Modelling of acoustic backscattering by southern Baltic herring

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Assessment of Baltic herring abundance can be carried out using acoustic techniques. Analysis of the relationship between the Baltic herring individual target strength, TS, and the total fish length, L, important for the acoustic assessment, showed the relationship to be dependent on the location of the study area. This finding motivated a detailed analysis of the relationship for the herring occurring in the southern Baltic ICES subdivisions 24, 25, and 26, in which Poland is responsible for the acoustic herring abundance assessment. The paper addresses the numerical analysis of the backscattering properties of the southern Baltic herring. The modelling approach used to study the backscattering was based on the Modal Series-Based Deformed Cylinder Model approximation. Details of the individual herring swimbladders were taken into account. Morphometric data necessary for the analysis was obtained from X-ray images of herring from the Polish coastal zone (ICES subdivision 26).

Keywords: acoustic biomass estimation, Baltic herring, target strength, modelling approach, X-ray images

1. Introduction

As an aid in effective Baltic clupeid resource management, remote acoustic methods are used in the fish abundance assessment. These methods are innovative as they make it possible to cost-effectively, non-invasively, and relatively fast to collect acoustic data from large areas (ICES Reports 2004, 2005a, b, 2006). Application of an acoustic technique in fish resource assessment requires information on the *TS(L)* relationship, i.e., the relationship between the size of the fish (*L*) and its backscattering characteristic (target strength, *TS*). The relationship is used to convert acoustic information to biological data (fish abundance and biomass) (MacLennan and Simmonds, 1992).

Acoustic assessments of the Baltic herring and sprat biomasses use *TS(L)* conversion factors recommended by ICES, and derived from data on Norwegian Sea fish. The *TS(L)* relationship in the Baltic Sea has been determined from *in situ* measurements (Rudstam et al., 1988, 1999; ICES, 2000; Didrikas and Hansson, 2004; Didrikas, 2005; Peltonen and Balk, 2005; Kasatkina, 2009) and from numerical modelling performed to aid in interpretation of the measurement results (Gorska, 2007; Fässler et al., 2008; Fässler and Gorska, 2009; Gorska and Idczak, 2010). The studies referred to showed large discrepancies in target strength (up to 8 dB) for fish at a certain size in different seasons, in different parts of the Baltic Sea, and with different methodology of acoustic and biological data collection and processing. In addition, the *TS* values for the Baltic fish proved higher than those recommended by ICES. Therefore, it is important to study the *TS(L)* relationship in subareas of the southern Baltic where Poland is responsible for the fish resource assessment in accordance with the international ICES convention (*ICES subdivisions 24, 25, 26*). According to recommendations issued by ICES Working Group on Fisheries Acoustics Science and Technology (*ICES WGFAST*), numerical modelling of acoustic backscatter should be conducted for the southern Baltic herring and sprat. Given that acoustic backscattering is significantly dependent on the shape of the swimbladder of individual fish (Blaxter and Batty, 1990), the detailed swimbladder shape of clupeids occurring in the area should be taken into account whilst modelling.

The paper presents results of studies on the backscatter properties of herring in the Polish coastal zone (*ICES subdivision 26*), obtained from numerical modelling of acoustic backscatter on individual herring, with due consideration to the detailed shapes of the fish body and swimbladder.

2. Materials and methods

2.1. Model description

The description of acoustic backscatter on the body and swimbladder of a fish, treated as objects with advanced shapes, is based on the *Modal-Series-Based Deformed Cylinder Model* (MSB-DCM) developed by Stanton (1988, 1989). The model made it possible to derive a solution with which to calculate the backscattering amplitude on an individual herring body (f_{bs}^{b}) and swimbladder (f_{bs}^{sb}). The model applies a cylinder of finite length and a cross-section radius varying along the axis. Information on the variability of swimbladder radius along the organ's main axis was derived from fish X-ray images. The corresponding variability of the body radius was retrieved from the biological materials collected. The modelling assumes that the cylinder (the body and/or the swimbladder) axis is a straight line. Under such assumptions, the Stanton model is simplified to:

$$f_{bs}^{b}(\theta_b) = -\frac{i}{\pi} L_b \int_0^1 \sum_{m=0}^{\infty} b_m^b (-1)^m \times \exp[2ikx_b \cos\theta_b]\, d\mu_b \tag{1}$$

for the fish body and

$$f_{bs}^{sb}(\theta_{sb}) = -\frac{i}{\pi} L_{sb} \int_0^1 \sum_{m=0}^{\infty} b_m^{sb} (-1)^m \times \exp[2ikx_{sb} \cos\theta_{sb}]\, d\mu_{sb}\ , \tag{2}$$

for the swimbladder, where: L_b, L_{sb} are fish body length and swimbladder length, respectively; k is the wave number ($= 2\pi f / c$, where c is the sound propagation velocity in seawater, and

f is the acoustic wave frequency). The variables $\mu_b = x_b / L_b$ and $\mu_{sb} = x_{sb} / L_{sb}$, where x_b and x_{sb} are distances along the main axis of the deformed cylinder (the fish body and swimbladder, respectively). The angles θ_b and θ_{sb} are the angles between the direction of the acoustic wave incidence onto the scattering target and the axes of the fish body and the swimbladder, respectively (Fig. 1).

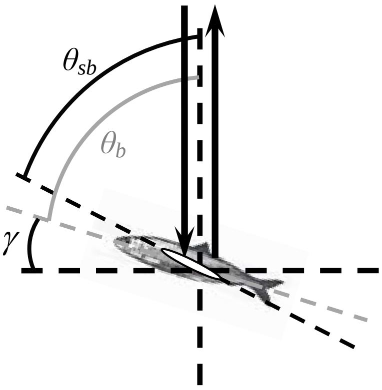

Fig. 1. Geometry of acoustic wave scattering on the fish body and swimbladder.

In equations (1) and (2) the modal coefficient b_m is described by the equation:

$$b_m = -\frac{\varepsilon_m}{1 + iC_m}, \tag{3}$$

where $\varepsilon_m = 1$ for $m = 0$ and $\varepsilon_m = 2$ for $m > 0$.
The coefficient C_m is defined by the equation:

$$C_m = \frac{[J'_m(K'a)N_m(Ka)]/[J_m(K'a)J'_m(Ka)] - gh[N'_m(Ka)/J'_m(Ka)]}{[J'_m(K'a)J_m(Ka)]/[J_m(K'a)J'_m(Ka)] - gh}, \tag{4}$$

where, for the fish body, $C_m = C_m^b$, $a = a_b$ is a half of the body width, dependent on the coordinate x_b; by analogy, for the swimbladder: $C_m = C_m^{sb}$, $a = a_{sb}$ and is dependent on the coordinate x_{sb}. Here $K = \frac{2\pi f}{c}\sin\theta$ and $K' = \frac{K}{h}$ - inside the scattering object, where $K = K_b$, $\theta = \theta_b$ for the fish body and $K = K_{sb}$, $\theta = \theta_{sb}$ for the swimbladder. The sound velocity contrast h is defined by the ratio of sound propagation velocity in a scattering object and the sound propagation velocity in the seawater; the density contrast g is a ratio of a scattering object density to the ambient seawater density ($h = h_b$, $g = g_b$ for the fish body and $h = h_{sb}$, $g = g_{sb}$ for the swimbladder). Functions denoted as $J_m(X)$ and $N_m(X)$ are Bessel functions of the first and second kinds, respectively, of order *m*, whereas $J'_m(X)$ and $N'_m(X)$ are the respective first order derivatives relative to X.

