Oceanologia 64 (2022) 198—211

Available online at www.sciencedirect.com

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journal homepage: www.journals.elsevier.com/oceanologia

ORIGINAL RESEARCH ARTICLE

On Baltic herring morphometry and its impact on the backscattering properties.

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Received 26 April 2021; accepted 20 October 2021
Available online 12 November 2021

KEYWORDS
Backscattering;
Target strength;
Numerical modelling;
Baltic herring

Abstract Previous studies, dedicated to backscattering properties of Baltic herring, have shown the different target strength (*TS* — which is a measure of fish capacity to scatter sound) values, for the same species in different regions and seasons. The intraspecies differentiation in fish physiology and morphology as well as fish swimbladder morphometry between herring aggregations, occupying various parts of the Baltic Sea, has been supposed as one of the reasons for the variability.
The paper addresses analysis of herring swimbladder morphometry and its impact on *TS* of individuals from ICES subdivision 26, one of the areas where Poland is responsible for herring biomass estimation. The collection of the X-rays images for 74 herring individuals, sampled in this subdivision, was created. The two-dimensional digitized dorsal images of herring swimbladder and body, as well as the angles between the swimbladder and the body longitudinal axis, were used to compute the target strength. The differentiation of herring morphometry within particular fish size classes was analysed and its consequences for the averaged target strength within the class was discussed. The difference from the previous numerical studies, in which the simplified herring morphometry was used, was also demonstrated. The computational results were considered in regard to the available in situ measured data on Baltic herring *TS*. The study of the Baltic herring target strength is important for increasing accuracy of acoustic biomass estimation of this ecologically and economically important species.

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Peer review under the responsibility of the Institute of Oceanology of the Polish Academy of Sciences.

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https://doi.org/10.1016/j.oceano.2021.10.001

1. Introduction

Accurate information on fish biomass is critical for ecosystem-based approach to management of marine resources. The biomass, acoustically estimated, is recognized as one of the "hydroacoustic metrics" to evaluate a marine ecosystem state (Godø et al., 2014; Trenkel et al., 2011, 2016).

The central role of *Clupeids* as a link between lower and higher trophic levels makes this ecologically and economically valuable species important in a management of the pelagic ecosystem. It is recognized that biomass of herring, patchily distributed in dense aggregations, can efficiently be estimated by acoustic techniques (e.g. Fässler, 2010).

To increase the accuracy of acoustic biomass estimation, it is necessary to deepen the knowledge of the fish backscattering properties — the target strength (*TS*), a measure of individual capacity to scatter sound — and its variability. The *TS* depends on a range of factors: e.g., morphometry of fish and its swimbladder (impacted by fish physiology and behaviour), as well as acoustic frequency of the measuring device (Simmonds and MacLennan, 2005).

The variability, according to these factors, of herring from the northeast Atlantic and the North Sea has been carefully examined. *TS* measurements were based on insonification of immobilised fish (Nakken and Olsen, 1977) or active fish within a cage (Edwards and Armstrong, 1981, 1983, 1984; Edwards et al., 1984; Ona, 2003; Pedersen et al., 2009) as well as wild fish, behaving normally (Foote et al., 1986; Huse and Ona, 1996).

It was found that *TS* is strongly dependent on the herring individual tilt (Blaxter and Batty, 1990; Edwards et al., 1984; Huse and Ona, 1996; Huse and Korneliussen, 2000; Nakken and Olsen, 1977; Ona, 2001). Ona et al. (2001) demonstrated how herring *TS* is dependent on fish physiology (on the gonadosomatic indices (*GSI*)). Edwards and Armstrong (1981), Edwards et al. (1984), Ona (1990, 2003), Pedersen et al. (2009) showed the impact of depth on herring target strength. Theoretical backscatter models have helped to improve the understanding and interpretation of empirical herring *TS* data (Fässler, 2010; Gorska and Ona, 2003a, 2003b).

The findings of these empirical and theoretical studies helped to strengthen the credibility of herring *TS-L* relationship, which in the following form:

$$TS = 20\log_{10}(L) + b_{20} \tag{1}$$

is used in acoustic fish abundance estimates (Foote et al., 1986). Here the fish total length *L* is in cm, *TS* in dB. Consideration of the sensitivity of the intercept b_{20} to the herring physiology and behaviour allowed to improve the accuracy of the herring abundance estimates in the northeast Atlantic and the North Sea.

The situation is different for the Baltic herring, whose biomass has been assessed in acoustic survey methods since the 1980's, in line with ICES recommendations (e.g., ICES, 2017). It was justified in Fässler et al. (2008) that *TS-L* relationship derived for herring from the northeast Atlantic and the North Sea cannot be used for Baltic herring. The question — which *TS-L* relationship is appropriate to use in acoustic herring biomass estimation in the Baltic — is still open.

Direct in situ *TS* measurements were carried out in different locations (different ICES Baltic subdivisions) and different seasons (Didrikas, 2005; Didrikas and Hansson, 2004; Kasatkina, 2009; Lassen and Stæhr, 1985; Peltonen and Balk, 2005; Rudstam et al., 1988, 1999; Schmidt et. al., 2011). The collected *TS* data were highly variable: it has been obtained up to 8 dB difference in the intercept b_{20}. This means the differentiation of the target strength of the same fish total length.

Unfortunately, the factors, which could impact the individual backscattering properties (fish physiology and orientation as well as the depth occupied by herring) and explain the variability, were not controlled during the measurements.

A complementary numerical *TS* modelling was also applied, providing a deeper understanding of the 8 dB difference. The variability has been partly explained by (i) different depths at which the herring aggregations could be identified during the particular measurements (Fässler and Gorska, 2009; Fässler et al., 2008), (ii) possible fish orientation difference within the studied aggregations (Fässler and Gorska, 2009; Fässler et al., 2008; Idczak and Gorska, 2016; Idczak and Kniaź-Kubacka, 2012) and (iii) the different acoustic frequencies used by the researchers (in the range from 38 kHz to 120 kHz) (Fässler and Gorska, 2009).

Moreover, some researchers collected *TS* data for mixed herring and sprat aggregations and analysed them as a single set (Didrikas, 2005; Didrikas and Hansson, 2004). Meanwhile, the others (Kasatkina, 2009; Peltonen and Balk, 2005; Schmidt et al., 2011) used the data gathered for single-species aggregations of herring and sprat and treated them as two independent collections. It has been found that the different approaches could also contribute to the 8 dB-variability (Fässler, 2010; Fässler and Gorska, 2009; Gorska and Idczak, 2010).

Summarizing, the *TS* modelling results have identified the difference in fish depths, tilt angle distributions, the applied acoustic frequency as well as discrepancies in the methods of data collection and analysis, as main factors responsible for the observed up to 8 dB difference in herring. However, these factors can explain only partially the 8 dB-differentiation. The final explanation remains an open question. This motivated us to look for other important factors.

Blaxter and Batty (1990), as well as Horne (2003) pointed out that in some cases, the physical environment may impact the fish physiology and morphology as well as fish swimbladder morphometry, resulting in intraspecies variability in target strength. Because of its long north—south extension (of more than 1500 km), the Baltic Sea is characterised by strong meridional differentiation in environments the herring live in, e.g. salinity value is about 1 unit for the north Baltic and 10 units for the South Baltic (Kullenberg, 1981). Moreover, there are the periods when the differentiation does intensify. This is related to the North Sea salt water inflow with more oxygenated water (Kullenberg, 1981) that improves herring living conditions in the areas which the inflow reaches. These inflows affect different areas of the Baltic Sea in different degrees. The study area (Subdivision 26) has a stronger inflow effect compared to the areas north of it and a lower impact compared to the areas west of it.

