ON THE ACOUSTIC BACKSCATTERING BY BALTIC HERRING AND SPRAT

NATALIA GORSKA, JAKUB IDCZAK

Institute of Oceanography, University of Gdańsk
Marszałka Piłsudskiego 46, PL-81378 Gdynia, Poland
natalia.gorska@univ.gda.pl, kubid@wp.pl

Accurate abundance estimate of Baltic clupeids, herring and sprat, is required for their sustainable exploitation. The understanding the sound backscattering of individual fish is important for employing the acoustical techniques, which are widely used in the estimation. The previous studies demonstrated that the improvement of the understanding is critical for the Baltic herring and sprat. It was the main motivation of the paper. The main objective was understanding the difference in acoustic backscattering by herring and sprat in the Baltic Sea. The study was based on a numerical modeling of backscattering by the individual fish. The model input data (morphometric parameters of fish) are obtained using available X-ray images of Baltic sprat and herring. The difference in the backscattered energy, backscattering directivity pattern, and the body contribution into the backscattering of the total fish was demonstrated for the considered species.

INTRODUCTION

Herring and sprat are the key elements of the pelagic ecosystem of the Baltic Sea (Raid and Kaljuste, 2005) and the economically valuable species. To manage the resources of these two species reasonably, their abundance monitoring is required. The acoustic monitoring method is recognized as effective because of the relatively quick and not invasive collection of data from large areas. The dependence of the fish backscattering characteristics, target strength (*TS*) on its total length (*L*): *TS(L)*, is important in using the acoustical assessment technique. This dependence is required in the conversion of the collected acoustic data (echo energy) into the biological data (fish abundance or biomass).

Currently the same empirical dependencies *TS(L)* are used to estimate the biomass of both species: herring and sprat. It would be reasonable, if the backscattering properties of both species are the same. Previous theoretical (Gorska, 2007; Fässler *et al.*, 2008; Fässler and Gorska, 2009) and experimental research (Rudstam *et al.*, 1988, 1999; ICES, 2000; Didrikas and Hansson, 2004; Didrikas, 2005; Peltonen and Balk, 2005; Kasatkina, 2007) indicated that the dependencies *TS(L)* for herring and sprat are different. The difference in the backscattering properties of herring and sprat has not been explained yet completely and the further study is reasonable.

The main motivation of the paper is understanding the difference in mechanisms of backscattering by herring and sprat in the Baltic Sea. The study is based on a numerical modeling of acoustic waves backscattered by an individual fish (the model is described in Section 1.1). The model input data, such as the fish morphometric parameters, were determined on the basis of the X-ray images of twenty one sprat individuals and twenty five herring individuals (Section 1.2). The difference in the backscattering of acoustic waves by the herring and sprat in the Baltic Sea is discussed in the Section 2.

1. MATERIALS AND METHODS

1.1. MODEL DESCRIPTION

Backscattering by the fish body

To describe shape of the fish body a simple geometric form – straight cylinder was used. The model of Stanton (1989) („high-pass model") was applied to calculate backscattering cross-section of fluid-like straight cylinder. In the model backscattering cross-section of the fish body (σ_{bs}^{b}) is described by the following equation:

$$\sigma_{bs}^{b} = \frac{\frac{1}{4} L_{st}{}^{2} (Ka)^{4} \alpha_{\pi c}^{2} s^{2} G}{1 + [\pi (Ka)^{3} \alpha_{\pi c}^{2}]/(R^{2} F)}, \tag{1}$$

where

$$\alpha_{\pi c} = \frac{1 - gh^{2}}{2gh^{2}} + \frac{1-g}{1+g},$$

$$R = \frac{gh-1}{gh+1},$$

g and h are the density and sound speed contrasts of fish flesh respectively, $G = F = 1$, L_{st} describes standard length of fish and a denotes half the width of the fish (cylindrical radius of straight cylinder). Backscattering cross-section σ_{bs}^{b} depends on the fish orientation (Figure 1) through the following terms:

$$K = k \sin\theta, \tag{2}$$

and

$$s = \frac{\sin(kL_{st} \cos\theta)}{kL_{st} \cos\theta}, \tag{3}$$

where the angle θ is the angle between the axes of the cylinder (fish body) and the incident acoustic wave. Here $k = \frac{2\pi f}{c}$, k is the acoustic wavenumber, f denotes wave frequency and c describes speed of sound in the surrounding sea water. The equation is applicable over entire range of the parameter ka.