Considering that the relationship between the backscattering amplitude and the backscattering cross-section is given by (Simmonds and MacLennan, 2005):

$$\sigma_{bs} = \left| f_{bs}(\theta) \right|^2 , \tag{5}$$

equations (1) and (2) can be used to derive solutions for backscattering cross-sections of the body (σ_{bs}^{b}) and the swimbladder (σ_{bs}^{sb}) in the form of:

$$\sigma_{bs}^{b} = \frac{L_b^2}{\pi^2} \left| \int_0^1 \sum_{m=0}^{\infty} b_m^b (-1)^m \times \exp\left[2ikx_b \cos\theta_b \right] d\mu_b \right|^2 , \tag{6}$$

$$\sigma_{bs}^{sb} = \frac{L_{sb}^2}{\pi^2} \left| \int_0^1 \sum_{m=0}^{\infty} b_m^{sb} (-1)^m \times \exp\left[2ikx_{sb} \cos\theta_{sb} \right] d\mu_{sb} \right|^2 . \tag{7}$$

The target strength, *TS* can be calculated from the definition given by Simmonds and MacLennan (2005) as a sum of backscattering cross-sections of the body and swimbladder:

$$TS = 10\log(\sigma_{bs}^{tot}) , \tag{8}$$

where

$$\sigma_{bs}^{tot} = \sigma_{bs}^{sb} + \sigma_{bs}^{b} . \tag{9}$$

Considering the fact that the fish in a school differ in terms of their spatial orientation, the description of acoustic wave backscattering on aggregated herring individuals involved a mean backscattering cross-section:

$$< \sigma_{bs}^{tot} > = \int_{\gamma_{\min}}^{\gamma_{mac}} d\gamma \, W_\gamma(\gamma)(\sigma_{bs}^{tot}) . \tag{10}$$

where $W_\gamma(\gamma)$ is the Probability Density Function (PDF) and describes fish distribution according to their orientation; γ is the angle of the fish body axis deviation from the horizontal (Fig. 1). Based on experimental research (e.g., Ona, 2001) and theoretical considerations (e.g., Foote and Traynor, 1988), Gaussian PDF was assumed for fish orientation with mean and standard deviation: $\overline{\gamma}$ and S_γ respectively.

The mean backscattering cross-section can be converted to "mean" target strength, TS_m using the equation:

$$TS_m = 10\log_{10} < \sigma_{bs}^{tot} > . \tag{11}$$

2.2. Input data to the model

When modelling the backscattering characteristics, morphometric data obtained from X-ray images of 74 individual herrings from the Polish coastal zone (*ICES subdivision 26*) were used. Biological data was collected and X-raying was performed in November 2011.

X-ray images of the individual fish were used to digitise the body and swimbladder contours, and to measure the angles between axes of the swimbladder and the fish body.

In addition, for the purposes of numerical modelling, the following values of computation parameters were assumed: acoustic frequency, f = 38 kHz, selected as the frequency used most often in acoustic fish abundance estimation (Yasuma et al., 2003); sound propagation velocity in seawater, c = 1450 m/s. The density (g) and sound velocity (h) contrasts were 1.04 and 1.04, respectively, for the fish body and 0.00129 and 0.23, respectively, for the swimbladder (Gorska and Ona, 2003a, b).

3. Results and discussions

Equations (6) - (11), with a due consideration to variability of fish body and swimbladder radii along the axes, were used to calculate mean backscattering cross-sections and the "mean" target strength, TS_m for a herring school.

Fig. 2 shows relationships between the "mean" target strength, TS_m and the total fish length, L. Results of numerical calculations for individual fish in the collection (74 individuals) are visible as points. The lines correspond to the regression curves (logarithmic function). The results were generated for different standard deviation of fish orientation distribution: S_γ = 2° (blue-coloured curve and data points), S_γ = 5° (red-coloured curve and data points), S_γ = 10° (black-coloured curve and data points), and S_γ = 20° (grey-coloured curve and data points). For each case, the mean angle of fish body deviation from the horizontal, $\bar{\gamma}$ was assumed as equal to 0°. The selection of values of $\bar{\gamma}$ and S_γ for numerical calculations was based on results of experimental studies for herring (Beltestad, 1973; Olsen et al., 1983; Ona, 1984; 2001). The calculations took into account angles between the axes of the fish body and the swimbladder, measured in each individual fish.

