

Article

Comparison of Target Strength of Pacific Herring (*Clupea pallasii* Valenciennes, 1847) from Ex-Situ Measurements and a Theoretical Model

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Abstract: Pacific herring (*Clupea pallasii* Valenciennes, 1847) is a commercially important species that inhabits the coastal waters of the North Pacific from Korea to California, USA. This study analyzed the target strength (TS; dB re 1 m²) of Pacific herring individuals ($n = 14$, total length (L_T) = 21.3–32.3 cm) at 38 and 120 kHz using ex-situ measurements and the Kirchhoff-ray mode (KRM) model. The least-squares regressions of the TS– L_T relationship for the ex-situ measurements were $TS_{38\text{kHz}} = 20 \log_{10}(L_T) - 70.10$ ($r = 0.17$) and $TS_{120\text{kHz}} = 20 \log_{10}(L_T) - 70.59$ ($r = 0.10$). The least-squares regressions for the KRM model were $TS_{38\text{kHz}} = 20 \log_{10}(L_T) - 68.39$ ($r = 0.40$) and $TS_{120\text{kHz}} = 20 \log_{10}(L_T) - 69.74$ ($r = 0.49$). The b_{20} value of the KRM model was 1.71 dB higher than that of the ex-situ measurement at 38 kHz but similar at 120 kHz. These results provide basic data to evaluate the distribution and abundance of Pacific herring using fisheries' acoustic technology.

Keywords: Pacific herring; target strength; acoustic survey; ex-situ; KRM model



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1. Introduction

Pacific herring (*Clupea pallasii* Valenciennes, 1847), a fish in the family Clupeidae of the order Clupeiformes, is widely distributed in the North Pacific [1–3]. The distribution patterns showed that herrings characteristically form dense, round, or tall pelagic schools. The schools are typically small in size during summer and form a consistent, dense layer associated with the bottom in submarine gullies during winter [4]. It is an economically important fishery resource, especially in the northern latitudes of Korea and Japan [5,6]. The maximum catch of Pacific herring in South Korea in 2008 was approximately 45,000 tons, but this decreased to 25,000 tons in 2011 [7]. Records indicate fluctuations in herring catchment and variability in fishery productivity; thus, a reasonable approach to manage and evaluate the status of the stock of Pacific herring is required for the sustainable use of this resource.

Acoustic surveys using scientific echosounders can rapidly provide quantitative data and have been used for fish stock assessment [8]. The volume backscattering strength (S_V ; dB re 1 m^{−1}) can be obtained via acoustic surveys, but its conversion into abundance levels requires information on the target strength (TS; dB re 1 m²) [9,10]. Accurate acoustic estimates of target fish density are most often made by estimating TS vs. $\log(L_T)$ regression. TS measurement methods can be classified as experimental or theoretical [11,12]. Experimental approaches include ex-situ measurements of dead or live fish and in situ

measurements of freely swimming live fish in the natural habitat. The TS changes, owing to physical and biological factors such as frequency, wavelength (λ), sound speed contrast (h), and density contrast (g) as well as the body shape, length, swim bladder, depth, and tilt angle of the fish [13–16]. It is difficult to measure the TS for every change in these factors. Therefore, data are collected by actual measurements and then compared to acoustic models to calculate the TS of the targeted species under various conditions [17]. Accurate TS calculations must incorporate both experimental and theoretical methods [18].

The main objective of this study was to provide estimates of TS to convert acoustic density into abundance of Pacific herring. TS estimates were obtained by tilt angle combined with ex-situ measurement and theoretical modeling calculated at 38 and 120 kHz. This study presents the relationship between TS and total length L_T of Pacific herring as a factor in acoustic survey.

2. Materials and Methods

2.1. Fish Sample

Pacific herring were 14 individuals sampled by set net in Muk-ho port, Gangwon-do Province, Korea. The sampled fish were quick-frozen in seawater in a plastic bottle, packed on ice, and transported to the laboratory. The samples were defrosted using seawater.

