ON ACOUSTIC BACKSCATTERING BY BALTIC ZOOPLANKTON

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Zooplankton is an important part of Baltic ecosystem and ecosystem-based management requires productivity assessment of the region what involves zooplankton identification and abundance estimation. Acoustics is recognized as a reliable monitoring method. Thus, the ability of understanding of backscattering by zooplankton becomes a priority. It was the main motivation of the paper. The main approach is based on (i) the numerical modeling of acoustic backscattering by the typical representative of Baltic zooplankton, mysids and (ii) comparison of the theoretical results with the measured acoustic data. The Modal Based Deformed Wave Born Approximation (MB-DWBA) model was employed. The readily available biologic data for mysids were used. The sensitivity of the backscattering to acoustic frequency, individual size, width of orientation distribution and acoustic properties of biologic tissue was analyzed. The results of modeling were verified using the measured acoustic and biologic data collected in August 2003 in the Swedish coastal zone near Stockholm.

INTRODUCTION

Baltic zooplankton, being at or near the bottom of the food chain, is a significant part of the Baltic ecosystem (ICES. 2005 Report of the Study Group on Baltic Sea Productivity Issues in Support of the BSRP (SGPROD)). The zooplankton is a prey for commercially important fish, like, for example Baltic herring and sprat, and it competes with fish for food, what significantly impacts on the fish population dynamics (Viherluoto, 2001; ICES. 2005

Report of the Study Group on Baltic Sea Productivity Issues in Support of the BSRP (SGPROD)). Thus, the abundance estimation of Baltic zooplankton is important.

Despite that non-destructive and rapid acoustics is recognized as the reliable assessment method (Simmonds and McLennan, 2005), in the Baltic Sea it was used mainly in assessment of fish not zooplankton (Didrikas and Hansson, 2004; Orłowski, 2001; 2003; 2004; Peltonen and Balk, 2005). That is the reason of lack of the information about the Baltic zooplankton scattering characteristics. However, to explain the echo sounder data and to develop the zooplankton identification algorithms, it is required to improve the understanding of the backscattering by Baltic zooplankton. This motivates that the study of Baltic zooplankton backscattering characteristics is a priority.

Theoretical scattering models are recognized as primary tool for interpreting zooplankton echoes (Simmonds and MacLennan, 2005). Thus, our approach includes (i) the numerical modeling of acoustic backscattering by the typical representative of Baltic zooplankton and (ii) comparison of the obtained theoretical results with the available measured acoustic data. Main dominants of Baltic zooplankton are crustaceans (Szymelfenig and Urbański et all., 1998). Mysids, as an important representatives of crustaceans (Margoński and Maciejewska, 1999; Viherluoto, 2001, Witek, 1995), became an objective of this study.

The Modal Based Deformed Wave Born Approximation (MB-DWBA) model was applied. The readily available biologic data and the experimental biologic data for mysids were used as input modeling data (Materials and methods section). The sensitivity of the backscattering to acoustic frequency, individual size, width of orientation distribution and acoustic properties of biologic tissue was analyzed. The obtained modeling results were compared with the measured acoustic data (Results and discussion).

1. MATERIALS AND METHODS

Main backscattering equation

The Modal Based Deformed Wave Born Approximation (MB-DWBA) model for finite length deformed cylinders was used to describe backscattering by zooplankton individuals (Stanton and Chu, 2000). This model is assumed to be applicable because: (i) mysid body has a cross-section that can be described, to first order, as circular; (ii) mysids can be referred to as weak scattering targets because their material properties are similar to those of the surrounding water.

Assuming also that the material properties vary only axially, zooplankton individual backscattering length can be expressed as (see Equation (6) in Stanton and Chu, 2000) the one-dimensional integral along the body axis:

$$f_{bs} = \frac{k}{4} \int_{\vec{r}_{pos}} a\left(\gamma_\kappa - \gamma_\rho\right) \exp\left(2i(\vec{k}_i)_1 \cdot \vec{r}_{pos}\right) \frac{J_1\left(2k_1 a \cos\beta\right)}{\cos\beta} \left|d\vec{r}_{pos}\right| \qquad (1)$$

where the parameters k and k_1 are the acoustic wavenumbers in surrounding water and inside the body, respectively. $\vec{r}_{pos}$ denotes the position vector of the body axis and $a = a(\vec{r}_{pos})$ is a cross-section radius. The terms γ_κ and γ_ρ are related to the density and sound-speed contrasts (g and h, respectively) of the body (Morse and Ingard, 1968). The contrasts are described as $g = \rho_1/\rho$, $h = c_1/c$, where ρ and c are the mass density and sound-speed of the surrounding fluid and the subscript 1 refers to these parameters in body medium. $(\vec{k}_i)_1$ describes the incident wavenumber vector evaluated inside the body. J_1 is the Bessel function of the first kind of order one. The angle β is the angle between $\vec{k}_i$ and the thin disc of cross-section of the body at the point $\vec{r}_{pos}$ (Figure 1).