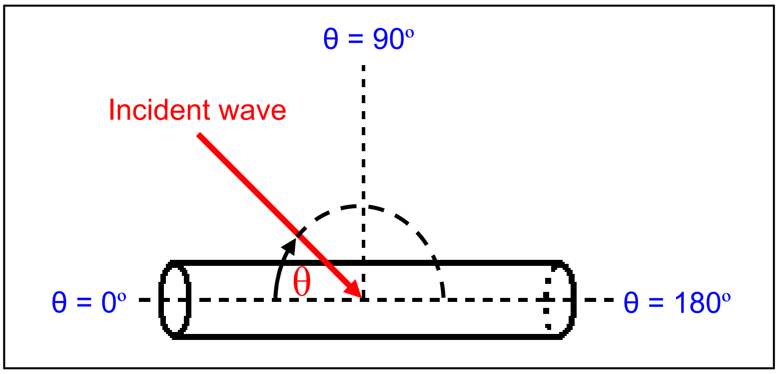

Fig.1. The geometry of the backscattering of acoustic wave at fish body

<u>Backscattering by the fish swimbladder</u>

To determine the amount of energy reflected back from the swimbladder a different model was used, because the swimbladder is an organ whose acoustic impedance differs significantly from the surrounding sea water impedance. The shape of the swimbladder was described as an prolate spheroid. The model was developed by Stanton and Chu (their presentation at the Acoustic Backscattering Workshop, Friday Harbor, USA, 2008).

The backscattering cross-section of the fish swimbladder (σ_{bs}^{sb}) can be expressed as:

$$\sigma_{bs}^{sb} = \frac{\frac{1}{h_{sb}^{2}}\left(\frac{L_{sb}}{2}\right)^{2}\left(\frac{w_{sb}}{2}\right)^{2}}{\left(\left(\frac{L_{sb}}{h_{sb}}\right)^{2}\cos^{2}\theta_{sb} + \sin^{2}\theta_{sb}\right)^{2}}, \tag{4}$$

Here h_{sb} is the height of swimbladder, w_{sb} describes the width of the swimbladder, L_{sb} denotes the length of the swimbladder, θ_{sb} is the angle between the axis of the swimbladder and the direction of the incident wave (Figure 2). The equation (Eq. 4) is accurate for ka_{sb} greater than 0.1 (the Kirchhoff scattering approximation). Here $a_{sb} = \frac{w_{sb}}{2}$ (Figure 2).

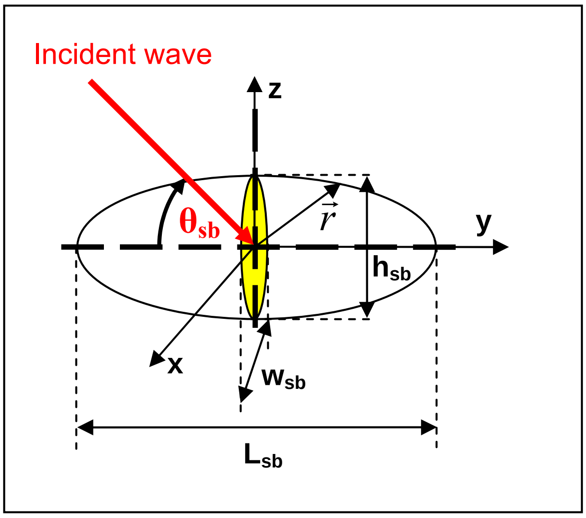

Fig.2. The geometry of the backscattering of acoustic wave at swimbladder

Backscattering by the fish body and swimbladder

Using the equations (Eqs. (1) and (4)) for the backscattering cross-section of the fish body (σ_{bs}^{b}) and swimbladder (σ_{bs}^{sb}) the cross-section of the whole fish (σ_{bs}) can be calculated as:

$$\sigma_{bs} = \sigma_{bs}^{b} + \sigma_{bs}^{sb} . \tag{5}$$

The target strength *TS* (Simmonds and MacLennan, 2005) can be expressed as:

$$TS = 10\log(\sigma_{bs}^{b} + \sigma_{bs}^{sb}) . \tag{6}$$

1.2. INPUT DATA TO THE MODEL

For the calculation of the backscattering cross-section of the fish body σ_{bs}^{b} and the swimbladder σ_{bs}^{sb} the fish morphologic data are required. The fish used in this study were collected during the cruise of Nils Håkansson and Fredrik Arrhenius (National Board of Fisheries, Lysekil, Sweden), held in October 2002 near the north-east coast of the Sweden. The stations are marked by the dark blue points on the study area map presented in Figure 3.