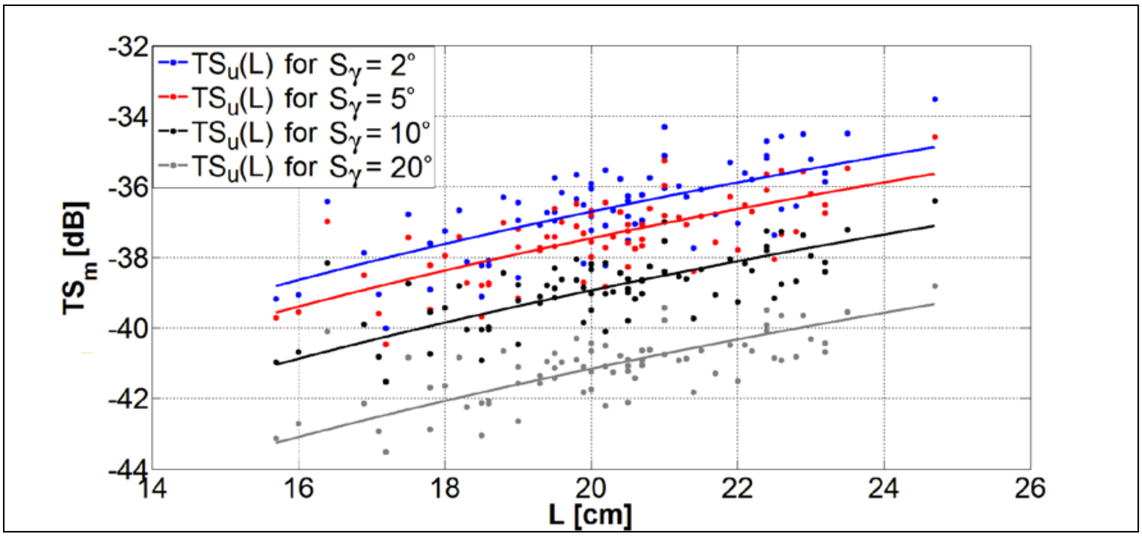

Fig. 2. The "mean" $TS_m(L)$ relationships for $\bar{\gamma}$ = 0° and S_γ = 2°, 5°, 10° and 20° (blue-, red-, black- and grey-coloured curves and data points, respectively) for the 74 herring individuals caught in the Polish coastal zone (*ICES subdivision 26*).

Analysis of results shown in Fig. 2 demonstrates the $TS_m(L)$ characteristics to decrease with increasing S_γ. Character of these dependencies is in agreement with the results of previous studies (e.g., Fässler and Gorska, 2009), and is based on the decrease of backscattering with γ increase (Fig. 1) for individual fish **(**Simmonds and MacLennan, 2005). A comparison of differences between the individual characteristics shows that, for example, a difference between $TS_m(L)$ for S_γ equal to 2° and 10° exceeds 2.2dB, the difference between $TS_m(L)$ for $S_\gamma = 2°$ and 20° being about 4.5dB.

Fig. 3 compares $TS_m(L)$ characteristics produced by numerical modelling (Fig. 2) with the $TS(L)$ characteristic based on *in situ* hydroacoustic measurements for clupeids from the Baltic Sea areas adjacent to the area where data for this study was collected (Didrikas, 2005; yellow-coloured curve) and the $TS(L)$ characteristics recommended by ICES (dashed black curve), currently used for clupeid resources assessment in the area in which Poland is responsible for the acoustic monitoring.