The difference in the herring living environment could result, e.g. in the differentiation over herring growth rate (it means the differentiation in fish size and its swimbladder morphometry) as well as herring fat content and condition (Bignert et al, 2007; Cardinale and Arrhenius, 2000; Grygiel and Wyszyński, 2003; Ojaveer, 1988; Wyszyński, 1997). It could be a potential reason of the variability in Baltic herring *TS* in different parts of Baltic (Fässler and Gorska, 2008; Peltonen and Balk, 2005).

Fässler and Gorska (2008), as well as Fässler (2010) underlined that the studies of the backscattering properties of fish from different locations and at different times in the Baltic Sea are important.

Previously, Baltic herring swimbladder morphometry and its effect on the *TS* were only examined using the herring collection taken from the south-eastern (ICES subdivision 25) and eastern (ICES subdivisions 27 and 29) of Sweden during the Swedish component of the Baltic International Acoustic Survey (BIAS project) in October 2002 (Fässler et al., 2008; Fässler and Gorska, 2009; Idczak and Gorska, 2016; Idczak and Kniaź-Kubacka, 2012).

It means that research of herring target strength in other particular Baltic ICES subdivisions (local approach) remains to be important. Our work focused on the study of fish morphometry and its impact on the backscattering by herring in another unexplored part of the Baltic Sea — ICES subdivision 26, one of the areas where Poland is responsible for the acoustic assessment of herring biomass. Therefore, we created our own collection of the X-rays images for 74 herring individuals sampled in the ICES subdivision 26. The morphometric features of this collection were studied (Section 3.1). The variability of herring morphometry within particular fish size classes was analysed and its impact on the averaged target strength differentiation within the classes was demonstrated (Sections 3.2, 4.1).

The previous modelling studies of Baltic herring backscattering considered a simplified body and swimbladder morphometry (Fässler et al., 2008; Fässler and Gorska, 2009; Gorska and Idczak, 2010; Idczak and Kniaź-Kubacka, 2012). In our study backscatter model has been improved for Baltic herring in the ICES subdivision 26. Accurate morphometry data, defined from the X-ray images, were used to compute the dorsal backscattering cross-section of herring in this area. The distinction with the previous approach, using the simplified herring morphometry, has been also explored (Sections 3.3, 4.2).

The computational results were considered in light of the measured Baltic herring *TS* data. The herring *TS-L* relationship in the ICES subdivision 26 was discussed (Section 4.2).

Considering that our research was carried out only in one region of the Baltic Sea, it did not explain directly the observed 8 dB variability of Baltic herring *TS*. The explanation requires further studies in the remaining Baltic ICES subdivisions and the comparison of their results. However, our research deepened the understanding of the backscattering properties of Baltic herring and so is an important step towards solving the problem.

2. Material and methods

The averaged target strengths of Baltic herring were modelled using the Modal-Series-Based Deformed Cylinder Model (MSB-DCM; Stanton, 1988a,b, 1989).

The swimbladder and the body of the fish were modelled as deformed cylinders filled with gas and liquid respectively, the radius of which varies along their straight longitudinal axis. For both herring swimbladder and body, the radius at each point of the axis was half the object dorsal width at this point. The axis of the swimbladder cylinder is inclined with respect to the axis of the fish body.

The application of this approach has been justified. Firstly, the detailed analysis of the digitised X-ray images of 74 herring, caught in the Polish coastal zone (ICES subdivision 26), demonstrated that:

- herring swimbladder and body were elongated objects (the mean aspect ratios were ca. 8 and 12 for herring swimbladder and body respectively),
- the cross-sectional radius changed slowly with respect to position along the axis of these objects.

Secondly, it was assumed that also the material properties changed slowly with respect to position along the axis. Thirdly, the backscattering modelling was restricted to considering the geometries where the direction of the incident sound wave was normal or near-normal to the longitudinal straight axis of fish body and swibladder. According to the publication (Jech et al., 2015), MSB-DCM approach could be applied.

The body and swimbladder geometry, and the angle between the swimbladder and the body longitudinal axis were defined from X-ray images of 74 specimens caught in the Polish coastal zone (ICES subdivision 26).

2.1. MSB-DCM Model

Following the paper of Idczak and Gorska (2016), the backscattering cross-sections of herring individual swimbladder σ_{sb} and body (σ_b) could be presented in the form of:

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

and

$$\sigma_{b} = \frac{L_{b}^2}{\pi^2}\left|\int_0^1 \sum_{m=0}^{\infty} b_m^{b}(-1)^m \times exp[2ikL_{b}\mu_{b}cos\theta_{b}]d\mu_{b}\right|^2 \quad (3)$$

The Equations (6) and (7) from Idczak and Gorska (2016) were used. Here: L_b and L_{sb} are fish standard length and swimbladder length, respectively; k is the wave number ($k = 2\pi f/c$, where c is the sound speed 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 longitudinal axis of the cylinders (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 longitudinal axes of the fish body and the swimbladder, respectively (Figure 1).

In Equations (2) and (3), the modal coefficient b_m is described by the equation:

$$b_m = \frac{-\varepsilon_m}{1 + iC_m} \quad (4)$$

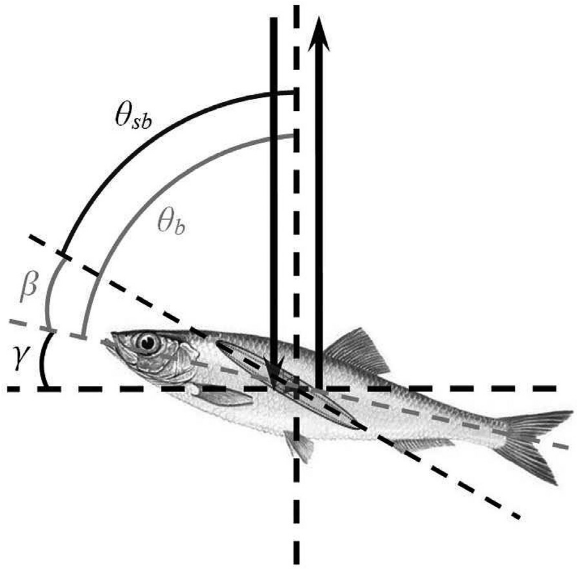

Figure 1 Geometry of acoustic wave scattering by the fish body and the swimbladder.

where $\varepsilon_m = 1$ for $m = 0$ and $\varepsilon_m = 2$ for $m > 0$.

The coefficient C_m is defined by the equation:

$$C_m = \frac{[J'_m(K'a)N_m(Ka)]/[J_m(K'a)J'_m(Ka)] - gh[N'_m(Ka)/J'_m(Ka)]}{[J'_m(K'a)J_m(Ka)]/[J_m(K'a)J'_m(Ka)] - gh} \quad (5)$$

where: for the fish body, $C_m = C_m^b$, $a = a_b$ is a half of the body dorsal width, dependent on the coordinate x_b; by analogy, for the swimbladder: $C_m = C_m^{sb}$, $a = a_{sb}$ is a half of the swimbladder dorsal width and are dependent on the coordinate x_{sb}. $K = \frac{2\pi f}{c}\sin\theta$ and $K' = \frac{K}{h}$ — inside the scattering object, where $K = K_b$ and $\theta = \theta_b$ for the fish body and $K = K_{sb}$, $\theta = \theta_{sb}$ for the swimbladder. The sound speed contrast h is defined by the ratio of sound speed in a scattering object and the sound speed in the ambient seawater. The density contrast g is a ratio of the target material density to the ambient seawater density. Here $h = h_b$, $g = g_b$ 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 kind, respectively, of order m, whereas $J'_m(X)$ and $N'_m(X)$ are the respective first order derivatives relative to X. These equations, based on Equation (8) from Stanton (1989) are valid for incidence direction perpendicular to the swimbladder axis $\pm$ 20° (Jech et al., 2015).