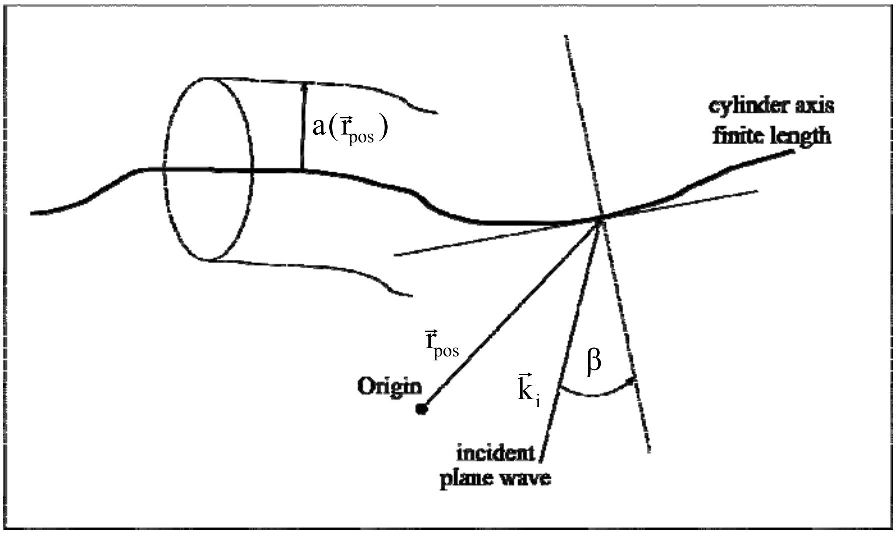

Fig.1 Scattering geometry

In the paper we study:

(i) the target strength TS of individual zooplankton (Medwin and Clay, 1998):

$$TS = 10\log|f_{bs}|^2 = 10\log\sigma_{bs} \qquad (2)$$

where σ_{bs} is individual backscattering cross-section and f_{bs} describes individual backscattering length,

(ii) the backscattering cross-section of zooplankton individual $<\sigma_{bsc}>$ averaged over the ensemble of zooplankton aggregation realizations differing in animal orientation (this characteristic is important in study of scattering by aggregated animals). It can be expressed as:

$$<\sigma_{bsc}> = \int W(\beta)|f_{bs}|^2 d\beta \qquad (3)$$

where the brackets $<\ldots>$ denote the average and the function $W(\beta)$ represents probability density function (PDF) of zooplankton orientation distribution,

(iii) the reduced target strength RTS of individual zooplankton:

$$RTS = 10\log\left(\frac{<\sigma_{bs}>}{L^2}\right) \qquad (4)$$

where L denotes animal length,

(iv) the volume backscattering strength S_V (Simmondes and MacLennan, 2005).

The numerical analysis in the next sections are based on the equations (1) – (4).

Modeling parameters

Acoustic backscattering is a complex function of the geometric shape of individual body, the tissue material properties, the animal orientation in space, and the acoustic frequency (Medwin and Clay, 1998; Medwin *et all.*, 2005; Simmonds and MacLennan, 2005). Using the readily available data and the biologic mysid data, collected by the Department of

Systems Ecology of the Stockholm University (the experiment is described below), the following input modeling parameters are taken:

Animal size and acoustic frequency

In this paper three acoustic frequencies, f, 70 kHz, 200 kHz and 420 kHz, used in zooplankton study, are considered. The individual length range is estimated based on sampling permitted in Swedish coastal zone and the length varies from 3 mm to 28 mm. It corresponds to the variation of ka parameter from 0.05 to 3.2. (k is acoustic wavenumber in surrounding water and a is characteristic cross-section radius of the animal body). Parameter ka, controlling the scattering, varies within the Rayleigh scattering region and within the transition zone between Rayleigh and Geometric scattering regions.

Animal morphology (material properties and shape)

In this study the acoustic properties of the mysid tissue are assumed homogeneous. Zooplankton density and sound speed contrasts, g and h, vary over wide range (Medwin and Clay, 1998, Medwin *et all.*, 2005; Simmonds and MacLennan, 2005), but for crustaceans they take values within 1-2% of 1.04 for each of the contrasts (Stanton and Chu, 2000). Regarding to that, the range of g and h varying from 1.02 to 1.06 is considered.

Straight cylinder is used to present the shape of mysid body ($a = a(\vec{r}_{pos}) = \mathrm{const}$, cylinder axis is straight). The aspect ratio, describing the elongation of the mysid body, $e = L/a$, is set to 16 based on Conti *et all.* (2005).

