Paper

Tilt Angle and Theoretical Target Strength of the Japanese Sandeel, *Ammodytes personatus*, Captured on the Northern Coast of Hokkaido

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(Received February 8, 2013)

Abstract:

The tilt angle, i.e., the angle from horizontal made by the fish body as its head dives down or up, affects the readings on fish echo soundings. We measured the tilt angle of Japanese sandeels (*Ammodytes personatus* Girard) in a water tank, and calculated the acoustic target strength (TS) using a theoretical scattering model. This study examined the TS of sandeels from the northern coast of Hokkaido, which have a larger body size than those in other regions in Japan. TS values for sandeels, a swimbladderless fish, were estimated using a distorted-wave Born approximation (DWBA) model at two frequencies: 38 and 120 kHz. The mean tilt angle was 20.4° (S.D.=18.5°), which differed slightly from that of the lesser sandeel, *Ammodytes marinus*. The regression equations of the average TS values were $TS_{38\,\mathrm{kHz}}=8.2\log_{10}SL-74.2$ and $TS_{120\,\mathrm{kHz}}=20.9\log_{10}SL-92.6$, respectively. At 120 kHz, the slope was close to 20, suggesting that the acoustic backscattering strength was proportional to the square of the body length. This value was smaller at 38 kHz, suggesting that the acoustic backscattering strength was stable to differences in body length. We obtained a small discrepancy for both frequencies ($\Delta TS=TS_{120\,\mathrm{kHz}}-TS_{38\,\mathrm{kHz}}$) were $TS_{120\,\mathrm{kHz}}<TS_{38\,\mathrm{kHz}}$. Discrepancies of −1.3 dB for the maximum TS, and −1.8 dB for averaged TS were found in 72 fish samples, which would be useful for identifying sandeel schools in practical analysis using TS differences.

Classification: Fisheries acoustics, Bioacoustics

Keywords: Japanese sandeel, tilt angle, theoretical target strength

1. Introduction

The Japanese sandeel (*Ammodytes personatus*, "sandeel" hereafter) plays an important role in marine ecosystems, not only as a food source for several marine organisms but also as a target for Japanese fisheries.[1,2)]

The fishing season for the sandeel fisheries off the northern coast of Hokkaido occurs during the summer months (June–September) every year. Fish with a body length of 15–25 cm are caught using a bottom trawling technique. However, the relationship between oceanographic changes in the fishing grounds and the availability of prey are not well understood, although aggregations of sandeels in this area have been reported. To ensure efficient fisheries management policies in the future, it is necessary to determine how sandeel fishing grounds are formed. Quantitative echo soundings can be used to obtain vertical profiles, which are useful when investigating the relationships among environmental factors, prey species, and the abundance of sandeels.

Acoustic methods form the basis of estimates of fish abundance and their distribution in the field. The target strength (TS) of individuals of a particular species is a key factor when making fish abundance estimates during an acoustic survey. It can be used to convert acoustic data to numbers of individuals or fish biomass.[3)] Yasuma[4)] measured the TS of sandeel in Ise Bay, Honshu Island. However, the body length of sandeels in Ise Bay is smaller than that in Hokkaido, with a maximum body length of about 16 cm.[1)]

In acoustically derived TS measurements, the variability between individuals depends on biological and physical factors. Among these factors, the tilt angle of the fish is the most important factor influencing variability in TS.[5)] Especially since sandeels do not have a swimbladder, the TS value could be strongly influenced by their tilt angle, defined as the angle from true horizontal of the fish body as it orients itself with head up or head down. Measurements of the tilt angle of sandeels have not yet been reported. If the tilt angle frequency distribution is known, the expected average TS and the factors necessary to convert the integrated echo intensity to fish density can be calculated from the experimentally obtained directivity functions of individual fish.[6,7)]

In this study, we used a theoretical scattering model and tilt angle data to obtain the TS estimates for sandeel. We clarified the tilt angle distribution of larger sandeels by observing swimming behavior in an experimental water tank. TS values were examined using the distorted-wave Born approximation (DWBA) model.