The mean backscattering cross-sections for individual swimbladder $\langle\sigma_{sb}\rangle$ and body $\langle\sigma_b\rangle$ are considered to describe backscattering by aggregated herring:

$$\langle\sigma_{sb}\rangle = \int_{-\pi/2}^{\pi/2} d\gamma W_\gamma(\gamma)(\sigma_{sb}) \quad (6)$$

$$\langle\sigma_b\rangle = \int_{-\pi/2}^{\pi/2} d\gamma W_\gamma(\gamma)(\sigma_b) \quad (7)$$

where $W_\gamma(\gamma)$ is the Probability Density Function (PDF). It describes fish distribution according to their orientation γ. Symbol γ describes the angle of the fish body longitudinal axis deviation from the horizontal plane (Figure 1).

The angle γ is equal zero for the horizontal position of fish body. It is positive for head up position of fish and negative for its head down position.

Basing on experimental research (e.g., Ona, 2001) and theoretical considerations (e.g., Foote and Traynor, 1988), a Gaussian PDF was assumed for fish orientation with mean $\bar{\gamma}$ and standard deviation S_γ:

$$W_\gamma(\gamma) = \frac{1}{\sqrt{2\pi}S_\gamma} exp\left(\frac{-(\gamma - \bar{\gamma})^2}{2S_\gamma^2}\right) \quad (8)$$

Following the paper by Gorska and Ona (2003b) we did not consider the swimbladder and body as a coupled system. We limited our analysis to a simple summation of the averaged backscattering cross-sections of fish body and its swimbladder. When the swimbladder is the dominant scatterer (it was confirmed by our calculations), the equation:

$$\langle\sigma_{bs}\rangle = \langle\sigma_{sb}\rangle + \langle\sigma_b\rangle \quad (9)$$

is a good description of whole-fish backscattering.

The target strength (Simmonds and MacLennan, 2005), defined as:

$$TS = 10\log_{10}\langle\sigma_{bs}\rangle \quad (10)$$

is used in analysis and referred to as 'averaged target strength' in the following text.

2.2. Model input data

2.2.1. On fish sample, X-rays imaging and the morphometric data analysis

Studying fish backscattering properties, three noninvasive techniques are used for the reconstruction of the morphometric structure of fish body and swimbladder: X-rays imaging (e.g., Clay and Horne, 1994; Henderson and Horne, 2007; Sawada et al., 1999); computed tomography CT (Macaulay, 2002; Okumura and Masuya, 2004; Reeder et al., 2004), as well as magnetic resonance imaging MRI (Pena and Foote, 2008). The first method provides digitized dorsal and lateral images of a fish which could be used to present the body and swimbladder as circular or deformed cylinders (or set of short cylinders). The two other techniques generate three-dimensional images of fish anatomy. Morphometry of Baltic herring in the ICES subdivision 26 was studied, using X-rays imaging techniques.

The catch was conducted from the fishing boat HEL — 125 in early November 2011 in the Gulf of Gdańsk southeast of the Hel Peninsula (ICES subdivision 26). The coordinates of the start and end points of the transect were (54°27.026'N and 19°02.745'E) and (54°30.510'N and 18°57.036'E) respectively. While catching fish, the pelagic trawl (codend was of 11 mm mesh) moved as close to the surface as possible, vertically covering the water layer from about 5 to 25 meters deep. The trawling speed was 3.5 knots and haul duration was one and half hour.

To obtain good quality X-ray images of herring swimbladder and body, the methodology of fish capture, transportation, storage and X-raying, initiated in 2010 (Idczak et al., 2011), was used. The methodology followed the recommendations of Horne and Jech presented in the *Manual for radiographing fish* (version 24.04.2001 in Appendix B of

ICES, 2002 Report). The main concern during the fish collection, preparation and X-raying was an individual swimbladder which should remain intact and noncollapsed with a shape not substantially differing from that in the natural environment.

The methodology, developed in 2010, was not effective enough. Only for 18% of the individuals, taken from the haul, the X-ray images were of good quality, sufficient to digitize dorsal and lateral images of a fish.

Therefore, the methodology was improved in 2011, i.e. fish were:

(i) Collected closer to the sea surface.
(ii) Stored before the X-raying, not in the small aquarium (400 l volume), which was the case in 2010, but in the aquaculture specialized tank of 2000 l volume, with a continuous flow of seawater pumped directly from the Gulf of Gdańsk. As a result, the values of temperature, oxygen content and salinity of water were similar to the values of these parameters occurring in the natural environment. Fish were stored in the tanks 12—24 hours before the X-raying. This time allowed for the adaptation of individuals to hydrostatic pressure change. The vast majority of fish individuals were in a good state: they swam naturally throughout the entire volume of the tank and even formed small shoals.
(iii) Transported from fishery boat to the tanks as well as from the tanks to the hospital, where the X-ray images were done, in smaller portions in the bags with more oxygenated marine water than it was in 2010.
(iv) The multiple-fish scanning (few fish were scanned simultaneously) was conducted, reducing the waiting time for scanning for each individual. It was important to keep fish in a good condition.

This provided an increase in the rate of good quality X-ray images.

The X-ray outlines of the bladders of 31% (74 individuals) of the fish, sampled from the haul, were clearly visible and satisfactory for digitizing. The assessment of the normality of the swimbladder shape was based on the experience of X-raying of a large number of herring individuals, collected in 2010 and 2011.

We did not consider in further analysis:

(i) Herring smaller than 15 cm in length (about 4% of the fish, sampled from the haul) that did not survive the preparation to X-ray analysis.
(ii) Fish whose behaviour or X-ray images demonstrated that their swimbladders were damaged due to the pressure jump (38% of the haul sample).
(iii) Fish with undamaged swimbladders, the X-ray images of which were not acceptable for the digitizing (27% of the sample). The reasons for bad quality images were of random character: e.g., some fish did not hold a proper position on the X-ray cassette during the analysis — their bodies were not perpendicular to the cassette plane.

A method for herring body and swimbladder contour digitization was developed. For the image processing, the AutoCAD LT 2013 software was used.

The digitised contours of fish swimbladders and bodies were obtained for selected 74 fish collection. Herring morphometric dimensions were then measured. The radii of swimbladder and body (both modelled as deformed cylinders), varying over the cylinder longitudinal axis and equating to half of the object dorsal width at each axis point, were defined for each fish (see Equations (2), (3), (5)).

As the target strength *TS* of a Baltic herring individual is primarily sensitive to the swimbladder morphometry (Fässler and Gorska, 2009; Gorska and Idczak, 2010), the analysis, presented in section *3.1.2 Differentiation in swimbladder morphometry within particular fish size classes*, concerned mainly the swimbladder data series. Therefore, swimbladder length L_{sb} and maximum width w_{sb}, measured to the nearest 0.1 cm using good quality X-ray herring images, were chosen for the presentation. The swimbladder dorsal cross-section was determined for each individual herring using the AutoCAD LT 2013 software. In addition, the total fish length L (measured to the nearest 0.1 cm) and the angle β (Figure 1) between the longitudinal body and swimbladder axes (measured to the nearest 0.1 degree) were defined using good quality X-ray images.

The comparison of the Probability Density Functions (PDFs) of total fish length was done between our 74-fish collection and the herring sample (219 individuals), randomly taken from the haul during the cruise dedicated to herring biomass estimation in Polish Marine Areas. The cruise was conducted in October 2010 by National Marine Fisheries Research Institute in Gdynia (r/v *Baltica*). It was related to the Polish component of the BIAS (Grygiel et al., 2011). This comparison was reasonable because both collections were taken in the autumn season and at the same area — ICES subdivision 26. Moreover, in both selected hauls, herring was the dominant species (not less than 95% of the entire haul fish sample). The mean total lengths and their standard deviations (SD) were also compared for these two collections.