2.2. Ex-Situ Measurement

The TS measurements were conducted from August to October 2016 in a seawater acoustic tank (5 m (L) $\times$ 5 m (W) $\times$ 5 m (H)) at the Fisheries Science Institute, Chonnam National University, located on the south coast of South Korea. To conduct TS measurements on dead fish of various lengths ($n = 14$), the total length L_T range was 21.3–32.3 cm (mean = 26.7 cm), and the wet weight W range was 75.5–269.8 g (mean = 150.2 g). The L_T – W relationship can be expressed as Equation (1) (Figure 1).

$$W(\text{g}) = 0.0045 \times L_T(\text{cm})^{3.1596}, R^2 = 0.93 \quad (1)$$

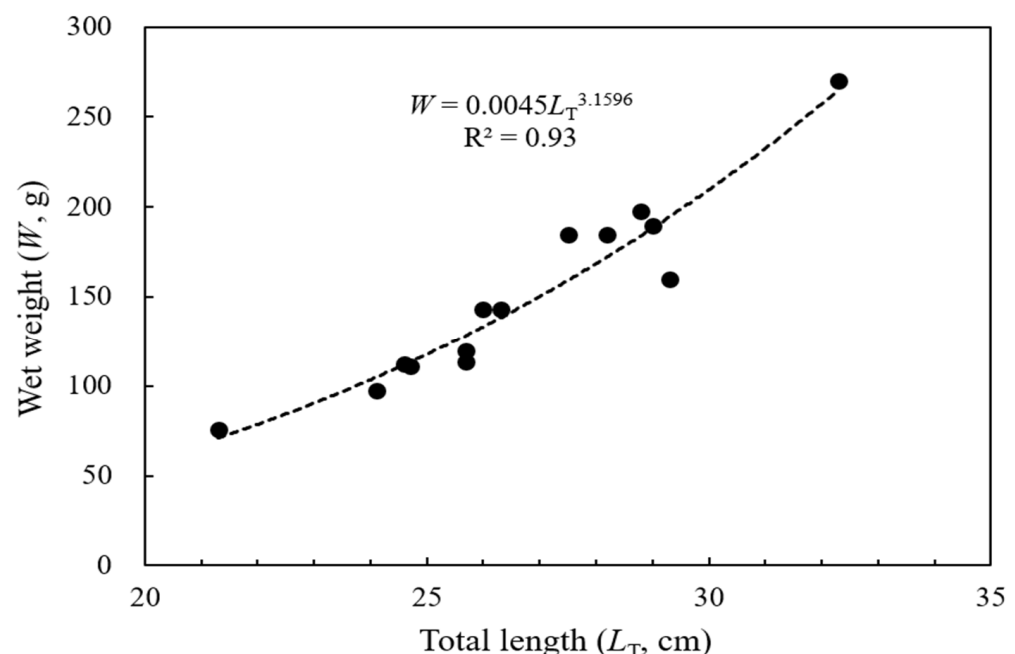


Figure 1. The relationship between total length (L_T , cm) and wet weight (W , g) in the Pacific herring used to measure TS.

Figure 2 illustrates the experimental setup and system used in the experiment. A scientific echosounder (EK60, Simrad, Kongsberg, Norway) was used to measure the TS of Pacific herring at 38 and 120 kHz (split-beam), and an underwater camera (T-water-

7000DX, WIRELESS TSUKAMOTO, Suzuka, Japan) was used to observe changes in the tilt angle. A video capture card was connected to a signal generator (WF1944A, NF Electronic Instruments, Yokohama, Japan). A square wave trigger signal was created by the signal generator, the pulse interval was controlled by an external trigger (0.5 s), and the images were saved on a computer using the video capture card (VCE-Pro, ImperX, Boca Raton, FL, USA). The ping interval of the scientific echosounder was also set to 0.5 s to synchronize with the tilt angle. The fish were tethered using long, weighted monofilament lines attached to the mouth and tail (Figure 1). It is difficult to adjust the tilt angle of dead fish; thus, a weighted monofilament line was connected to the ventral portion of the body so that the herring stayed 3.5–4.0 m below the transducers.

