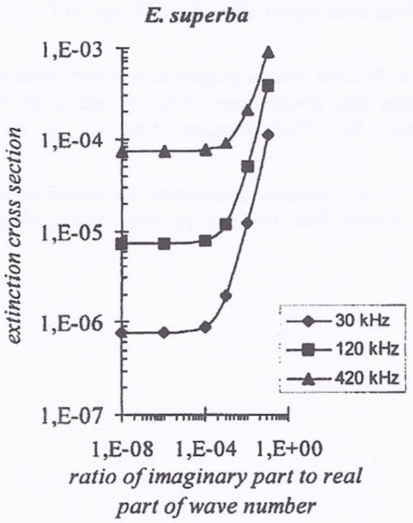

Fig. 8. Effect of absorption in krill tissue on the extinction cross section (m^2). 70 mm krill individual.

The effect of changing the absorption (the parameter ε) at various sound frequencies is shown in Figs. 7, 8 for a 30 mm and 70 mm krill individual respectively. The evaluations are made on the base of the equation (6) with complex wave numbers k' for the aspect ratio $e = 1/15$, the ratio $\rho_c / l = 2/1$ and minimum values of g and h for *E. superba*. The relative variations of extinction cross section are in the range $10 - 10^3$ due to the change of the parameter ε over the range from 0 to 0,1. The comparison of the results presented in these figures indicates, that the absorption influence is more significant for smaller organisms, for which the scattering is weaker.

The evaluation shows, that the extinction cross section is not sensitive to the ε - changes for ε smaller than 10^{-4}. In this ε - range the variation of the extinction cross section is less, than 15% for 70 mm krill individual.

4. Conclusions

A theoretical study of the extinction cross section of krill is presented in this paper. The analytical formulae for this characteristic are obtained on the basis of the optical theorem and Stanton's model, describing the scattering at krill individual.

The evaluations of the extinction cross section are made for *Thysanoessa sp.*, *M. norvegica* and *E. superba*. The dependence of this characteristics on the sound frequency and krill individual parameters is demonstrated.

I carried out the sensitivity analysis on the parameters: sound speed and mass dense contrasts, aspect ratio, the ratio of radius of curvature of the cylinder axis to the arc length of the cylinder (ρ_c / l). This analysis is especially important because of the lack of full information concerning these parameters. My calculations indicate that extinction cross section is sensitive to these characteristics. The accurate data for them are important in investigating the attenuation effect in zooplankton aggregation This situation is similar to the situation for backscattering by zooplankton aggregation for which many researchers [14] also proved the sensitivity of the backscattering cross section of zooplankton individuals to the parameters: $g, h, e, \rho_c / l$.

The influence of sound absorption in krill tissue on the extinction cross section is demonstrated. This effect is more significant for smaller organisms, which scatter sound weaker.

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