The herring X-ray images are accessible due to the project “MOST DANYCH — Multidisciplinary Open System of Knowledge Transfer — Stage II: Open Research Data”, co-financed by the European Regional Development Fund under the Operational Program Digital Poland for 2014—2020 (X-ray images of Baltic herring, 2019, DOI: https://doi.org/10.34808/s4sj-b755, https://mostwiedzy.pl/pl/business/open-research-data/x-ray-images-of-baltic-herring,102102842142204-0).

2.2.2. Other calculation parameters

Computations were made for acoustic frequency $f = 38$ kHz (used in acoustic herring stock assessment in the Baltic Sea (ICES, 2017)) and sound speed in seawater $c = 1450$ m/s (Grelowska, 2000). The density g_{sb} and sound speed contrasts h_{sb} of 0.00129 and 0.23, respectively, were taken for the swimbladder and 1.04 and 1.04 (g_b and h_b), — for the fish body. To define the density contrast of the swimbladder, a seawater density was evaluated using an algorithm (Fofonoff and Millard, 1983) implemented in a web-based calculator (Chapman, 2006). The calculations were done for the seawater temperature varying from 10°C to 15°C and constant salinity of 7.26 (Rak and Wieczorek, 2012). This reflects the hydrographic conditions in October—November at the location, where the biological material was collected. It resulted in a seawater density variation from 1004.6 kg

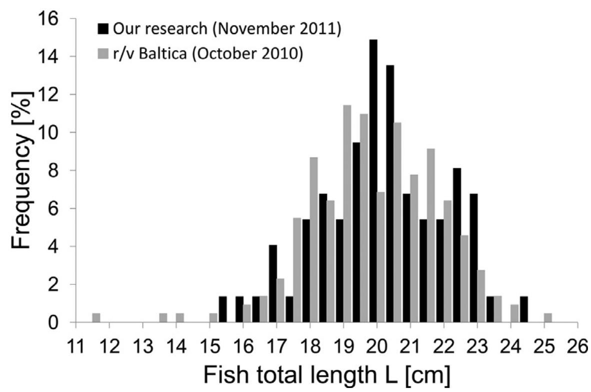

Figure 2 PDFs of fish total length for two herring samples including 74 (black colour) and 219 (grey colour) individuals.

m^{-3} to 1005.4 kg m^{-3}. The density of the swimbladder gas was assumed to be 1.3 kg m^{-3} (Brawn, 1969). The other contrasts were chosen following the papers of Gorska and Ona (2003a, 2003b).

The orientation distribution of free-swimming herring in the natural environment has not been studied in the Baltic Sea as it has been done for herring from the northeast Atlantic and the North Sea (Beltestad, 1973; Blaxter and Batty, 1990; Edwards et al., 1984; Huse and Korneliussen, 2000; Huse and Ona, 1996; Nakken and Olsen, 1977; Olsen et al., 1983; Ona, 1984, 2001). It has been obtained that the mean fish body tilt angle ($\bar{\gamma}$) varied from near 0°-values to about 10°, while the standard deviation (S_γ) varied from about a few degrees to about 20°. Just these ranges of $\bar{\gamma}$ and S_γ were considered in our analysis. For all the performed calculations, selecting $\bar{\gamma}$ and S_γ for the calculations, the care about the applicability of the MSB-DCM approach (the near-normal incidence) (Jech et al., 2015) was taken.

3. Results

3.1. Input data collection

The main features of the morphometric data collection were analysed and discussed below.

3.1.1. PDFs of fish total length

In Figure 2, the PDFs of fish total length for the two considered collections are compared. The first collection was acquired by us and the second one — during the r/v *Baltica* cruise (Grygiel et al., 2011). The mean total lengths were 20.21 cm and 19.85 cm for the first and second data sets respectively, while the SDs were respectively 1.90 cm and 1.95 cm. It allowed us to conclude that the PDFs of these two samples were comparable (1.7% and 2.5% difference in the mean values and SD respectively). This similarity confirms the reasonability of further analysis of our collection.

3.1.2. Differentiation in swimbladder morphometry within particular fish size classes

In further analysis of the morphometry data (this subsection) as well as of the TS — differentiation in Section 3.2, the entire range of the herring total length was divided into 0.5 cm-intervals. 14 size classes were considered. The appropriateness of 0.5 cm interval with not more than a few individuals in each one is discussed below in the Discussion section.

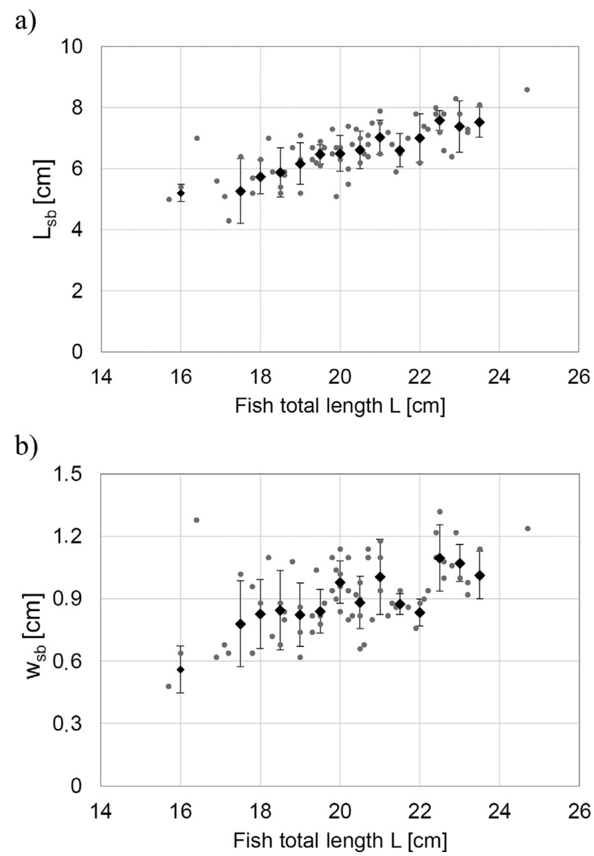

Figure 3 The dependence of swimbladder length (plot a) and maximum width (plot b) on fish total length. Grey points at each plot correspond to the dimensions of 74 herring individuals. For each size class the mean value (black rhombs) and standard deviation (black whiskers) are presented.

The results of the measurements of swimbladder length and maximum width over the entire fish total length range are presented respectively in Figures 3a and 3b. The mean values with the standard deviations were: 6.6 ± 0.9 cm and 0.9 ± 0.2 cm for the fish swimbladder length and width respectively.

It was demonstrated that for herring individuals of the same size class, the standard deviation could achieve up to 20% for swimbladder length and up to 27% for swimbladder maximum width (for fish size class 17—17.5 cm). The large difference between maximum and minimum dimensions in relation to mean value is also shown: this parameter varied from 16.4% (23.0—23.5 cm length class) to 46.4% (17.0—17.5 cm length class) for swimbladder length and from 13.1% (23.0—23.5 cm length class) to 61% (18.5—19.0 cm length class) for swimbladder maximum width. The mean values for all fish length classes were 25.9% and 36.3% for the swimbladder length and width, respectively.