2. Materials and Methods

2.1 Fish samples

Fish samples ranged from approximately 21.0 to 28.7 cm in standard length (*SL*) caught by otter trawling (a commercial fishery technique) in the Sarufutsu waters (northern coast of Hokkaido), Japan, in July 2011. Sample fish were used for the measurement of the tilt angle and in July 2012 for estimates of TS. The sampling periods selected fell within the main fishing season for sandeel. After capture, samples were transferred as soon as possible to a tank. Prior to tilt angle measurements, fish were kept in a stock tank to reduce the possibility of stress during transfer, and only fish observed to display normal swimming behavior were chosen. Subsequently, fish were transferred from the stock tank and placed in an experimental water tank.

2.2 Measurement of tilt angle

Tilt angle data were collected from free-swimming sandeel from 20 to 21 July 2011, at the

Wakkanai Fisheries Research Institute, Hokkaido Research Organization, Japan. The experiment was conducted in a rectangular tank (2.05×2.0×1.2 m) (**Fig. 1**), with no sand at the bottom to prevent the fish from burrowing. The tank was filled with seawater without any water flow. Recordings were made under a light intensity of 275 lx at the water surface.

The tilt angle of sandeels was recorded using a digital HD video camera recorder (HDR-SR12; Sony, Tokyo, Japan). A video camera was set up in front of the experimental tank. The video recordings obtained were converted to images at 30-second intervals during the experimental periods. The images were analyzed with image-editing software (SCM Measure; Moritex Corp., Tokyo, Japan). In the image analysis, the centerline of the fish being measured could not bend and the body axis was located in or near the plane perpendicular to the camera's focal axis. The angle measured was that between the center line of the fish, an imaginary line running from the root of the tail to the tip, and the true horizontal. Positive angles were obtained for fish with their heads up, and negative angles were obtained for those with their head down. The tilt angle distribution from the images was used to calculate the average TS (TS_{avg}) according to Foote[6] after the normalization of the distribution of tilt angle using a probability density function (PDF), which can be formulated as

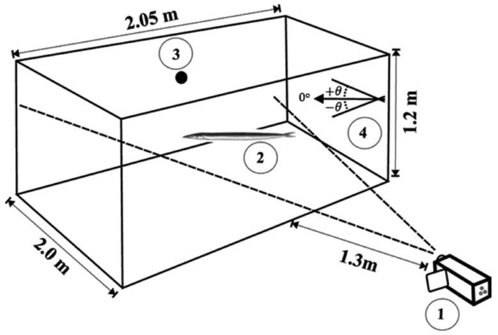

Fig. 1 Schematic diagram of the experimental tank: (1) camera, (2) specimen, (3) reference point, and (4) the tilt angles. The camera was installed at the front of the experiment tank.

$$PDF\,(a \le x \le b) = \int_a^b f(x)\,dx \tag{1}$$

where the PDF of x is a function $f(x)$. It is expressed in terms of an integral between two points, and a and b are the minimum and maximum values, respectively, of the tilt angle.

2.3 Theoretical scattering model

The DWBA model was used to estimate the theoretical TS.[8–11] The DWBA model was originally developed for studies of zooplankton. However, it has also been applied to fish such as Atlantic mackerel[12] and Japanese anchovies.[13] Scattering models based on a simplified DWBA method were estimated with two frequencies (38 and 120 kHz) related to fish orientation from −90° to +90° at 1° intervals (tilt angle: head-down, head-up position).