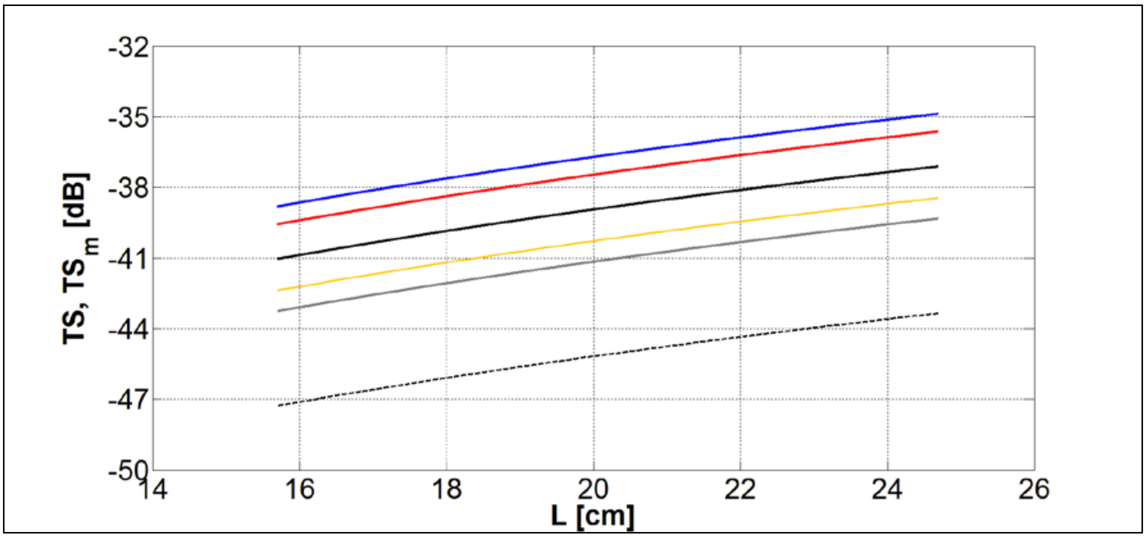

Fig. 3. Comparison of the theoretical $TS_m(L)$ relationships (blue-, red-, black- and grey-coloured curves) with the $TS(L)$ obtained empirically: yellow curve pertains to data of Didrikas (2005); dashed black curve is the characteristic recommended by ICES.

Analysis of Fig. 3 shows both the theoretical $TS_m(L)$ curves and the empirical one produced by Didrikas (2005) are above the $TS(L)$ characteristics recommended by ICES, derived from data on Norwegian Sea clupeids. The reason of this difference, caused by the difference in salinity between Baltic and Norwegian Sea, was discussed by Didrikas and Hansson, 2004; Peltonen, and Balk, 2005; Fässler et al., 2008. Moreover, the $TS_m(L)$ characteristics generated by this study are close to the $TS(L)$ curve obtained by Didrikas (2005). This mean that the ICES characteristic for acoustic assessment of herring abundance in the southern Baltic Sea is not be appropriate and ultimately lead to over-estimation of the herring biomass in the area.

4. Conclusions

When studying backscattering characteristics of clupeids in the southern Baltic Sea (*ICES subdivision 26*):

1. "Mean" $TS_m(L)$ characteristics were obtained, with a due consideration to the natural shapes of the fish body and swimbladders of individuals collected, as well as angles between the axes of the body and swimbladders. The backscattering characteristic modelling was based on data for 74 fish captured in the Polish coastal zone;
2. A strong effect of the orientation-based parameters (mean and standard deviation of fish orientation distribution) on the "mean" backscattering characteristics, $TS_m(L)$ was demonstrated;
3. A difference was obtained between the $TS_m(L)$ characteristics generated by the model and the $TS(L)$ characteristic recommended by ICES and currently used to assess clupeid resources in the area in which Poland is responsible for acoustic monitoring.

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