It is also important to remind that for herring from the northeast Atlantic and the North Sea the swimbladder length is 0.26 times the total length of the fish (Gorska and Ona, 2003b). The linear approximation of the data se-

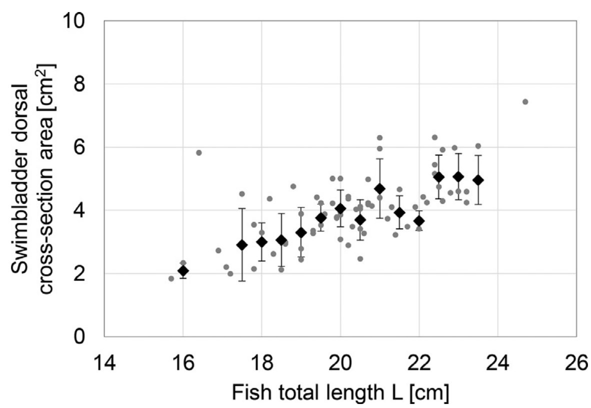

Figure 4 The dependence of swimbladder dorsal cross-section area on fish total length. Grey points at each plot correspond to particular herring individuals. For each size class the mean value (black rhombs) and standard deviation (black whiskers) are presented.

ries presented in Figure 3a, showed that for Baltic herring the swimbladder length is 0.348 times the fish total length ($R^2 = 0.49$). This is in line with the publication of Fässler et al. (2008), which showed larger dimensions of the Baltic herring swimbladder for the same total fish length in these compared herring groups.

The differentiation in swimbladder dimensions within one size class could result in the variability of the swimbladder dorsal cross-section area for individuals of the same size class. The dorsal cross-section area is an important parameter to which the backscattering could be sensitive. It determines the dimensions of swimbladder surface, as seen from the transmitting transducer, on which the echo energy depends (Simonds and MacLennan, 2005). The results of the calculation of swimbladder dorsal cross-section area are presented in Figure 4. The standard deviation, standardized by the average value of cross-section area of the size class, reaches up to 39.5% for 17—17.5 cm length class.

Figure 5 a—b shows an example of X-ray outlines illustrating the different swimbladder patterns between two individuals of the same size class, which results in the difference of their dorsal cross-section area. The dorsal cross-section areas were 2.94 cm^2 and 4.76 cm^2 for the individuals in plots a and b respectively (1.62 times difference).

In Figure 6, the result of the measurements of the angle β (Figure 1) between the longitudinal body and swimbladder axes is presented. It was shown that the mean standard deviation (standardization by average angle for each size class) was 39.6%, while the mean ratio of maximum to minimum angle for one fish size class was equal to 3.23.

The effect of variability of herring swimbladder morphometry within particular fish size classes on the *TS* variability is considered in the next section, where the results of *TS*-modelling are presented.

3.2. *TS* differentiation within particular fish size classes

The averaged target strength *TS* growth with fish total length is shown in Figure 7a. The calculations were made for $\bar{\gamma} = 0°$ and $S_\gamma = 10°$. As in the previous calculations, the entire range of the total length was divided in 0.5 cm intervals. The borders of these intervals are presented in the plot by vertical lines. We can see the difference in the averaged target strength of the individuals in particular size classes.

To evaluate this effect, the difference between the highest and lowest values of averaged target strength, $\Delta TS_{Lclass0.5cm}$ was calculated. The results are presented in Figure 7b not only for $\bar{\gamma} = 0°$ and $S_\gamma = 10°$ (grey columns), but also for $\bar{\gamma} = 0°$ and $S_\gamma = 5°$ (black columns) and $\bar{\gamma} = 0°$ and $S_\gamma = 20°$ (white columns). In the horizontal axis of the plot b, the border length of fish size classes is presented.

The analysis of Figure 7b has shown that:

- for each size class, the larger S_γ (from darker to lighter columns in plot b), the smaller the difference $\Delta TS_{Lclass0.5cm}$;
- the largest differences were observed for individuals of 17—17.5 cm length class: 3.1 dB; 2.8 dB and 2.7 dB for S_γ equalling to 5° 10° and 20° respectively;
- over the range $5° \leq S_\gamma \leq 20°$, for six size classes the $\Delta TS_{Lclass0.5cm}$ difference is higher than 1.5 dB.

The analysis for fixed $S_\gamma = 10°$ and $\bar{\gamma}$ variating from 0° to 10° has been also made (results are not presented graphically). It was shown, that for most classes the $\Delta TS_{Lclass0.5cm}$ difference increased with $\bar{\gamma}$. The largest differences in the $\Delta TS_{Lclass0.5cm}$ were observed for individuals of 17—17.5 cm length class: 3.8 dB; 3.3 dB and 2.8 dB for $\bar{\gamma}$ equalling to 0°, 5° and 10° respectively. Similarly, to the case presented above for more than six size classes $\Delta TS_{Lclass0.5cm}$ is higher than 1.5 dB.

3.3. Fish morphometry: effect on *TS*

In this section, the target strengths, calculated using fish and swimbladder morphometry data from the X-ray images and applying the simplified shape of swimbladder and body (prolate spheroids) (Fässler et al., 2008; Fässler and Gorska, 2009; Gorska and Idczak, 2010; Idczak and Kniaź-Kubacka, 2012) are compared.

In the calculations with the simplified geometrical shape, it was assumed for each fish that the lengths of swimbladder prolate spheroids to be equal to the actual values of this parameter. To calculate the width of the swimbladder prolate spheroids, it was assumed that their volumes to be equal to the true swimbladder volumes providing that the prolate spheroidal swimbladder had the appropriate volume, ensuring neutral buoyancy of the fish.

These true volumes were calculated using Equations (1)—(3) from Fässler et al. (2008) as well as the volume proportions of various fish individual components and their densities, proposed by those authors. Using the calculated swimbladder volumes and their length data and applying the formula for a prolate spheroid volume, the width of the prolate spheroids were calculated.

Results for the shapes of the fish swimbladder (*TS*), as defined from the X-ray images, and from calculations for their prolate spheroid shapes (TS_{pr_sph}) are compared in Figure 8a. The dependence of the difference $\Delta TS = TS_{pr\_sph} - TS$ on the fish total length is presented. The up to about 2 dB difference of averaged target strength ΔTS was

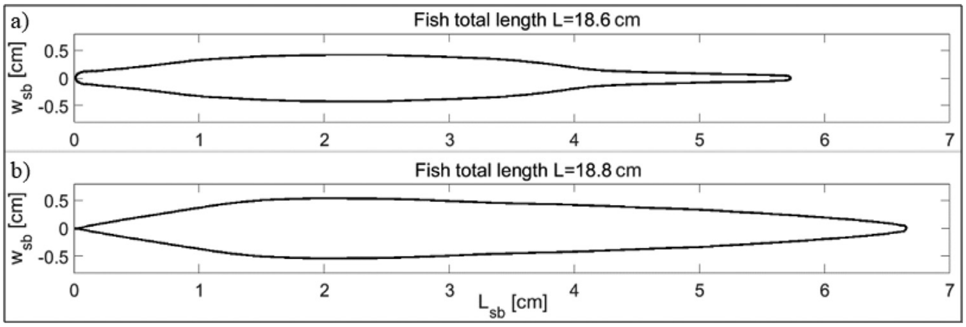

Figure 5 The X-ray outlines of the swimbladder dorsal cross-section of two individuals of the same size class (plots a and b).

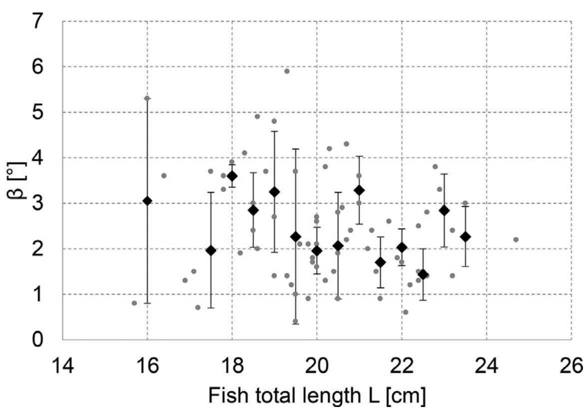

Figure 6 The dependence of the angle β on fish total length. Grey points correspond to the 74 herring individuals. For each size class the mean value (black rhombs) and standard deviation (black whiskers) are presented.