The images of fish samples were digitized based on the outline of body shape to calculate the theoretical model. To compute the theoretical TS, the sound speed contrast (h) and density contrast (g) were assumed to be constant throughout the fish's body. These values were taken from Yasuma[4] for adult sandeels: h=1.018, g=1.032. A DWBA model is composed of a volume integral that can be written as

$$f_{\mathrm{bs}} = \int_{\vec{r}_{\mathrm{pos}}} \frac{k_{\mathrm{sw}}^2 a_c}{4k_{\mathrm{animal}}} \left(\frac{1+h^2}{gh^2} - 2 \right) \times e^{2ik_{\mathrm{animal}}\vec{r}_{\mathrm{pos}}} \frac{J_1(2k_{\mathrm{animal}}\,\mathrm{a_c} \cos\beta_{\mathrm{tilt}})}{\cos\beta_{\mathrm{tilt}}} + \left| d\vec{r}_{\mathrm{pos}} \right| \tag{2}$$

where f_{bs} is the complex back-scattering amplitude, $\sigma_{\mathrm{bs}}=|f_{\mathrm{bs}}|^2$ is the relationship of this amplitude to the backscattering cross section σ_{bs}, $\vec{r}_{\mathrm{pos}}$ is the position vector along the body axis, and k is the wave number shown by $k=2\pi/\lambda$, where λ is the acoustic wavelength; the subscript sw refers to the surrounding seawater and the subscript animal refers to the sandeel. In addition, J_1 is a Bessel function of the first kind, a_c is the cross-sectional radius of the cylinder, and β_{tilt} is the local angle between the cylinder axis and the incident wave.[11,13,14] For each of the 72 specimens for which the body mass and sound speed were measured, images were digitized to obtain $\vec{r}_{\mathrm{pos}}$ and a_c values[8,9,12] (**Fig. 2**). This equation was calculated numerically using Matlab (version 7.9.0.529; MathWorks, Natick, MA, USA) codes to estimate the TS of a deformed cylinder.[11]

Using this result, the mean and standard deviation of the tilt angle distribution was substituted into a theoretical scattering model. Furthermore, the TS values of individual fish were used to obtain two TS measurements: the maximum dorsal aspect TS (TS_{max}) and the average dorsal aspect TS (TS_{avg}). TS_{max} was easily obtained from the measured TS functions. TS_{avg} was derived from Eq. (3) and (4)[6]:

$$\sigma_{\mathrm{avg}} = \int_{-\pi/2}^{\pi/2} \sigma(\theta) f(\theta)\, d\theta \tag{3}$$

$$TS_{\mathrm{avg}}=10 \log \sigma_{\mathrm{avg}} \tag{4}$$

where θ is defined as the tilt angle and $f(\theta)$ is assumed to be a truncated normal distribution function. The truncations were made at $\overline{\theta}-3S_\theta$ and $\overline{\theta}+3S_\theta$, where $\overline{\theta}$ and $3S_\theta$ denote the mean and standard deviation of the tilt angle, respectively. The relationship between TS and fish length[3,15] can be expressed as

$$TS=m\ 10 \log_{10} SL+b \tag{5}$$

where m and b are species-specific slopes and intercepts, and SL is the standard length of the fish, which was determined from the fish samples. For each regression, the slope, intercept, R^2, and p-value were calculated.[3,16]

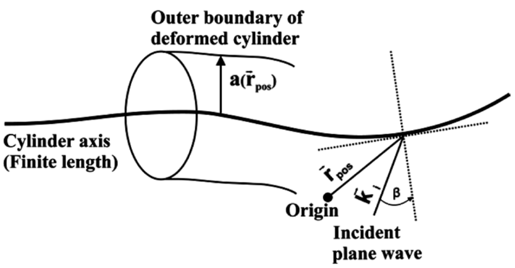

Fig. 2 Deformed finite cylinder and scattering geometry.