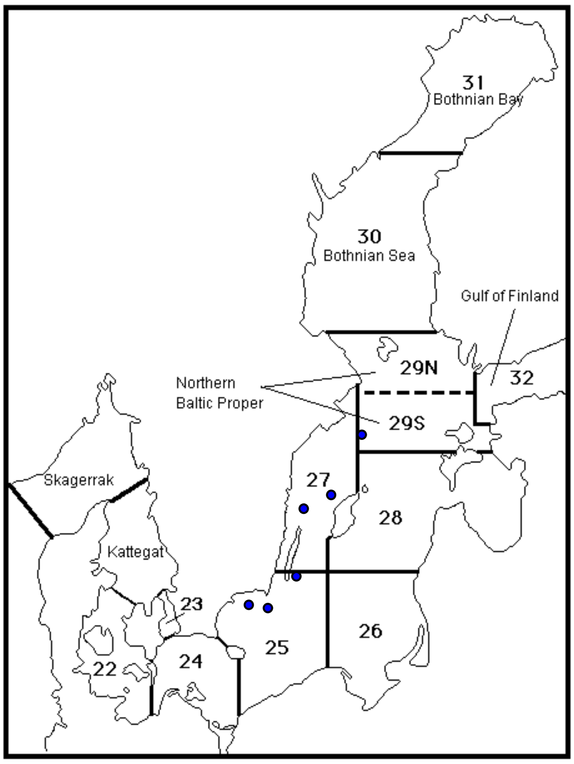

Fig.3. Study area

The X-ray images of the collected fish were done in the Swedish Museum of Natural History in Stockholm. Subsequently, the best quality images of the twenty five herring individuals and twenty one sprat individuals were selected and the length, width and height of the body and swimbladder were measured (Fässler and Gorska, 2009).

2. RESULTS AND DISCUSSION

2.1. MORPHOMETRY OF BALTIC HERRING AND SPRAT

The dependence of the ratios h_{sb}/L and w_{sb}/L on the fish total length (L) is presented in Figures 4 and 5 respectively for twenty five herring individuals (red points and line) and twenty one sprat individuals (blue points and line). Solid lines correspond to the regression logarithmic dependencies.

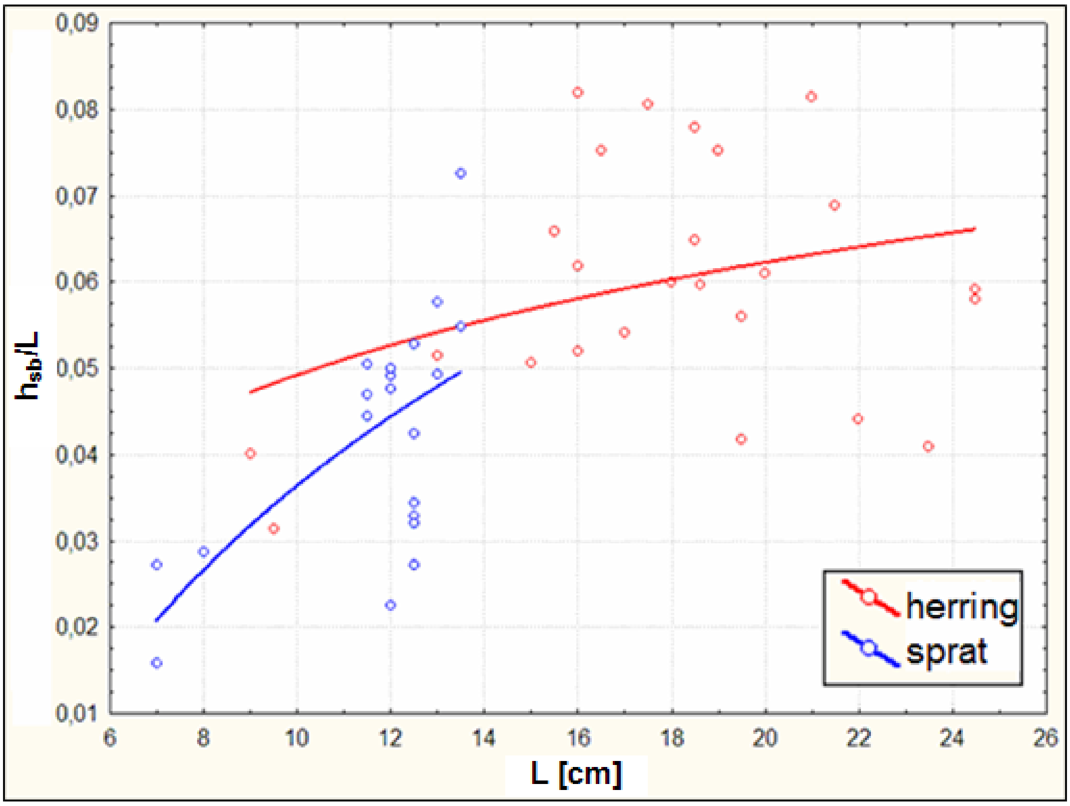

Fig.4. Morphometric characteristics of the swimbladder (dependence h_{sb}/L on L) of herring and sprat