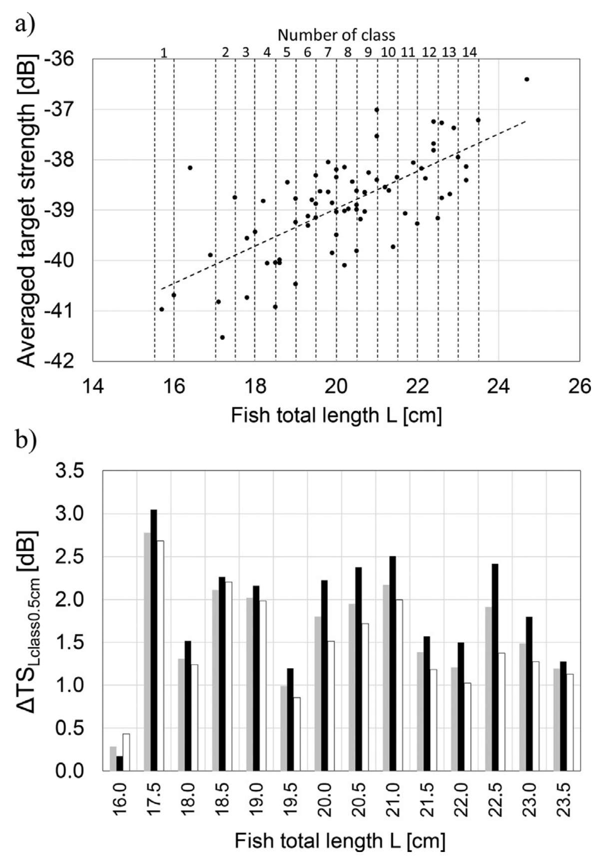

Figure 7 Averaged target strength vs. fish total length (plot a) and the $\Delta TS_{Lclass0.5cm}$ for each size class (plot b). A linear regression line is shown in plot a. In this plot data points correspond to calculated results for 74 herring individuals considered. The calculations assumed a mean angle of fish body orientation $\bar{\gamma}$ equalling to 0°. The standard deviation of the orientation distribution S_γ was equal to 10° (plot a and grey colour in plot b) and 5°and 20° — black and white (colours respectively in plot b). TS was calculated using Equations (2)—(9).

demonstrated. The trend of the regression line in the plot suggests that ΔTS increases with fish total length L from about 0.3 dB to 1.3 dB.

The effect of the angle β between the longitudinal axes of the swimbladder and the fish body on the averaged target strength TS is demonstrated in Figure 8b. Modelling results for values of β, as measured on X-ray images of the herring collection, and data from calculations for $\beta = 0°$ are compared. The dependence of the difference $\Delta TS_\beta = TS_{(\beta\neq0)} - TS_{(\beta=0)}$ on the fish total length is presented. Here $TS_{(\beta\neq0)}$ and $TS_{(\beta=0)}$ denote the target strength for the measured values of the angle β and for the angle $\beta = 0°$ respectively. Analysing the impact of the angle on the difference ΔTS_β, it can be noted that maximum observed difference between the calculation results amounted to about 3.4 dB. According to the regression line, the difference slightly depends on the fish length and amounted to about 1.35 dB.

Analysing the dependence of ΔTS and ΔTS_β on the fish total length, we considered the herring orientation distribution impact on the calculated results. The calculations demonstrated that the difference (ΔTS) (Figure 8a) was not sensitive to the parameters $\bar{\gamma}$ and S_γ over their entire range selected for the calculations (see subsection 2.2.2). Meanwhile, the difference ΔTS_β (Figure 8b) was sensitive to the mean angle of fish body orientation and its standard deviation. The analysis demonstrated that the difference ΔTS_β was highest for a mean angle of fish body orientation equalling to 10° and 5°-standard deviation. Just this result is presented in Figure 8b.

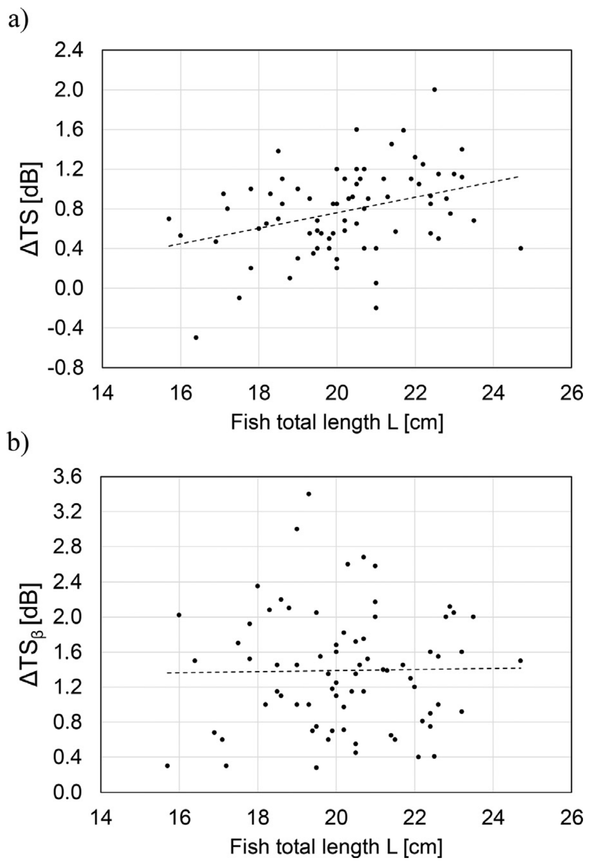

Figure 8 The difference (ΔTS) between averaged target strength *TS* for the prolate spheroid shapes of the fish body and swimbladder and for their shapes, obtained on the basis of digitised X-ray images, relative to *L* (plot a). The difference ΔTS_{β} between *TS* values obtained for the measured values of the β and those for $\beta = 0°$ (plot b). A linear regression lines are shown on both plots. Data points on both plots correspond to calculated results for 74 herring individuals considered. *TS* was calculated using Equations (2)—(9). The calculations assumed a mean angle of fish body orientation equalling to 0° and 10° — standard deviation of the orientation distribution (plot a) and respectively 10° and 5° (plot b).

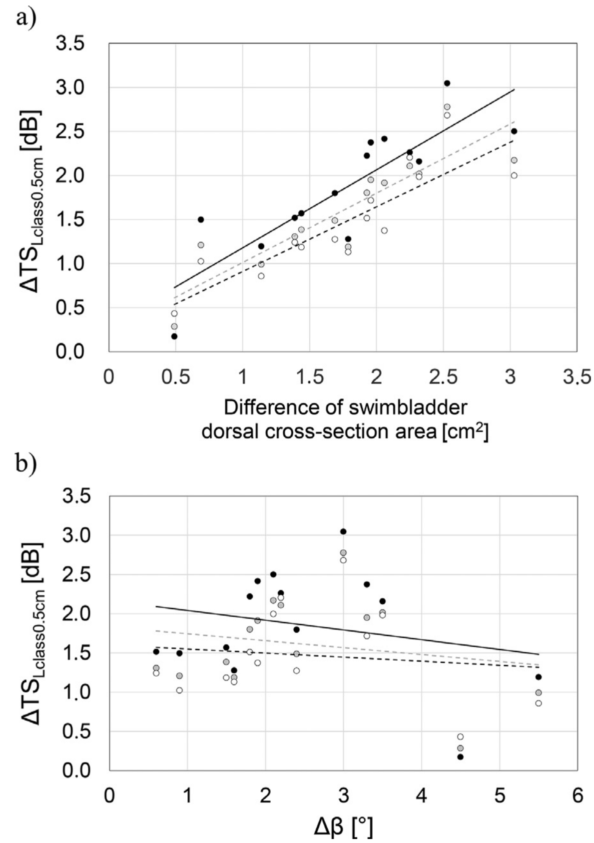

Figure 9 Scattering plots: $\Delta TS_{Lclass0.5cm}$ vs. the difference between the largest and smallest:
- swimbladder dorsal cross-section areas (plot a) and
- angle β between the longitudinal body and swimbladder axes for particular size classes. The calculations were made for a mean angle of fish body orientation $\bar{\gamma} = 0°$. The standard deviation of the orientation distribution $S_{\gamma}$was equal to 5° (black dots and black linear regression line), 10° (grey dots and grey dotted linear regression line) and 20° (white dots and black dotted linear regression line).