3. Results

3.1 Tilt angle

Twenty live fishes were used to measure the tilt angle. We assumed that their density was representative of the natural conditions of a sandeel school in the field during the daytime. To calculate the tilt angle of the sandeels, 1,197 images collected from approximately 11 hours of video records were used. Because of the poor image quality, further analysis was possible for only 95 ideal images. The results of the tilt angle distribution are shown in **Fig. 3**. Fish were in a head-up position for approxi-

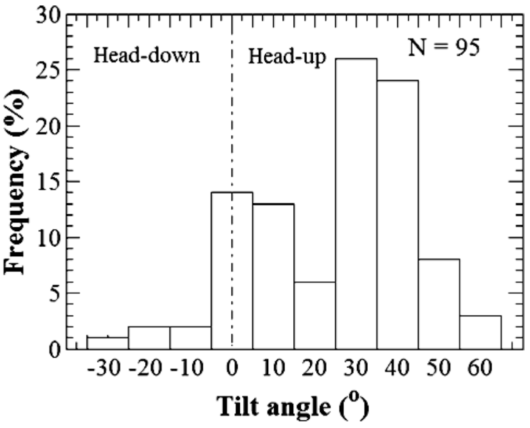

Fig. 3 Frequency distributions of the tilt angles of Japanese sandeels obtained from experiments. The mean and standard deviation were 20.4±18.5°, respectively.

mately 81.1% of the observations. Sandeels tend to display a positive head-up position as they are swimbladderless fish.

The mean tilt angle and standard deviation were 20.4±18.5°, respectively. Parameters such as the mean and standard deviation, for the distribution of tilt angles were substituted into the theoretical backscattering model, and the corresponding TS values were determined.

3.2 Theoretical target strength

Typical examples of TS as a function of tilt angle properties at 38 and 120 kHz are shown in **Fig. 4**, where the frequencies commonly used in acoustic fish abundance estimates were calculated by DWBA models. The variation in TS in relation to changes of tilt angle displayed a peak around 0° (main lobe) at both frequencies. The side lobes also displayed a small discrepancy at both frequencies, although it was higher at 120 kHz. The peaks were relatively sharp, especially for the higher frequency, suggesting that slight changes in the tilt angles of fish have a major effect on TS.

The TS values at both frequencies for small fish peaked near the main lobe. However, the values of $TS_{\max}$ and TS_{avg} at 38 kHz were higher than those at 120 kHz for the large fish, indicating that fish length had a considerable impact on TS variability.

3.3 TS–SL relationships

We determined theoretical TS values using the 72 dead fish ranging from 16.1 to 28.7 cm in standard length. The TS values for Japanese sandeels were influenced by the tilt angle and acoustic frequency. The values of $TS_{\max}$ and the TS_{avg} as functions of linear values of fish standard length (cm) at both frequencies are plotted in **Fig. 5**. The values of $TS_{\max}$ and the TS_{avg} showed difference between the two wavelengths. In most cases, the values of $TS_{\max}$ and the TS_{avg} at 38 kHz were higher than those at 120 kHz.

Positive correlations were found between TS values and fish length at both 38 and 120 kHz (Fig. 5, **Table 1**). The best fit regression lines of TS_{avg} were $TS_{38\,\mathrm{kHz}}=8.2\log_{10} SL-74.2$ and $TS_{120\,\mathrm{kHz}}=20.9\log_{10} SL-92.6$, respectively. The linear values of SL of the regression lines were around 20 for TS_{avg} at 120 kHz, which was lower than those at 38 kHz. A small discrepancy was noted in the values of $TS_{\max}$ and the TS_{avg} between 38 kHz and 120 kHz ($\Delta TS=TS_{120\,\mathrm{kHz}}-TS_{38\,\mathrm{kHz}}$), where $TS_{120\,\mathrm{kHz}}<TS_{38\,\mathrm{kHz}}$.