Orientation distribution

Averaging of the echoes over a range of orientations requires knowledge of the orientation distribution of the scatterers (Medwin and Clay, 1998; Medwin *et all.*, 2005; Simmonds and MacLennan, 2005). Very little information is available regarding the orientation distribution of zooplankton (Chu et all., 1993; Endo, 1993; Foote et all., 1990; Kils, 1982; Miyashita, 1996; Stanton *et all.*, 1993; Stanton and Chu, 2000). It was demonstrated that the modeling results, obtained basing on the Gaussian orientation distribution of zooplankton, fit to the measured data (Stanton *et all.*, 1993). Thus, the Gaussian distribution is assumed. The PDF function can be expressed as:

$$W(\beta) = \frac{1}{\sqrt{2\pi}S_\beta} \exp\left(\frac{-(\beta - \bar{\beta})^2}{2S_\beta^2} \right) \qquad (5)$$

where $\bar{\beta}$ and S_β are respectively: the mean orientation angle and the standard deviation of the Gaussian orientation distribution. Given the lack of available information in the averaging process for the Baltic zooplankton, $\bar{\beta}$ is set to 0 (horizontal orientation) and the S_β varies over the range from 2° to 30°.

Zooplankton concentration

To compute volume backscattering strength, zooplankton aggregation densities are taken from Kotta and Kotta (2001a), Kotta and Kotta (2001b) and Margoński and Maciejewska (1999). The concentration varies from 0.04 ind·m^{-3} to 2946 ind·m^{-3}. This value strongly depends on the environment conditions and the productivity of the region, where the data were collected, what is the reason of wide variation of the aggregation densities. However, usually concentration does not exceed 20 ind·m^{-3} (Kotta and Kotta, 2001b, Margoński and Maciejewska, 1999).

Experimental data

The experimental acoustic and biologic data were collected on 12th August 2003 in the Swedish coastal zone near Stockholm (r/v “Marika”). The station, in which the biological sampling was taken, was at the position 58 55.973 N, 17 43.617 E with bottom depth ~50 m. The acoustic measurements were performed using two synchronized EY500 Simrad systems working at 200 kHz (master, single beam) and 70 kHz (slave, split beam). Sampling was made using the vertical net with the opening diameter of 1 m^2 and mesh size 0.5 mm. The haul was taken from 50 m depth (bottom) to the surface. Species composition was complex with main domination of mysids (*Mysis mixta, Mysis relicta* and *Neomysis integer*). Length of the animals varied from 3 mm to 28 mm.

2. RESULTS AND DISCUSSION

The analysis of the sensitivity to bio-acoustic parameters is made for backscattering characteristics of individual and aggregated zooplankton (mean-backscattering cross-section).

Backscattering by zooplankton individual. Sensitivity to the orientation

Modeled target strength, TS, of individual zooplankton animal is presented versus individual orientation angle at frequencies: 70 kHz, 200 kHz and 420 kHz in Figures 2a, b and c, respectively. The backscattering predictions correspond to mysid of 20-mm-length with homogenous tissue acoustic properties: density contrast and sound-speed contrasts are set to g = h = 1.04. The other parameters are as discussed in the MATERIALS AND METHODS. Figures demonstrate very strong dependence on orientation: in the considered orientation range the target strength varies from -130 dB to -80 dB, from -132 dB to -66 dB and from -142 dB to -70 dB at frequencies: 70 kHz, 200 kHz and 420 kHz, respectively.

Comparison of the plots confirms that the width of the lobes of the directivity pattern and their number are controlled by the acoustic frequency. For the higher frequency the individual lobe width is smaller and number of the lobes is larger. The TS maximum value of lobes decreases monotonically with the increasing $|\beta|$ at the frequencies 70 kHz and 200 kHz. Much more complicated dependence is observed at the frequency 420 kHz. There is the minimum of the lobe TS maximum values at the angle $\beta = \pm 27.5°$.

Echoes averaged over orientation. Sensitivity to the orientation distribution

The results presented on the Figure 3, are designed to study the influence of the standard deviation S_β on the mean-backscattering cross-section. The calculations of the RTS are made for the mean angle of orientation $\bar{\beta} = 0°$ and uniform morphology of mysid: the contrasts are set to g = h = 1.04. The other parameters are as discussed above. The regions corresponding to the different acoustic frequencies are indicated in the plot.

It is demonstrated that in the Rayleigh scattering region (ka < 0.2) the reduced target strength is not sensitive to the standard deviation. This region corresponds to the acoustic frequency not larger than 70 kHz and the individual length smaller than 10 mm. Figure 3 shows that at the larger ka, the RTS increases with the standard deviation decreasing.