4. Discussion

4.1. *TS* differentiation within particular fish size classes

The finding, regarding the swimbladder geometry differentiation of the same size class individuals (Section 3.1), has been confirmed by studies reported in (Fässler et al., 2008). Figure 1 from that paper, where a relationship between the Baltic herring swimbladder volume and fish weight is presented, demonstrated a considerable scatter of swimbladder volumes in fish of the same weight (i.e. an identical total length).

Baltic herring *TS* is strongly sensitive to swimbladder morphometry and fish orientation (Fässler et al., 2008; Fässler and Gorska, 2009; Idczak and Gorska, 2016; Idczak and Kniaź-Kubacka, 2012). Therefore, the differentiation for fish of similar length in swimbladder morphometry (Figures 3—5) and the angle β between the longitudinal body and swimbladder axes (Figure 6), which defines the angle between the longitudinal axis of swimbladder and incident wave, Θ_{sb}, governing the backscattering, could provide the differentiation of averaged *TS* within particular fish size classes.

To check this, the dependence of the $\Delta TS_{Lclass0.5cm}$ on the swimbladder morphometry and the angle β was analysed. The obtained results are presented in Figure 9a and b for a mean angle of fish body orientation $\bar{\gamma} = 0°$ and the standard deviations of the orientation distribution S_{γ}: 5°, 10° and 20°. In both plots a and b the results are marked by black, grey and white dots respectively. The respective linear regression lines are: black solid, grey dotted and black dotted.

In Figure 9a, the high correlation between the $\Delta TS_{Lclass0.5cm}$ and the difference of the largest and smallest swimbladder dorsal cross-section areas for particular size classes (see Figure 4), is demonstrated. The square of correlation coefficients (R^2) were 0.73; 0.78 and 0.75 for S_γ: 5°, 10° and 20° respectively. For $S_\gamma = 10°$ and mean orientation $\bar{\gamma}$ 5° and 10° (the results were not presented in Figure 9b) the coefficient R^2 was equal to 0.62 and 0.41 respectively.

In Figure 9b, the lack of correlation between the $\Delta TS_{Lclass0.5cm}$ and the difference of the largest and smallest angles β for particular size classes is shown over the entire considered range of parameters of orientation distribution ($\bar{\gamma}$ and S_γ). The R^2 coefficient varies in the range from 0.005 to 0.06. The lack of correlation could be related to the smaller difference of the angles β in particular size classes (about a few degrees) in relation to the width of fish backscattering directivity pattern, which varies from 12.6° to 22.6° for 74-herring sample, and parameter S_γ (varies from 5° to 20° in our calculations).

The sensitivity of the difference between the highest and lowest values of averaged target strength, demonstrated in Section 3.2, is related to the strong orientation sensitivity of the averaged target strength to the fish orientation distribution parameters (Idczak and Gorska, 2016). However, if averaged target strength increased by about 4 dB for some size classes with S_γ growth from 5° to 20° ($\bar{\gamma} = 0°$) (Idczak and Gorska, 2016), the $\Delta TS_{Lclass0.5cm}$ difference varied not more than 1 dB over this S_γ range.

Analysing the target strength differentiation of individuals of the similar length, individuals were divided in 0.5-cm size classes. It was done because we would like to understand the effect on TS only of differentiation of the swimbladder morphometry of fish with a similar total length, and to eliminate the effect of the total length itself within the class.

Due to the limited number of considered fish (74) the division in 0.5-cm size classes resulted in a small number of fish in particular classes. Although this does not allow to perform deep statistical analysis for each size class, the results obtained are important. Due to different objective reasons, it is difficult to obtain morphometry data for large fish collection. As a result, in the studies of fish backscattering properties, collection of no more than ca 30 fish within a wide range of total lengths was considered (e.g. Hazen and Horne, 2003, 2004). In this approach, it is important to understand the possible difference in the swimbladder morphometry of the selected fish of the same length.

Accounting for the differentiation of the target strength within particular size classes, it could be concluded that in the *TS* modelling for the Baltic herring it is important to use sufficient amount of morphometric input data: one should be very careful with theoretical prediction of fish *TS* basing on a few fish individuals.

4.2. Improvement of the backscatter model for herring in the ICES subdivision 26

4.2.1. Fish morphometry: effect on *TS*

The previous modelling studies of Baltic herring backscattering used simplified body and swimbladder shapes — prolate spheroids (Fässler et al., 2008; Fässler and Gorska, 2009; Gorska and Idczak, 2010; Idczak and Kniaź-Kubacka, 2012). Some of the authors ignored the angle between the swimbladder and the body longitudinal axis (Fässler et al., 2008; Fässler and Gorska, 2009). In our study, the backscatter model has been improved:

- the two-dimensional digitized dorsal images of herring swimbladder,
- the angles β between the swimbladder and the body longitudinal axis, defined from the images,
- were used as input data.

The effect of swimbladder shape, and the angle β on the averaged target strength *TS* have been evaluated (section 3.3). Comparing panels a and b from Figure 8 it was concluded that the effect of taking into account the actual measured values of the β angle on the *TS* is stronger than of considering the actual shape of the swimbladder:

— for 99% fish, ΔTS is smaller than 1.6 dB, but ΔTS_β exceeds this value for 35% individuals;
— the differences ΔTS and ΔTS_β could achieve up to about 2 dB and 3.4 dB (the biggest values).

The sensitivity of the averaged target strength to the angle β between the longitudinal body and swimbladder axes, which impact the angle between longitudinal axis of swimbladder and incident wave, Θ_{sb}, governing the backscattering, is in line with result of the previous studies which demonstrated the strong effect of fish orientation on the *TS* (Idczak and Gorska, 2016).

4.2.2. Comparison of calculated *TS* with the values measured during the r/v *Baltica* cruise

As the next step, it was important to understand, the accuracy of the MSB-DCM approach used to describe the herring backscattering in ICES subdivision 26. Possible verifications have been made: *TS* modelling results were compared with the available measured data.

The two PDFs of fish total length of two herring collections: our 74-fish collection and 219-fish sample, taken during the mentioned above r/v *Baltica* cruise, are comparable (Figure 2). Therefore, it is reasonable to compare target strengths calculated using our herring data set with the *TS* measured just before the haul, from which the herring sample (219 individuals) was taken (Grygiel et al., 2011).

The dependence of the non-averaged target strength of individual fish calculated as:

$$TS = 10\log_{10}(\sigma_{sb} + \sigma_b) \tag{11}$$

on individual orientation angle γ (Figure 1) is presented in Figure 10 for the 74-fish collection (thin black curves). Similar to the averaged case, due to the dominance of swimbladder in the backscattering by herring, the swimbladder and body were not considered as a coupled system. It could impact slightly the difference between theoretical and measured results presented below.