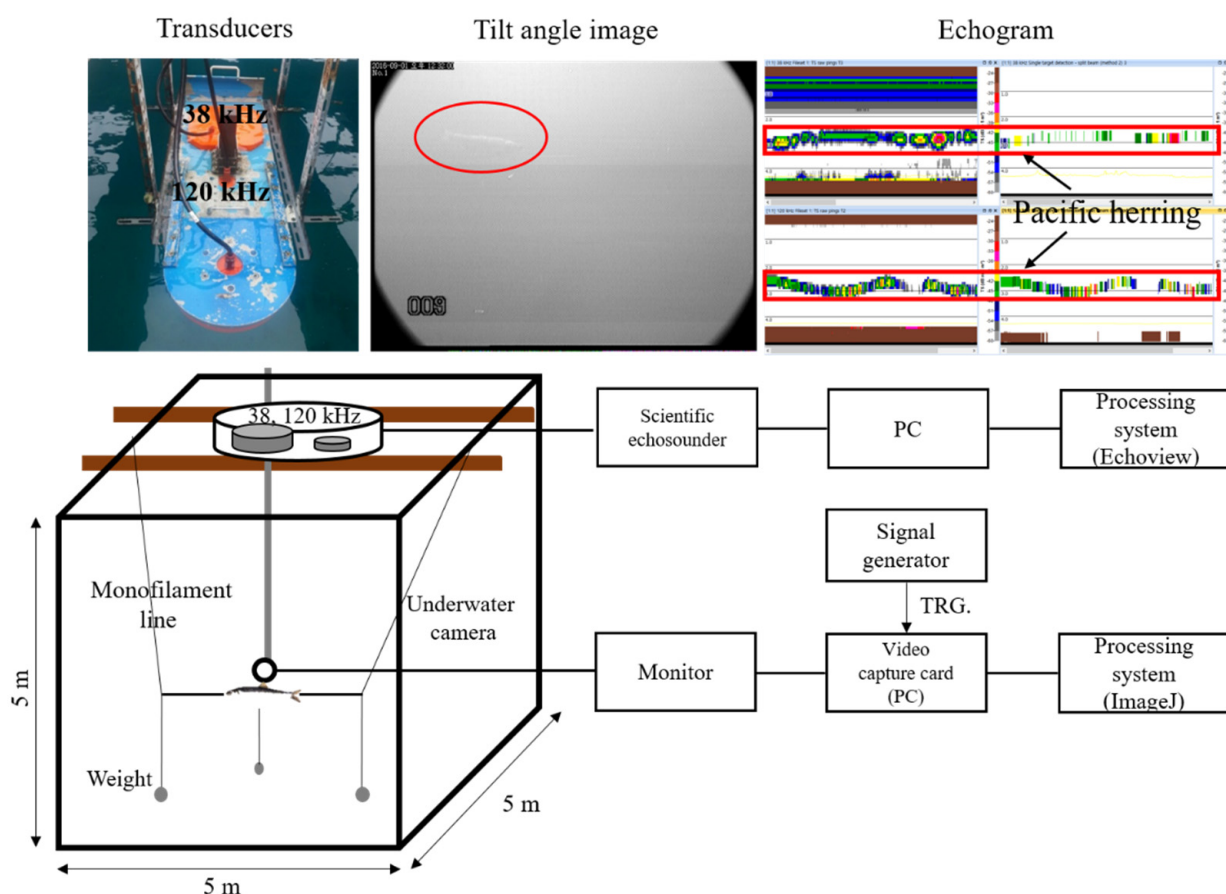


Figure 2. Block diagram of the experimental system, and a picture of the equipment used to measure Pacific herring TS.

Before the TS measurements, the echosounders were calibrated using a standard method at 38 and 120 kHz with 60 mm and 23 mm diameter copper spheres, respectively [19]. The calibration results and parameter settings at 38 and 120 kHz are shown in Table 1.

Table 1. Calibration data and parameter settings of scientific echosounder at 38 and 120 kHz.

Frequency (kHz)	38	120
Two-way beam angle (dB)	−15.5	−21.0
Transducer gain (dB)	21.0	26.20
3-dB beam angle (athwart/along) (deg.)	12.16/11.82	6.37/6.35
Absorption coefficient (dB km ^{−1})	6.0	42.7
Sound speed (m s ^{−1})	1535.6	1535.6
Power (W)	1000	250
Pulse length (ms)	0.512	0.512