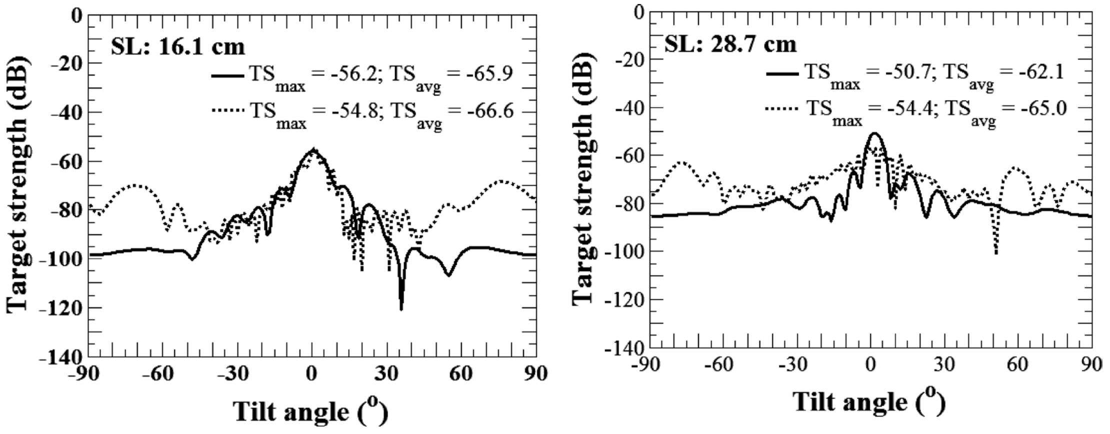

Fig. 4 Theoretical TS values as a function of tilt angle, estimated by a DWBA model at 38 kHz (solid lines) and 120 kHz (dashed lines), respectively. Fish sizes are noted for each frequency.

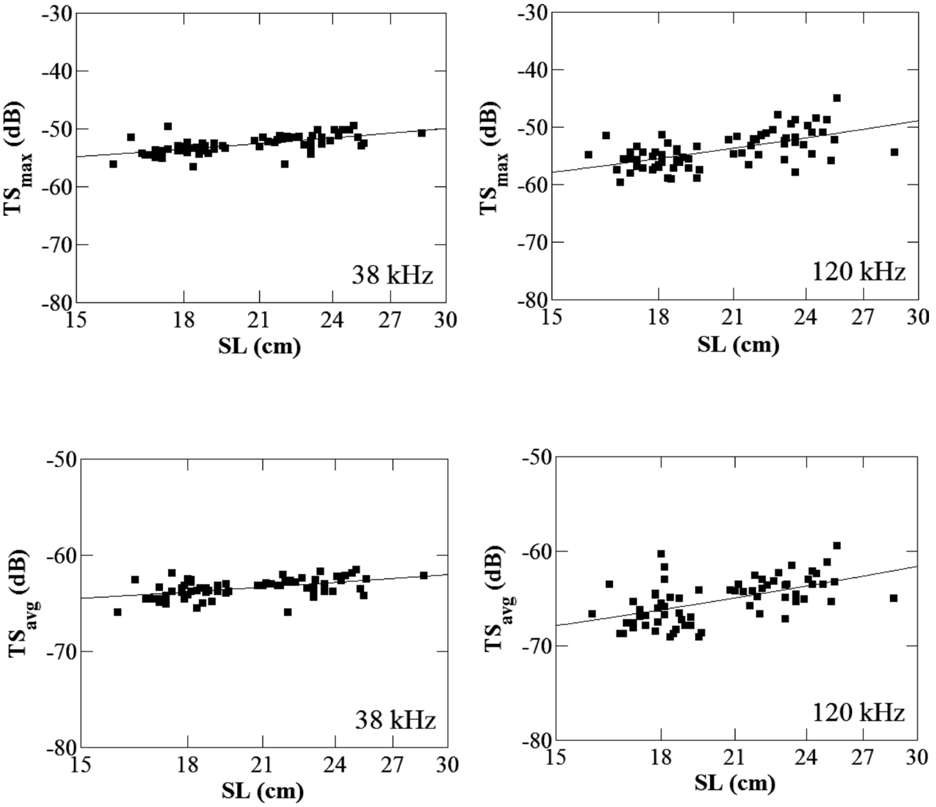

Fig. 5 The relationship between TS ($TS_{\max}$, TS_{avg}) and the linear values of standard length (cm) at 38 and 120 kHz, n=72.