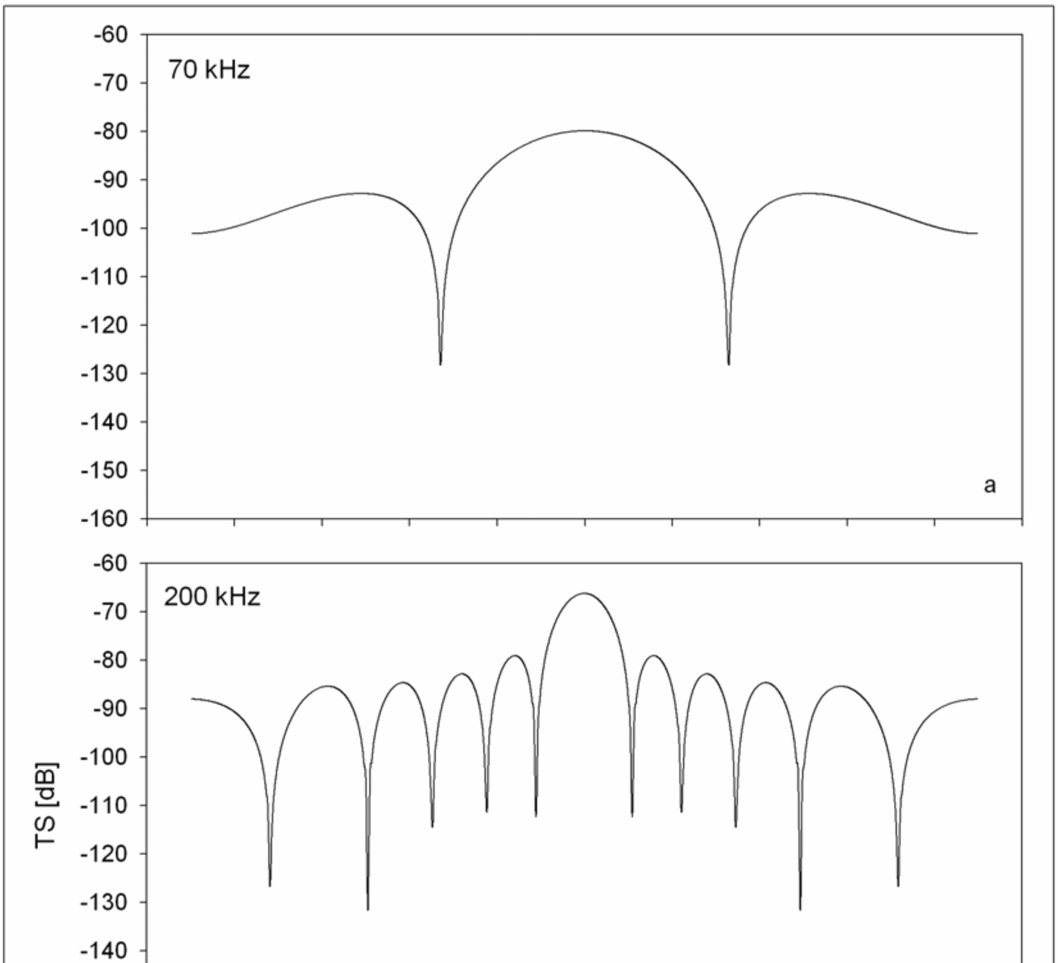

Fig.2 Directivity pattern of individual 20-mm-long mysid

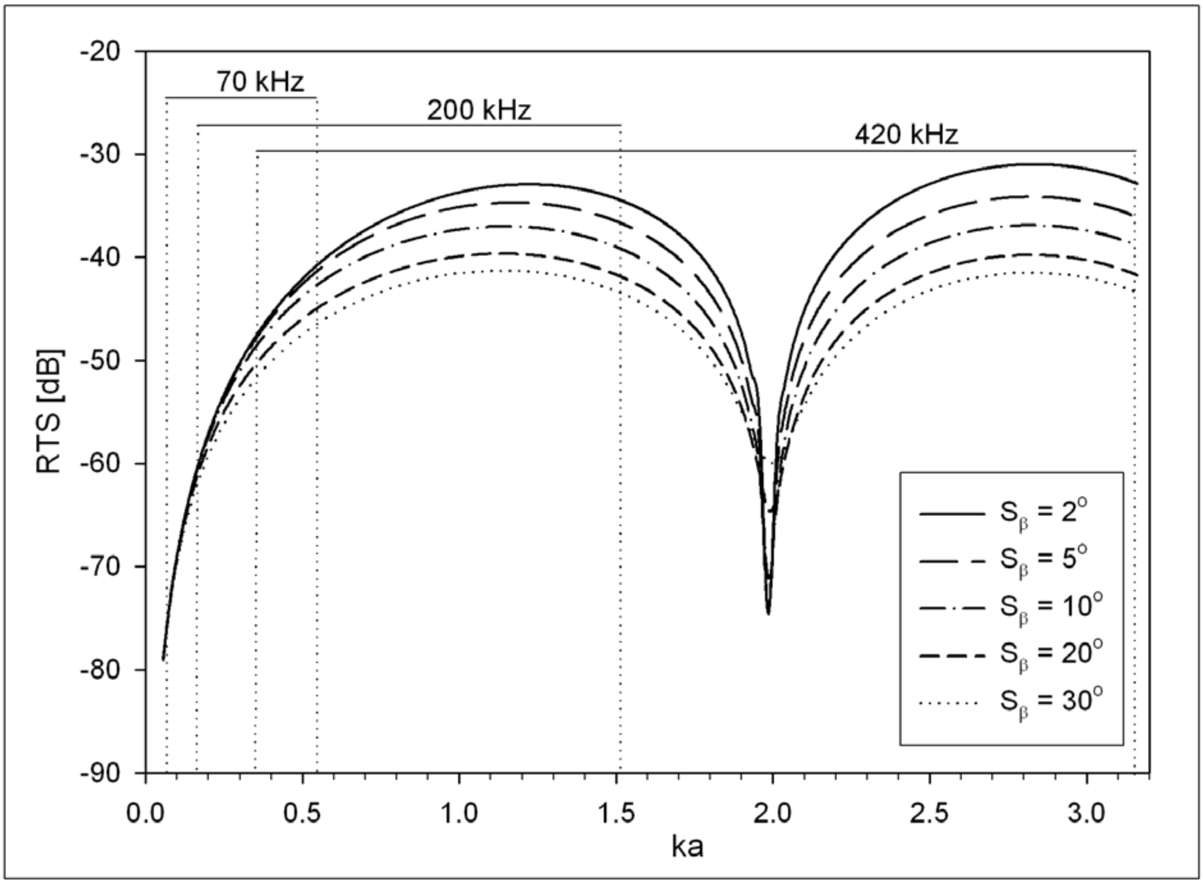

Fig.3 Reduced target strength RTS vs. ka parameter at the different standard deviation S_β

Echoes averaged over orientation. Sensitivity to the material properties

Figure 4 shows the sensitivity of the reduced target strength to the density and sound-speed contrasts and the standard deviation of the Gaussian orientation distribution. The regions corresponding to the different acoustic frequencies are indicated. The calculations were made at $S_\beta = 10°$ and $S_\beta = 20°$ (red and blue color in the figure, respectively). The different curves correspond to the different contrasts as it is shown in the legend. The other parameters are as discussed in the MATERIALS AND METHODS.

The figure demonstrates that for both orientation distributions the curve shapes are similar but the reduced target strength is higher at $S_\beta = 10°$. The calculations show significant RTS variability (up to 13 dB) over the range of the contrasts. The reduced target strength increases with the contrast (g and h) increasing. The RTS is very sensitive to the material properties over the entire ka range, while the influence of the standard deviation is not significant at low ka ($ka < 0.2$).