2.3. The Theoretical Model

The Kirchhoff-ray mode (KRM) model [20] was used to calculate the theoretical TS of Pacific herring. The KRM model combines the breathing mode and Kirchhoff approximation to estimate the intensity of reflected sound based on the sound speed and density contrasts among water, the fish body, and swim bladder [18]. This model presents the fish body and swim bladder as a fluid-filled and gas-filled cylinder, respectively. The same Pacific herring used in the ex-situ measurements were used in the KRM model. X-rays of the dorsal and ventral aspects were taken (Figure 3), and a digitizing software (GetData Graph Digitizer V 2.26; <http://getdata-graph-digitizer.com>, Release date: 19 June 2013) was used to separate the body and swim bladder by 0.2-mm slide spacing on the lateral and ventral sides to determine the coordinates of the body contour. The TS was calculated as reduced scattering lengths (RSL), a nondimensional, linear measurement. RSL is equivalent to the square root of the backscattering cross-section (σ_{bs} , m²) divided by the length of fish in meters [18]. RSL is converted to TS and length (L_T) using

$$TS = 20 \log(RSL) + 20 \log(L_T) \quad (2)$$

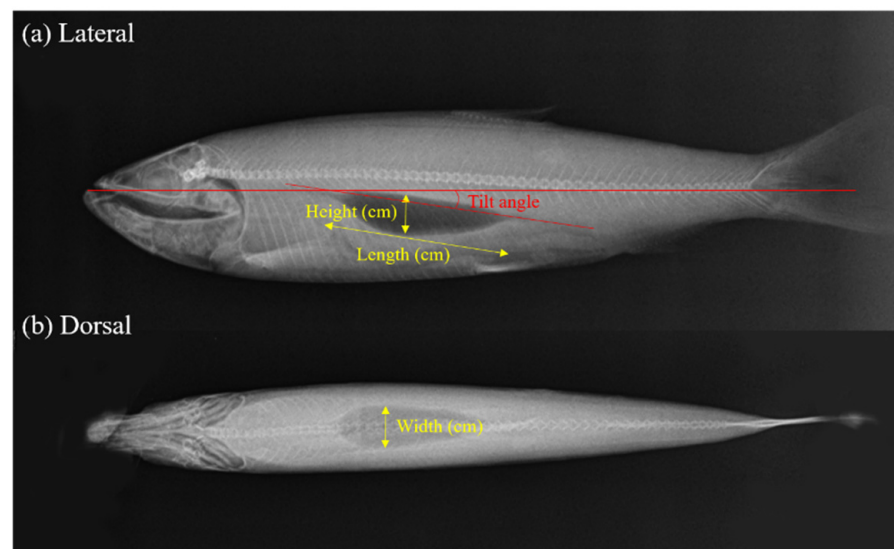


Figure 3. X-ray image of the (a) lateral and (b) dorsal aspects of Pacific herring. The swim bladder angle (θ) is indicated as the tilt angle of the swim bladder, centerline between anterior and posterior margins, according to the fish body. The swim bladder length is indicated by the distance between the swim bladder anterior and posterior margins. The swim bladder height is indicated as the maximum thickness of the swim bladder in the lateral aspect. The swim bladder width is indicated as the maximum thickness of the swim bladder in the dorsal aspect.

Sound speed and density parameters of the fish body, swim bladder, and seawater are required for TS calculations in the KRM model. The density and sound speed of the fish body and seawater were obtained from the experiment described above (ex-situ measurements), whereas the density [21] and sound speed [22] of the swim bladder were obtained from previously published reports. The following values were applied to the acoustic model: body density of 1.047 g/cm³ and sound speed of 1474.6 m/s, seawater density of 1.025 g/cm³ and sound speed of 1454.1 m/s, and swim bladder density of 1.3 kg/cm³ and sound speed of 340 m/s. The TS for each tilt angle of the 14 individuals used in constructing the KRM model was calculated at 1° intervals from −90° to 90°.

2.4. Analysis of TS Data

To assess the TS- L_T relationship between the ex-situ measurements and the theoretical model, a probability density function (PDF) was estimated for a mean daytime tilt angle ($\pm$ standard deviation; SD) of 3.8° ($\pm$ 6.0°) [23]. The TS estimated for every 1° was

transformed into a scattering cross-section, the area was multiplied by the PDF of the corresponding tilt angle, and then summed to obtain the mean TS.

$$\sigma_{bs} = \int_{-\pi/2}^{\pi/2} \sigma(\theta) f(\theta) d\theta \quad (3)$$

$$TS_{mean} = 10 \log_{10} \sigma_{mean} \quad (4)$$

where $\sigma(\theta)$ is the backscattering cross-section of each tilt angle θ and $f(\theta)$ is the occurrence frequency of each tilt angle.