The highest measured target strength was −30 dB (top black straight line), while the lowest one −60 dB (bottom black straight line) (Grygiel et al., 2011). Meanwhile, the calculations demonstrated that the maximum target strength was −34 dB and the minimum one −63 dB. These two ranges have a common part, but the measured one is shifted towards the larger *TS* with respect to the calculated range.

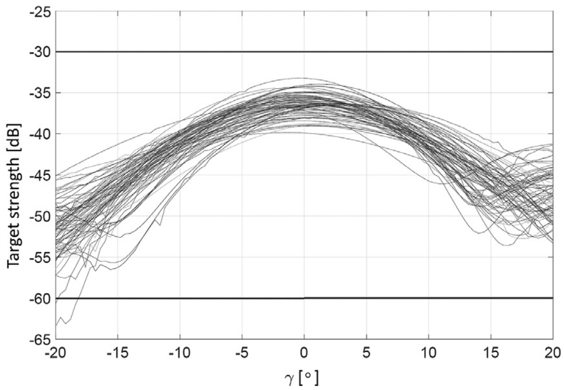

Figure 10 The dependence of calculated fish non-averaged target strength on individual orientation angle γ for 74 fish collection (different curves refer to different herring individuals). Horizontal black lines indicate the limits of the measured target strength variability range. The figure is generated using the MSB-DCM (Equations (2)—(5) and Equation (11)). The angle range, from −20° to +20°, in which the used MSB-DCM is accurate (Jech et al., 2015), was considered.

The larger measured minimum *TS* (−60 dB vs. −63 dB) could be explained e.g., by deviating the longitudinal axis of fish from a level less than about 17 degrees for the head down-position of herring individuals. However, the larger measured maximum *TS* (−30 dB vs. −34 dB) could be explained e.g., by the presence of a small number of cod (less than 3% (Grygiel et al., 2011)) in the haul.

It could be concluded that MSB-DCM approach enabled reasonable estimation of the variability range of target strength of individual herring in ICES subdivision 26.

4.2.3. Comparison of calculated and measured *TS*(*L*) regressions

The herring averaged target strength as a function of the total length was calculated for the 74 herring collection within the considered ranges of a mean angle γ and standard deviation of fish body orientation distribution S_γ. For each calculated set of *TS*(*L*) data, the *TS*-*L* relationship (Equation (1)) was introduced and the intercept b_{20} was determined. It was shown that the intercept changed from $b_{20} = -67.0$ dB ($\bar{\gamma} = 10°$ and $S_\gamma = 2°$) to $b_{20} = -62.6$ dB ($\bar{\gamma} = 0°$ and $S_\gamma = 2°$), i.e. by 4.4 dB. In this subsection, we compare the calculated intercept b_{20} with the results of measurements dedicated to ICES subdivision 26 and the adjacent subdivisions (Didrikas, 2005; Didrikas and Hansson, 2004; Kasatkina, 2009; Schmidt et al., 2011).

There is difficulty in the comparison of these modelling results with the in situ measured intercepts because the measured intercepts b_{20} were derived joining the backscattering data for different subdivisions:

— by Didrikas (2005) for subdivisions 25, 26, and 28,
— by Didrikas and Hansson (2004) for subdivisions 26 and 27
— by Schmidt et al. (2011) for subdivisions 24, 25 and 26.

Only Kasatkina (2009) analysed the data collected in the subdivision 26.

The values of the intercept b_{20}, obtained during in situ measurements, conducted by Didrikas (2005), Didrikas and Hansson (2004), and Schmidt et al. (2011), varied over the range from −67.8 to −66.3 dB, which is close to the lower part of the b_{20} calculated range (−67.0 dB). The intercept b_{20}, equalling to −67.5 dB (standard deviation 0.26 dB), obtained by Kasatkina (2009) for herring in ICES subdivision 26 at 38 kHz, is close to the minimum value (−67.0 dB) in the present study.

The actual reasons for some discrepancy could be only speculated inter alia because the most important influencing factors (e.g. fish orientation, physiological condition, behaviour) were not controlled during the measurements. Moreover, some of the available data were collected in years distant from the period of our research or the other seasons (Didrikas, 2005; Didrikas and Hansson, 2004; Kasatkina, 2009).

One of the limitations of the considered approach is that the backscattering by the fish backbone has not been considered. It has been shown theoretically (Pérez-Arjona, et al., 2018) that for the dorsal aspect (our case) the backbone shadows the swimbladder that decreases the backscattering and the *TS* values. This theoretical result is in good agreement with measurements of Knudsen et al. (2004). It was also confirmed by the measurements comparing swimbladder fish target strength in dorsal and ventral aspects (down-looking and up-looking measurement schemes respectively) (Knudsen et al., 2004; Wanzenböck et al., 2020). The lower *TS* was demonstrated in the dorsal aspect in which the incident acoustic wave interacts firstly with the backbone and then with the swimbladder.

The consideration of backscattering by backbone could decrease the TS value obtained by us and could give better agreement between calculated and measured intercept b_{20}.

5. Conclusions and recommendations

Accounting for that research of herring target strength, in particular, Baltic ICES subdivisions (local approach) remains an important challenge, the attempt to understand the fish morphometry features and their effect on the backscattering has been made for ICES subdivision 26.

The collection of the X-rays images for 74 herring individuals, sampled in this subdivision, have been created. The differentiation in swimbladder dimensions within one size class and hence the variability of the swimbladder dorsal cross-section area (the standard deviation up to 39.5%) has been demonstrated. The differentiation increased with fish total length.

Despite the fact that we also observe the differentiation of the angle between the longitudinal body and swimbladder axes, i.e. the factor which, as well as swimbladder dimensions, may affect the dorsal backscattering, it has been shown that the differentiation of the target strength within the same size class (up to 2.8 dB) corresponds to the dorsal cross-section area variation (the correlation coefficient 0.88).

It was shown that the impact of the shape of swimbladder and angle β on the averaged target strength *TS* could be important. The greater effect of taking into account the actual measured values of the β angle on the *TS* was found compared to the effect of considering the actual defined shape of the swimbladder.

The obtained modelling results have been considered in the light of the available measurement data on Baltic herring target strength that confirmed the reasonability of the approach we applied to study the herring *TS* in the selected subdivision.

The demonstrated differentiation of swimbladder morphometry within a particular herring size class as well as resulting from this *TS* variability, suggest that special concern should be given to a number of Baltic herring individuals, which morphometry supports numerical modelling of *TS*. We consider that this suggestion would be important independently of the methods (X-rays imaging, computed tomography, or magnetic resonance imaging) applied to determine the morphometry data, as well as of the studied fish species.

Our study focused on the study of fish morphometry and its impact on the backscattering by herring only in one region of the Baltic Sea — in ICES subdivision 26, so obtained results did not explain directly the observed 8 dB-variability of Baltic herring TS. The explanation requires research in the remaining Baltic ICES subdivisions and comparative result analysis. However, our study improves the understanding of the backscattering properties of Baltic herring and so could be considered as important for the problem solution.

Our findings confirmed that in order to obtain accurate *TS-L* relationships for Baltic herring, it is important to conduct controlled *TS* measurements, collecting data on water temperature, salinity, depth of herring occurrence, fat content and gonad state of individuals as well as herring orientation pattern.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We greatly appreciate National Marine Fisheries Research Institute in Gdynia for sharing the measurement data. We acknowledge the comments of two anonymous Reviewers, which improved the manuscript.

Funding

This work was partially supported by the University of Gdańsk (grant numbers: BW\G210-5-0499-0, 538-G210-0442-1 and 538-G210-B260-13); the project "Educators for the elite — integrated training program for PhD students, postdocs and professors as academic teachers at University of Gdańsk" (“Human Capital Operational Programme”, financial instrument: “European Social Fund”).

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