Table 1 Equations for the linear regression in Fig. 5 and the target strength at each frequency.

Target strength	Frequency (kHz)			
	38		120	
	Range	TS-length equation (R^2; p-value)	Range	TS-length equation (R^2; p-value)
$TS_{\max}$ (dB)	−56.7 to −49.5	$TS_{\max}=16.3 \log_{10} SL-74.1$ (0.40; <0.001)	−59.7 to −44.9	$TS_{\max}=29.9 \log_{10} SL-93.3$ (0.36; <0.001)
TS_{avg} (dB)	−65.9 to −61.5	$TS_{\mathrm{avg}}=8.2 \log_{10} SL-74.2$ (0.25; <0.001)	−69.1 to −59.5	$TS_{\mathrm{avg}}=20.9 \log_{10} SL-92.6$ (0.30; <0.001)

4. Discussion

4.1 Tilt angle

TS estimates should ideally include the tilt angle distribution if possible.[17] During the observations, the tilt angle varied depending on the activities of the sandeels. Figure 3 shows the bimodal distribution of the tilt angle of the sandeels. This bimodalism may have occurred due to a small sample size in measurements (n=95). If we get more images, the result might become a normal distribution as presented by Kubilius and Ona,[18] who measured the tilt angle of lesser sandeels in a small on-board fish tank and found a monomodal distribution of tilt angle (n=534). In this study, we used a monomodal distribution that was normalized by PDF to calculate the average target strength pattern as shown in the results herein. Future work is needed to obtain a more precise tilt angle distribution for the Japanese sandeel.

In addition, this distribution may have arisen because we measured only the pitch orientation of fish through a camera set in front of the tank; thus, future studies should consider using two cameras. The other camera could be installed to make recordings at the dorsal side, which can be used to verify that the individual being measured is perpendicular to the camera.

Sandeels are generally negatively buoyant. Hence, they must swim with some positive body tilt to maintain altitude.18) In line with Ona,17) who noted that negatively buoyant fish often swim with a slight head-up posture, we found that the mean tilt angle distribution of Japanese sandeels was 20.4° (S.D.=18.5°), which was slightly different from the results presented by Kubilius and Ona18) for the lesser sandeel, *A. marinus* (23.7°±18.2°). This difference probably results from variations between the species, experimental design, and environmental conditions during the measurements. Figure 4 shows that tilt angle has a larger effect on TS variation than fish length. After reviewing the literature published on swimbladderless fish, Hazen and Horne5) concluded that tilt angle is the more important factor, followed by the influence of length and depth.

Since sandeels do not have swimbladders, there is no dominating reflector inside the target. Thus, the TS values could be influenced by their tilt angle, fish sizes and frequency of the transducer. Measurements of tilt angle are required for the accurate estimation of the TS of sandeels. Fish orientation does not explain all of the variations observed in TS. However, the tilt angle of swimbladderless fish is the most important factor influencing the TS, and large variations in TS can be induced by changing the tilt angle.3) Because acoustic scattering depends strongly upon the tilt angle, knowledge of its distribution will help to interpret acoustic survey data.19) In the field, a small change in fish tilt angle relative to the transducer surface can have dramatic effects on the backscattering cross section.17,20)

We suggest further *in situ* measurements to provide more precise information regarding the tilt angle of Japanese sandeels. Probably, the most important sources of error when calculating the tilt angle calculation were generated by the artificial environment of the experimental tank, including its rectangular form and limited size, and also the need to simulate natural conditions in the tank such as water temperature, light intensity, and water flows.