The TS- L_T relationship can be expressed as Equation (5), assuming that TS is proportional to the square of the length,

$$TS = 20 \log_{10} (L_T) + b_{20} \quad (5)$$

where b_{20} indicates that the slope was fixed at 20.

3. Results

3.1. Biological Characteristics of Pacific Herring

The TS of fish is greatly affected by the size of the swim bladder; thus, the relationship between Pacific herring L_T and the swim bladder equivalent radius was investigated (Figure 4). The swim bladder equivalent radius (r) is calculated as $r = (\text{length} \times \text{height} \times \text{width})^{1/3}$ [24], where the length, height, and width refer to the dimensions of the swim bladder. The swim bladder equivalent radius increased as L_T increased, but the correlation coefficient was not significant.

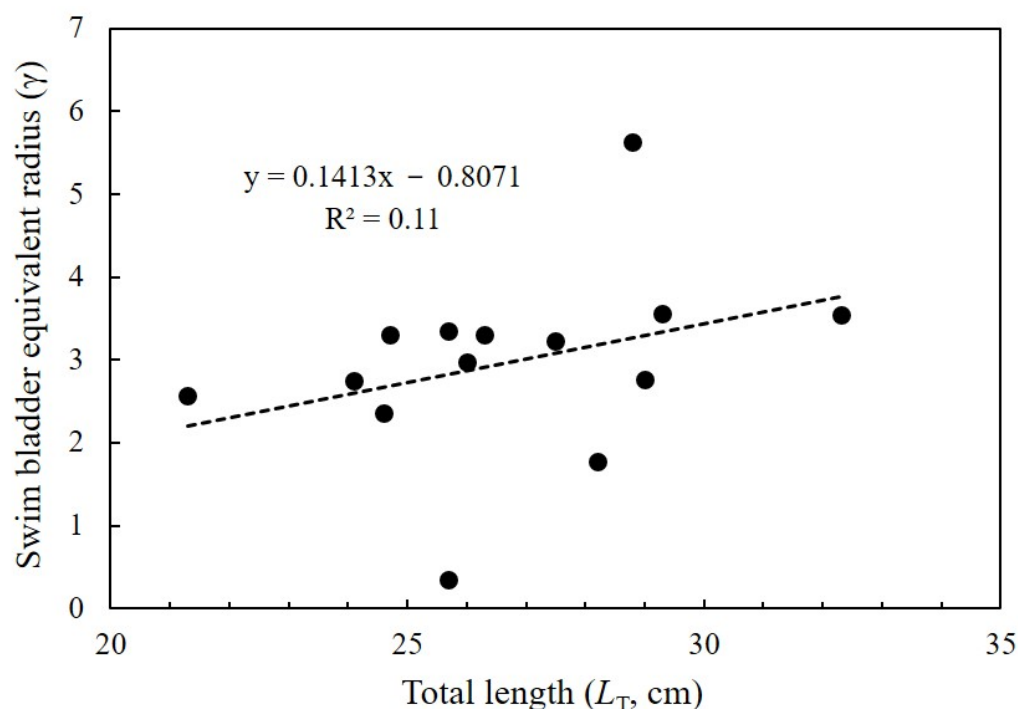


Figure 4. The relationship between Pacific herring L_T and the swim bladder equivalent radius (r).

Studies have shown that the herring swim bladder is affected by the body fat composition and gonad size [25,26]. The relationship between the swim bladder equivalent radius and gonad somatic index (GSI) is presented in Figure 5. GSI is calculated as $GSI = \text{gonad weight} \times 100 / (\text{weight} - \text{gonad weight})$. The swim bladder equivalent radius decreased as GSI increased, but the correlation was non-significant.

3.2. TS Changes with Tilt Angle

Figure 6 presents the TS results from the ex-situ measurements and the KRM model (L_T : 25.7 cm, swim bladder angle: 6°) with tilt angles ranging from -60° to 60° and at two frequencies (38 and 120 kHz). When the horizontal tilt angle of the Pacific herring is 0° , a head-up orientation results in a positive (+) angle with respect to the x-axis, and a head-down orientation results in a negative (−) angle. The greatest TS values were obtained with a head-down orientation at two frequencies (38 and 120 kHz) in the ex-situ measurements and the KRM model. Higher TS values were observed with a head-down orientation because the swim bladder's cross-sectional area becomes larger when in a horizontal position. At 38 kHz, the main TS scattering lobe showed a soft and wide boundary but narrowed as the frequency increased. There were also significant changes in the side-scattering lobe. The TS values of the ex-situ measurements and the theoretical model were comparable when the tilt angle changes were marginal but differed significantly when the tilt angle increased.