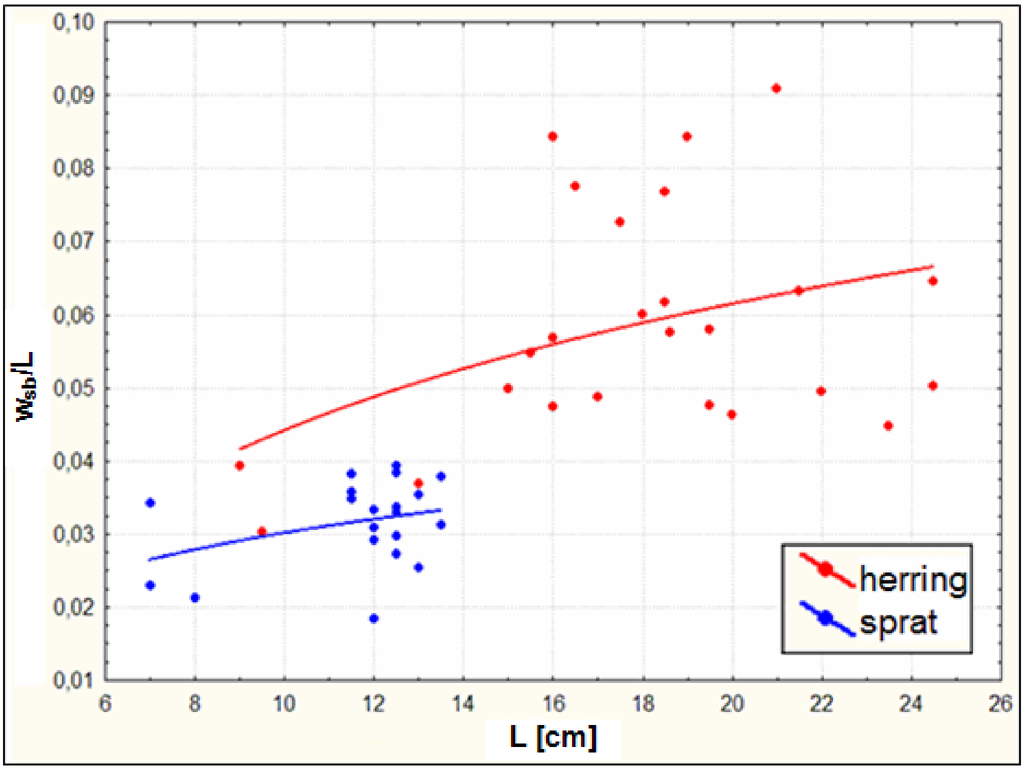

Fig.5. Morphometric characteristics of the swimbladder (dependence w_{sb}/L on L) of herring and sprat

The Figures 4 and 5 demonstrate that the both ratios h_{sb}/L and w_{sb}/L for sprat are smaller than for herring of the same total length. The study also shows (the result is not presented graphically here) that the swimbladder lengths of the herring and sprat of the same total length are comparable.

Another important factor controlling the backscattering by the whole fish individual is the shift of the axes of the body and swimbladder (they are not parallel). Shift angle α for each individual was estimated using the fish X-ray images. The dependencies of the shift angle on the total fish length are presented in Figure 6 for herring and sprat (marked respectively by red and blue colours). The mean shift angles and its standard deviations are indicated by the solid lines.