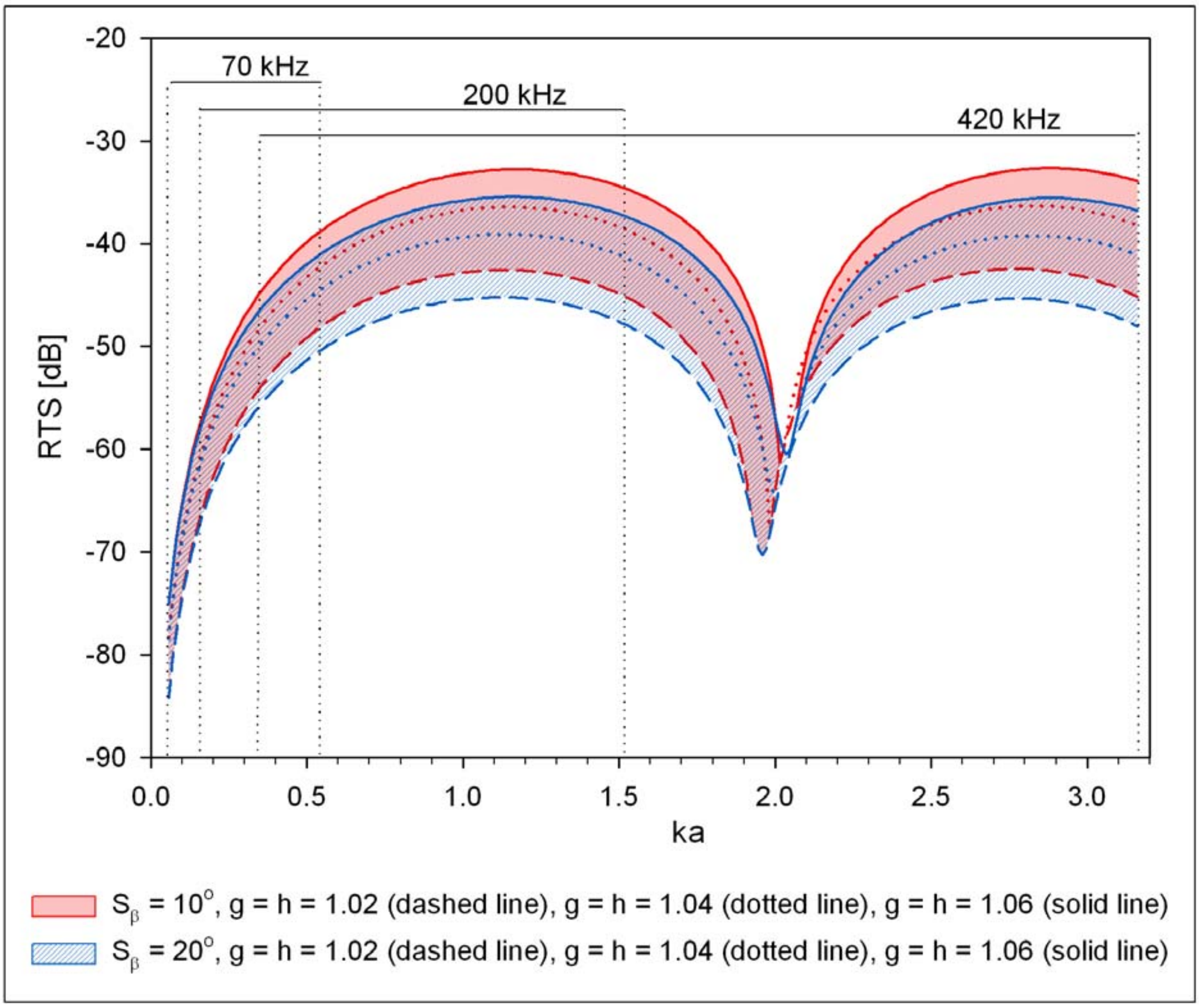

Fig.4 Reduced target strength vs. ka parameter. Sensitivity to the sound-speed and density contrasts for two different zooplankton orientation distributions

Echoes averaged over orientation. Volume backscattering strength prediction

The calculations of volume backscattering strength were performed using the following equation :

$$S_V = 10\log(<\sigma_{bs}> N) \qquad (6)$$

where N is the zooplankton concentration.

Predictions of the volume backscattering strength for mysids aggregations are made at the frequencies: 70 kHz, 200 kHz and 420 kHz. The results are presented in the Figures 5a, b, c, respectively. In each plot three curves, corresponding to the concentrations: 2496 ind·m^{-3} (dotted line), 20 ind·m^{-3} (solid line) and 0.04 ind·m^{-3} (dashed line), are presented. The standard deviation of the Gaussian orientation distribution S_β = 10° and mean angle of orientation $\bar{\beta} = 0°$ are used. The contrasts are set to g = h = 1.06 to evaluate the “top” values of the volume backscattering strength for mysids. The other parameters are as discussed in the MATERIALS AND METHODS.