3.3. The Pacific Herring TS– L_T Relationships

The TS– L_T regression equations of the ex-situ measurements were (Figure 7a):

$$TS_{38\text{kHz}} = 20 \log_{10}(L_T) - 70.10 \text{ (95\% CI: } -71.78 \text{ to } -68.43, r = 0.17) \quad (6)$$

$$TS_{120\text{kHz}} = 20 \log_{10}(L_T) - 70.59 \text{ (95\% CI: } -71.88 \text{ to } -69.31, r = 0.10). \quad (7)$$

The TS– L_T regression equations of the KRM model were (Figure 7b):

$$TS_{38\text{kHz}} = 20 \log_{10}(L_T) - 68.39 \text{ (95\% CI: } -70.11 \text{ to } -66.66, r = 0.40) \quad (8)$$

$$TS_{120\text{kHz}} = 20 \log_{10}(L_T) - 69.74 \text{ (95\% CI: } -70.88 \text{ to } -68.60, r = 0.49). \quad (9)$$

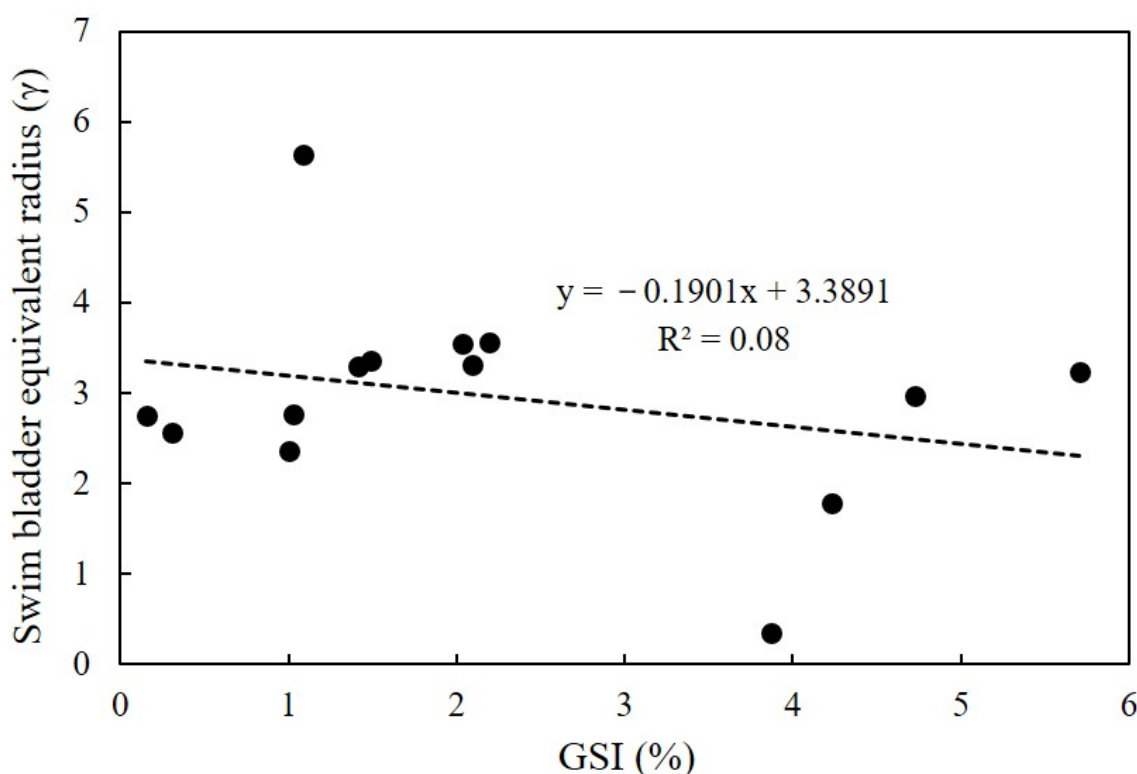


Figure 5. The relationship between Pacific herring GSI and the swim bladder equivalent radius (r).