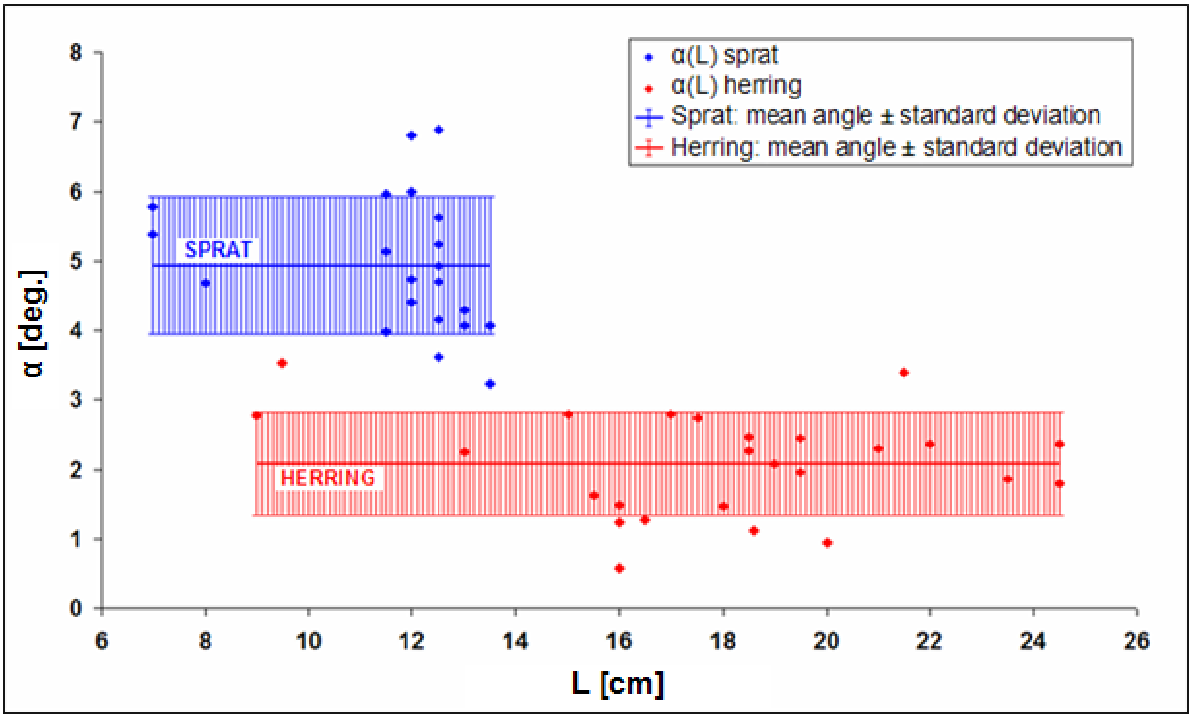

Fig.6. The dependencies of the shift angle α on the total fish length (L) for herring and sprat

It can be noted that the mean shift angle is smaller for herring than for sprat.

In the next section the calculations of the backscattering characteristics were done using the morphometric data described above on the basis of the equations (Eqs. (1) – (6)). Sound speed and density contrasts $h = g = 1.04$ and the sea water sound speed $c = 1450$ m/s were used in the calculations. The computations were made for fish occupying the near-surface layer and for the acoustic frequency $f = 38$ kHz.

2.2. ACOUSTIC CHARACTERISTICS OF HERRING AND SPRAT IN THE BALTIC SEA

Relationship TS(L) for Baltic herring and sprat

The dependence of the target strength *TS* on the fish total length *L*, is presented in the Figure 7 for the Baltic herring and sprat. The broadside incidence of the acoustic wave,

$\theta = 90°$ (Figure 1), was considered. The calculation results were indicated by red and blue dots for herring and sprat respectively. Regression lines of TS vs. total L (in cm) of the form $TS = m \log_{10} L + b_m$ were fitted to the modelled data for herring and sprat (respectively red and blue lines in the figure). The regression lines are described by the equations:

$$TS = 24.49 \log_{10} L - 69.31, \tag{7}$$

$$TS = 26.07 \log_{10} L - 74.59, \tag{8}$$

for herring and sprat respectively. The yellow regression line refers to the dataset, joining the computational data for herring and sprat. It can be expressed as:

$$TS = 34.17 \log_{10} L - 82.17 . \tag{9}$$

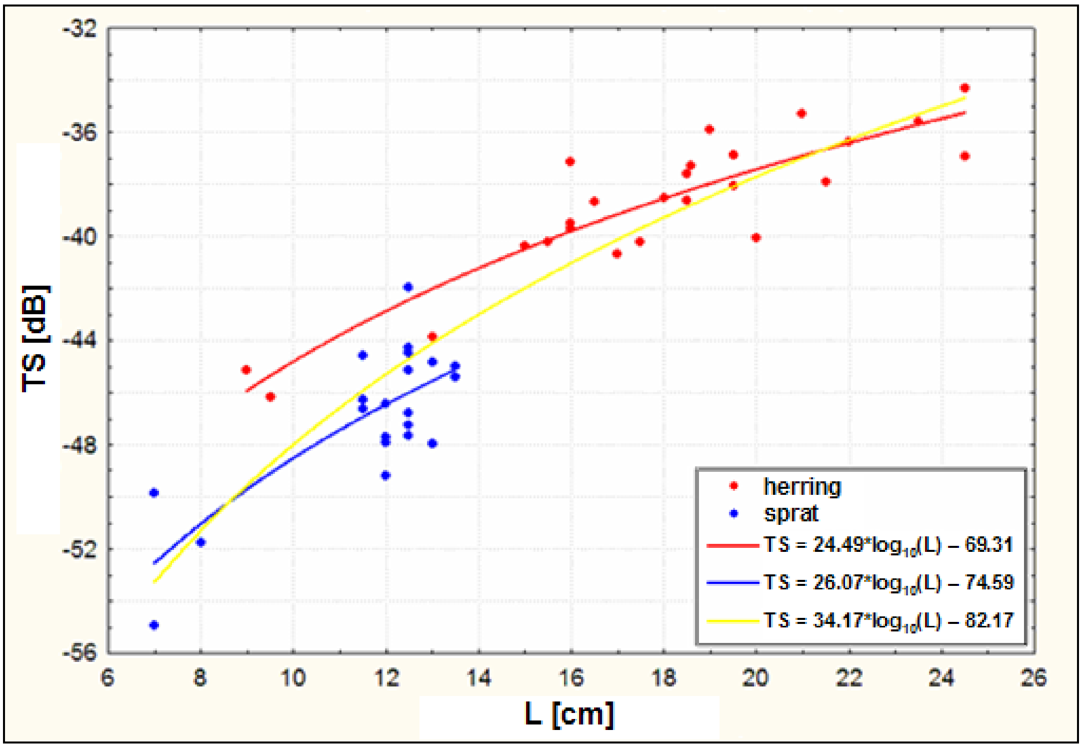

Fig.7. *TS(L)* dependence for Baltic herring and sprat

The calculations demonstrate about 4 dB – shift between the regression lines for herring and sprat. The regression line is located higher for herring than for sprat. If the relationship (Eq. (7)) obtained for herring was applied to estimate sprat abundance, sprat biomass would be underestimated. Conversely, if the relationship (Eq. (8)) for sprat were used in herring abundance estimation, it would result in an overestimation of herring biomass. Observed difference in TS between herring and sprat can be explained by the different morphologies of these two species. Comparison of the red and blue regression lines in the both Figures 4 and 5 demonstrated that the width and height of a Baltic herring swimbladder are larger than those of a sprat swimbladder for fish individuals of the same length. The measurements of the shift angles α between axis of body and fish swimbladder (Figure 6) show larger values for sprat than for herring. These two factors provided that the insonified swimbladder volume and dorsal-aspect area, which control the backscatter of the fish, are larger for herring than for sprat. The result is a larger *TS* for herring than for sprat individuals of the same length. Comparing the yellow regression lines with the red and blue lines it was concluded that the use of the regression relationship (Eq. (9)), fitted to the joint dataset, is not correct in the both herring and sprat abundance estimation.

<u>Directivity pattern of individual herring and sprat</u>

The dependence of the width of the backscattering directivity function of total fish individual ($\Delta\theta_{3dB}$) on the fish total length L was generated (Figure 8). The width $\Delta\theta_{3dB}$ was determined at the level 3 dB below the maximum value of the fish directivity pattern $TS(\theta)$. The results of the calculations for fish individuals are presented in the figure by red and blue points for herring and sprat respectively. The solid lines correspond to the logarithmic regression relationships fitted respectively to herring and sprat modelled data.

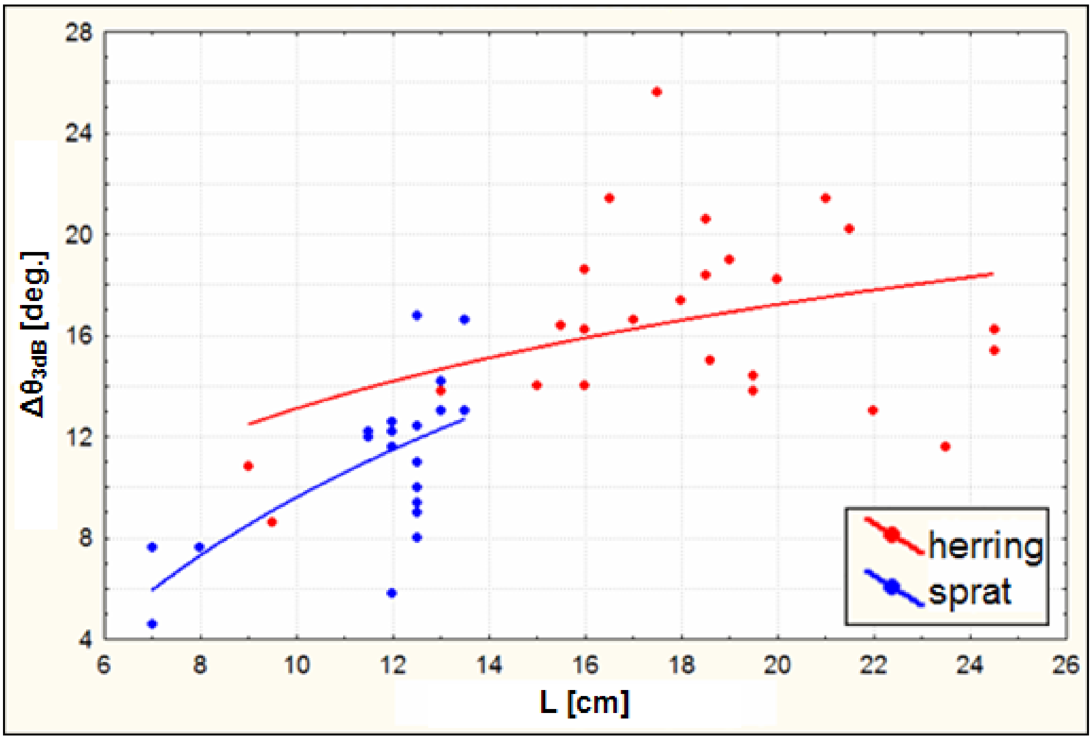

Fig.8. Dependence of the width of directivity function on the total length of fish L