4.2 Target strength

TS estimates of fish have been conducted in a wide variety of experiments because of their importance when analyzing acoustic data and further converting measurements to fish biomass. However, a lack of information exists regarding the TS of large sandeels. This study is a preliminary attempt to measure the TS of adult Japanese sandeels (Fig. 4).

Generally, the TS function from a theoretical backscattering model at 38 kHz, as shown in Fig. 4, fluctuates more on the side lobe. However, TS values for both frequencies tended to be consistent near the main lobe especially for small fish. Discrepancies in the results were found, not only due to the response to the frequencies used in the theoretical model, but also due to fish length; it seemed that at 38 kHz, a higher TS was found for larger fish, and so fish length contributes to the variability of TS (Fig. 4) and therefore is an important factor to consider. More reliable TS information from *in situ* measurements is required.

Figure 5 gives the SL-TS curves for 38 and 120 kHz. We found that the TS can differ near for fish having the same values of SL, such as within 18 cm. The difference of TS ranged near 7 dB at

120 kHz. Because in our analysis the TS of fish were obtained by digitizing the body shapes at the dorsal aspect. Therefore, the variation of TS was caused by differences in not only body length but also body width, which was not considered in these measurements. Measurements of TS results were more sensitive at 120 kHz than at 38 kHz. Future work is needed to verify these results.

The slope at 120 kHz was close to 20 (Fig. 5; Table 1), suggesting that the acoustic backscattering strength was proportional to the square of body length. However, this value was smaller at 38 kHz, suggesting that backscattering strength tended to be stable with changes in body length. One possible reason for this is that the body length of the fish samples used fell into a relatively narrow range. However, the fish lengths used are representative of the sandeel stock off the northern coast of Hokkaido. The differences in TS values at the two frequencies have important practical applications for identifying sandeel schools.

Little information has been available regarding TS values of Japanese sandeels. Previous results have been reported by Yasuma[4] for juveniles (3.4–6.7 cm, n=68) and adult fish (7.5–11.5 cm, n=20) using a liquid deformed cylinder model (liquid DCM) method. They reported that TS values of the near dorsal aspect and tilt-averaged TS values differed by up to 7 dB, and the slope logarithm standard length of adults was close to 20. They concluded that the TS-length regressions of *A. personatus* were $TS=20\log_{10}L-89.2$ at 38 kHz and $TS=20.7\log_{10}L-92.1$ at 120 kHz, respectively. TS-length equations for other sandeel species (*Ammodytes* spp.) have been reported previously. The TS of *A. hexapterus* was estimated by the following equations: $TS=20\log_{10}L-93.7$ at 38 kHz[21] and $TS=20\log_{10}L-80.0$ at 120 kHz.[22] Recently, Kubilius and Ona[18] proposed the TS-fish length relationship for *A. marinus* to be $TS=20\log_{10}L-93.1$ at 200 kHz. Our results were very different as shown in Table 1. The reason for the differences in the TS values is unclear, but may be due to our use of a different method to estimate the TS values and our consideration of data regarding the tilt angle in the TS calculation.

This is the first study to document the tilt angle of Japanese sandeels in an experimental tank and to apply a theoretical scattering model, such as a DWBA model. The results indicated that several factors affect the TS of sandeels, including tilt angle, fish length, and frequency responses. The TS information will be useful for estimating the abundance and distribution of sandeels in the field using echo sounders, which are commonly used on many commercial fishing vessels in Japan.

Acknowledgements

We thank the members of the Laboratory of Marine Ecosystem Changes Analysis, Hokkaido University, for their cooperation in preparing for and performing the experiments. We are very grateful to the two anonymous referees who contributed greatly to the manuscript improvement. We would like to acknowledge the Government of South Sulawesi Province, Indonesia, for their significant financial support of our studies at Hokkaido University, Japan. This study was supported by the collaboration between Hokkaido University and the Wakkanai Fisheries Research Institute, Hokkaido Research Organization, Japan.

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