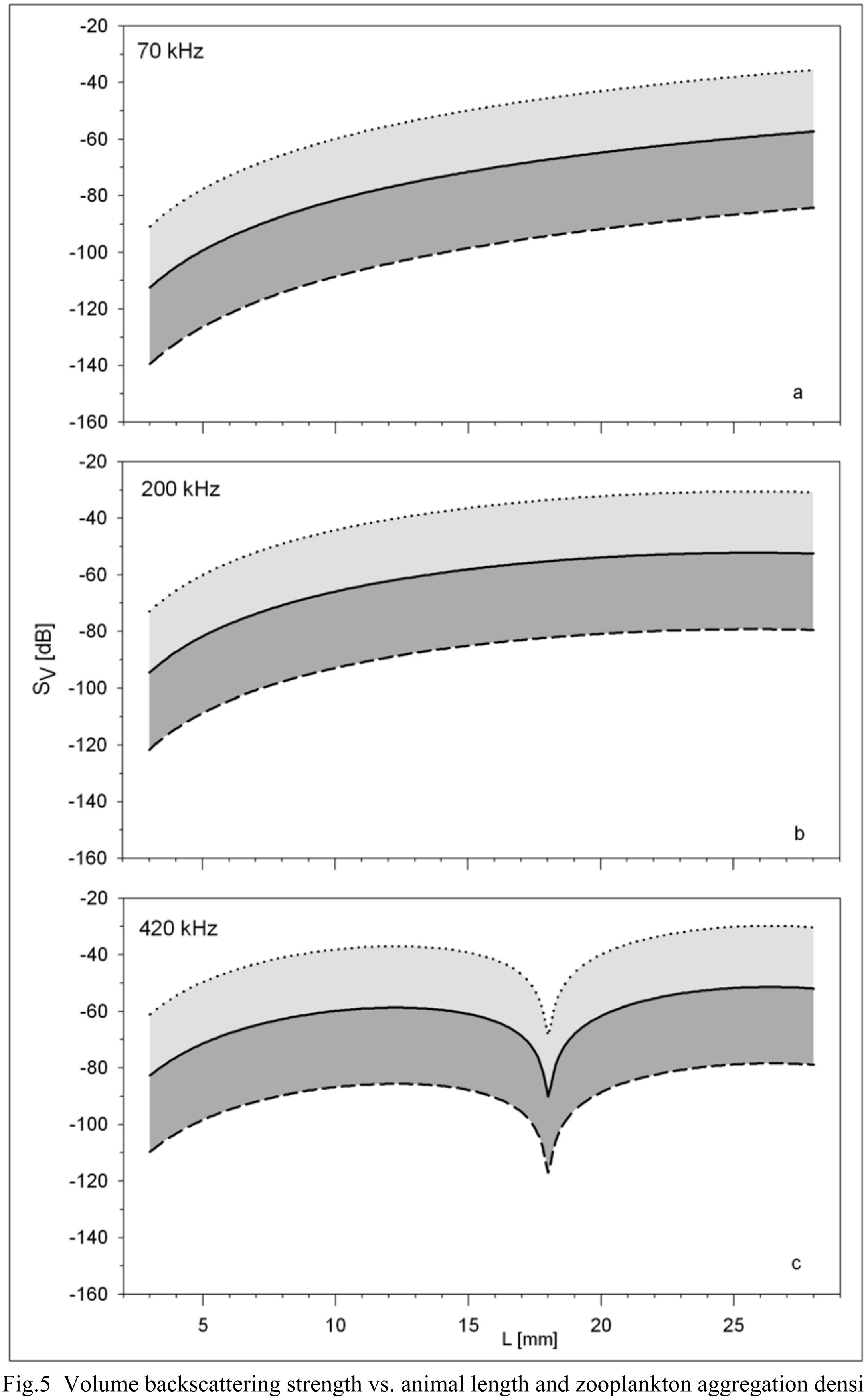

Fig.5 Volume backscattering strength vs. animal length and zooplankton aggregation density

The volume backscattering strength, increases with the aggregation density, acoustic frequency and animal body length. Its ranges vary from -139 dB to -36 dB, from -122 dB to -31 dB and from -117 dB to -30 dB at acoustic frequencies: 70 kHz, 200 kHz and 420 kHz, respectively. It is important to remark that typically the mysid concentration does not exceed 20 ind·m^{-3}. The domain of S_V variability corresponding to this concentration range is marked by dark grey in the plots.

Comparison modeling results with the measured acoustic data

The comparison of the modeling results with the acoustic data, collected by the Stockholm University, is presented in Figure 6. The measured volume backscattering strength for Baltic mysids varies from -90 dB to -75 dB (solid vertical line) and from -85 dB and -70 dB (dashed vertical line) at two used acoustic frequencies: 70 kHz and 200 kHz, respectively.

The calculations were made based on the measured Swedish biologic experimental data. Volume backscattering strength is calculated using the following equation:

$$S_V = 10\log\left(\sum_m < \sigma_{bs} >_m N_m\right) \qquad (7)$$

where N_m and $<\sigma_{bs}>_m$ describes respectively concentration and mean-backscattering cross-section of animals in the mysid length class number m.