Figure 8 shows that the width of directivity function increases with fish length. It is explained by the Kirchhoff backscattering at the surface of swimbladder which dominates the total backscattering by fish individual. The morphometry of the surface controls the Kirchhoff backscattering. Using equation (Eq. (4)) for backscattering cross-section of swimbladder, it can be shown that the directivity function width increases with decrease of the parameter L_{sb}/h_{sb}. The analysis of the morphometric data of herring and sprat demonstrated that this parameter decreases with the fish total length. It results in the width increase with the length.

<u>Fish body contribution into the total backscattering by herring and sprat</u>

To estimate how much backscattering energy comes back from the fish body, the ratio of fish body backscattering cross-section (σ_{bs}^{b}) to the swimbladder backscattering cross-section (σ_{bs}^{sb}) was calculated at different angles θ (Figure 1). Figure 9 was generated for three selected fish: one herring and two sprat individuals, the total length of which is presented in the legend. It was assumed that the shift angle α is 6° for all three individuals.

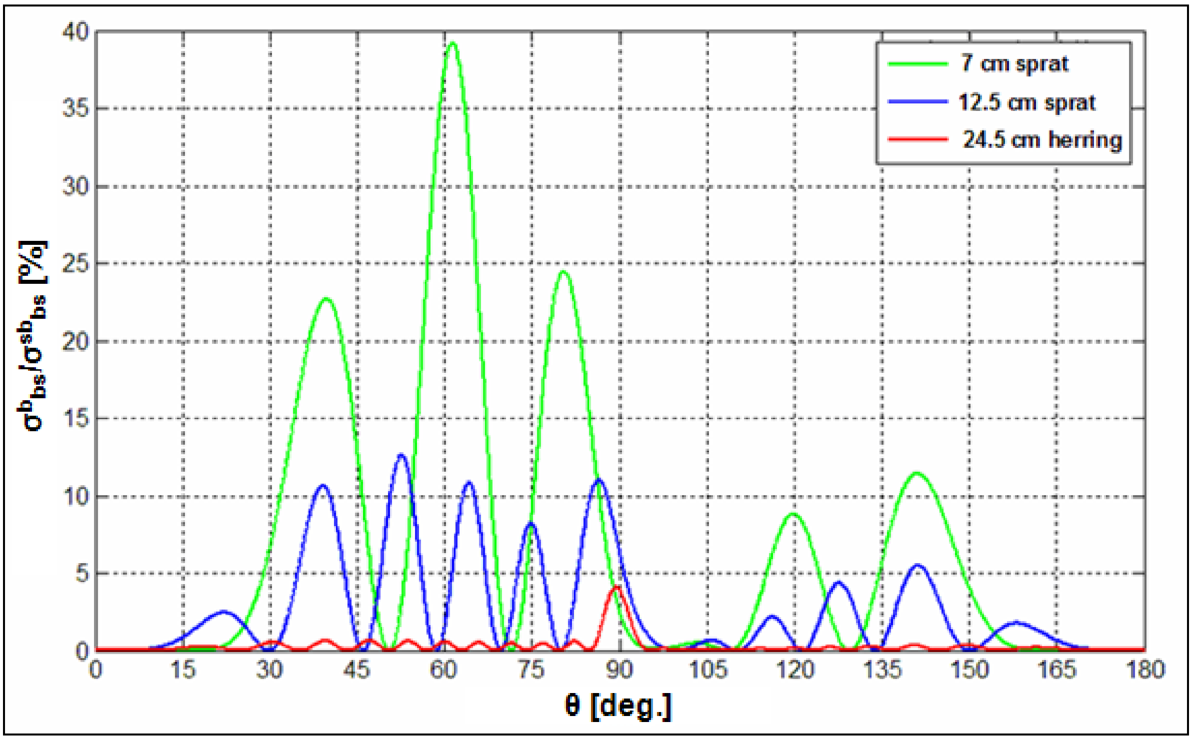

Fig.9. Dependence of the ratio $\sigma_{bs}^{b} / \sigma_{bs}^{sb}$ on the angle θ (Figure 1)

Figure 9 shows that for the broadside incidence the impact of body on the total backscattering by fish individual is small. However, in the case of not broadside incidence the impact may be significant: the ratio $\sigma_{bs}^{b} / \sigma_{bs}^{sb}$ can achieve 40% for fish of 7 cm total length. The fish body impact is more important for the smaller fish (green curve).