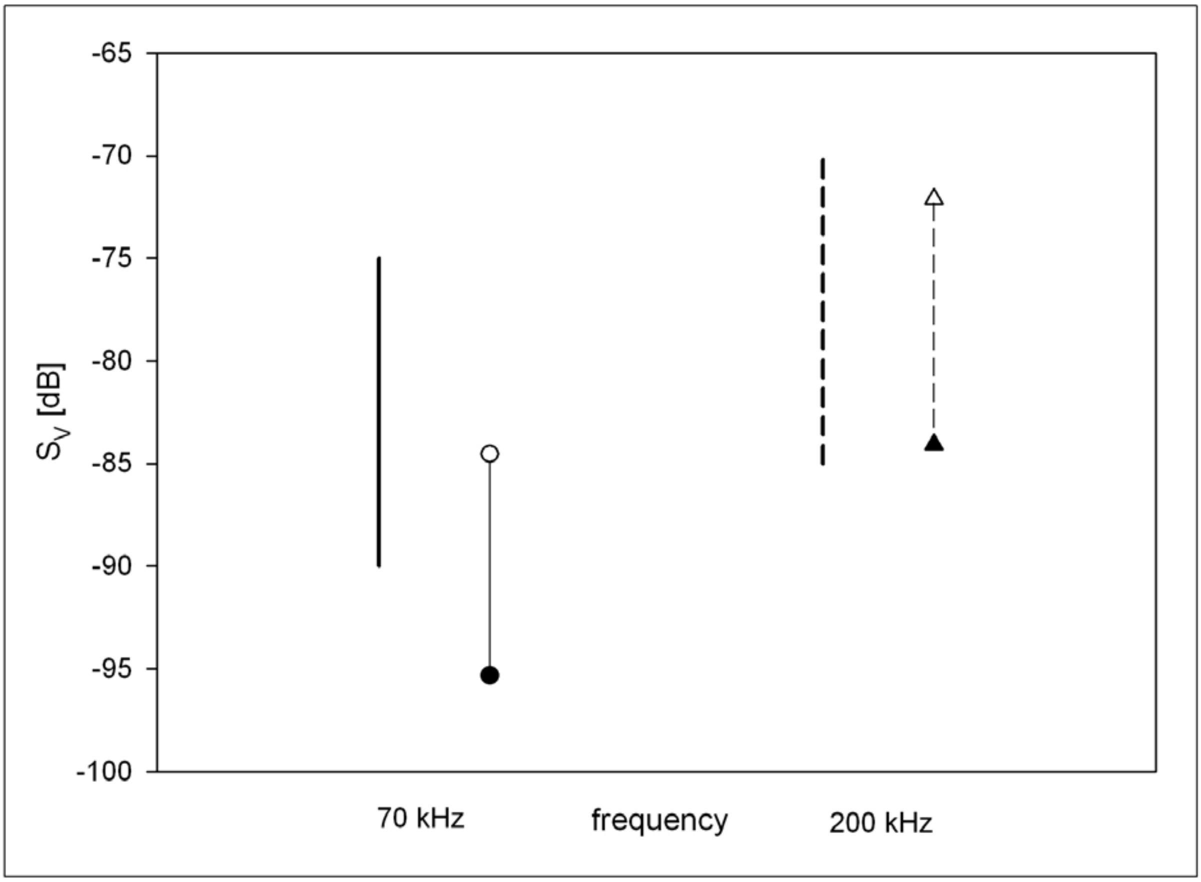

Fig.6 Comparison of the modeling results with the experimental data

Accounting for:

(i) the lack of data on the Baltic mysids sound-speed and density contrast and the animal orientations and

(ii) the backscattering sensitivity to these parameters (see results of the analysis, presented above)

it is reasonable to evaluate the range of possible variability of the volume backscattering strength. Taking into account that the backscattering increases with the growth of the density and sound-speed contrasts and with the decrease of the width of zooplankton orientation distribution, the “top” and “bottom” values of the variability range of the volume backscattering strength were evaluated. The highest S_V is obtained for $g = h = 1.06$ and $S_\beta = 10°$. They are indicated by empty circle (○) and triangle (Δ) for 70 kHz and 200 kHz, respectively. The lowest S_V are calculated for $g = h = 1.02$ and $S_\beta = 20°$. They are presented by dark circle (●) and triangle (▲) for 70 kHz and 200 kHz, respectively. The lines, joining the circles and the triangles indicate the calculated variability range of volume backscattering strength at 70 kHz and 200kHz, respectively.

Figure 6 demonstrates the good agreement between the measured and the calculated results. It suggests that the MB-DWDA model for finite length deformed cylinders is useful for study acoustic backscattering at Baltic mysids, which are the typical representatives of Baltic crustaceans.

3. CONCLUSIONS

The backscattering characteristics of Baltic mysids were analyzed using numerical modeling and comparison of the obtained results with the measured backscattering data. The detailed sensitivity analysis in regard to the bio-acoustic characteristics was made. It has been shown that for Baltic zooplankton:

(i) the target strength of the individual strongly depends on its orientation,
(ii) in case of aggregated animals (mean-backscattering characteristics) the reduced target strength is sensitive to the width of the Gaussian orientation distribution excluding the Rayleigh scattering region,
(iii) the reduced target strength strongly depends on the material properties over the entire ka range.

As the backscattering is sensitive to the animal orientation distribution and to the sound-speed and density contrast of mysid tissue the further investigation of these characteristics is suggested. Better knowledge on these may greatly improve the modeling results.

Accounting for that the present model is based on a simplified geometry of the mysid body and that the backscattering depends on the structure of the scatterer, the detailed mysid morphology is recommended to be considered.

This study results in a better understanding of the backscattering by Baltic zooplankton. It would be the basis of the improvement the acoustic data interpretation and the further development of the acoustic zooplankton assessment methods. Being essential for the acoustic monitoring it would cause better understanding of the Baltic Sea ecosystem.

4. LIST OF SYMBOLS

$a = a(\vec{r}_{pos})$	cross-section radius
β	angle of orientation – between the direction of incidence and the cross-section of the body at the point $\vec{r}_{pos}$
$\bar{\beta}$	mean orientation angle
c	sound-speed in surrounding water
c_1	sound-speed inside the body
e	aspect ratio of the animal
f	carrier frequency of sound
f_{bs}	backscattering length
$g = \rho_1/\rho$	density contrast
$h = c_1/c$	sound-speed contrast
i	$\sqrt{-1}$
$J_1(\ )$	Bessel function of the first kind of order one
k	acoustic wavenumber in surrounding water
k_1	acoustic wavenumber inside the body
$\vec{k}_i$	incident plane wave vector
$(\vec{k}_i)_1$	incident wavenumber vector evaluated inside the body
L	length of an individual
N	zooplankton concentration
N_m	zooplankton concentration of animal length class number m
$\vec{r}_{pos}$	position vector of the body axis
RTS	reduced target strength

ρ	mass density of surrounding water
ρ_1	mass density of animal tissue
S_β	standard deviation of the Gaussian orientation distribution
S_V	volume backscattering strength
σ_{bs}	backscattering cross-section
$<\sigma_{bs}>$	mean-backscattering cross-section
$<\sigma_{bs}>_m$	mean-backscattering cross-section of animal length class number m
TS	target strength
$W(\beta)$	probability density function (PDF)

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