Figure 10 presents the dependencies of the ratio of the fish body backscattering cross-section (σ_{bs}^{b}) to the swimbladder backscattering cross-section (σ_{bs}^{sb}) on the fish total length (L), for the herring (red dots) and sprat (blue dots). Figure 10 has been generated using the morphometric data of the selected twenty five herring individuals and twenty one sprat individuals, on the basis of the equations (Eqs. (1) – (6)). Other calculation parameters are also the same as used for Figures 7 and 8. The case of sound broadside incidence was considered. The regression lines (logarithmic and exponential for herring and sprat respectively) are marked by the appropriate colour.

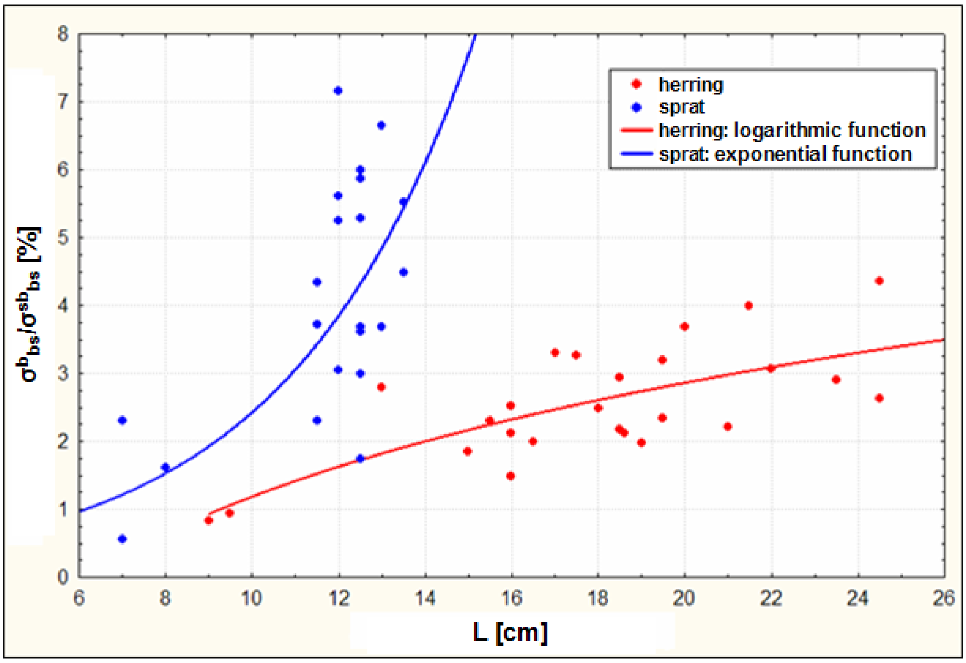

Fig.10. Dependence of the ratio $\sigma_{bs}^{b} / \sigma_{bs}^{sb}$ on the fish total length (L) for herring and sprat

Figure 10 demonstrates the difference in the dependence of the ratio $\sigma_{bs}^{b} / \sigma_{bs}^{sb}$ on the fish total length for herring and sprat. The calculations show that the impact of fish body is more significant for sprat than for herring.

3. CONCLUSIONS

In order to understand the differences in the backscattering of acoustic waves by herring and sprat numerical modelling of acoustic wave scattered by an individual fish was performed. The backscattering by herring and sprat in the Baltic Sea was modelled using morphometric data obtained analysing the available X-ray images of Baltic herring and sprat. The impact of the morphometry difference between herring and sprat on their backscattering properties was studied.

The following important results were obtained:

1. Basing on the fish X-ray images it has been demonstrated that the shift angle between the axis of fish swimbladder and body is smaller for herring than for sprat of the same length.
2. It has been shown that the difference in the morphometry of herring and sprat, including the difference in the swimbladder geometric dimensions and in the shift angles between the axis directions of fish body and swimbladder, is responsible for larger herring *TS*.
3. The different regression relationships have been obtained for herring and sprat. They can be expressed by the equations: $TS = 24.49\log_{10} L - 69.31$ and $TS = 26.07\log_{10} L - 74.59$ for herring and sprat respectively.
4. It has been also demonstrated that these two relationships are different from *TS(L)* fitted to the dataset in which the modelled data for the both species were joined. The relationship can be expressed as $TS = 34.17\log_{10} L - 82.17$.

5. The impact of the fish orientation and fish length on the fish body contribution into the total backscattering by fish has been studied. The sensitivity analysis shown that the contribution is more important for smaller fish and not broadside incidence of the acoustic wave. It has been demonstrated that the contribution is larger for sprat than for herring.
6. The interesting result for the backscattering directivity pattern of fish individual has been obtained. The width of the directivity function increases with fish total length in the considered case of Kirchhoff scattering. The physical justification was done.

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