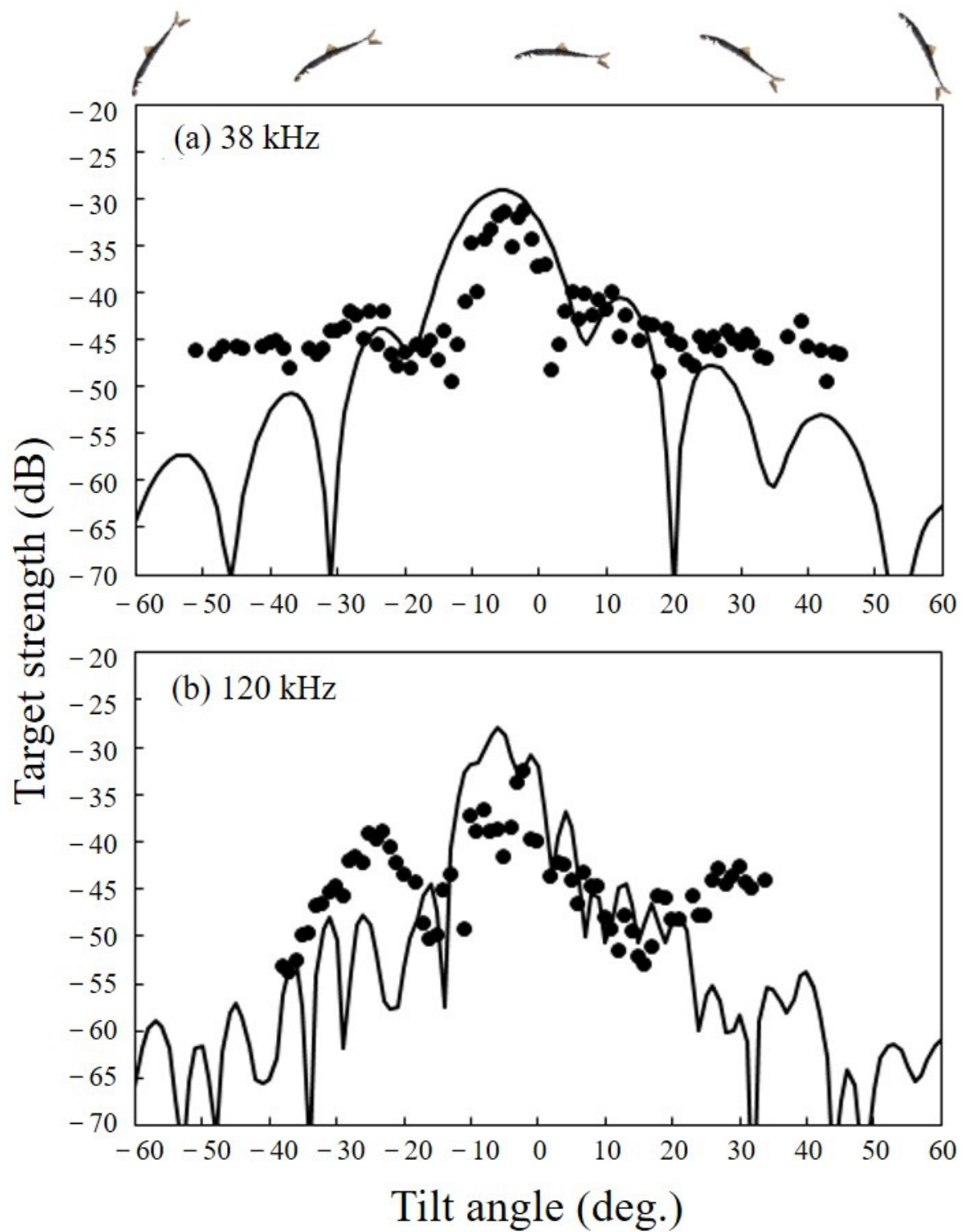


Figure 6. The relationship between Pacific herring TS and tilt angle (L_T : 25.7 cm, swim bladder angle: 6°) at three frequencies (a) 38 and (b) 120 kHz. The points represent the TS from the ex-situ measurements, and the lines represent the TS from the KRM model.

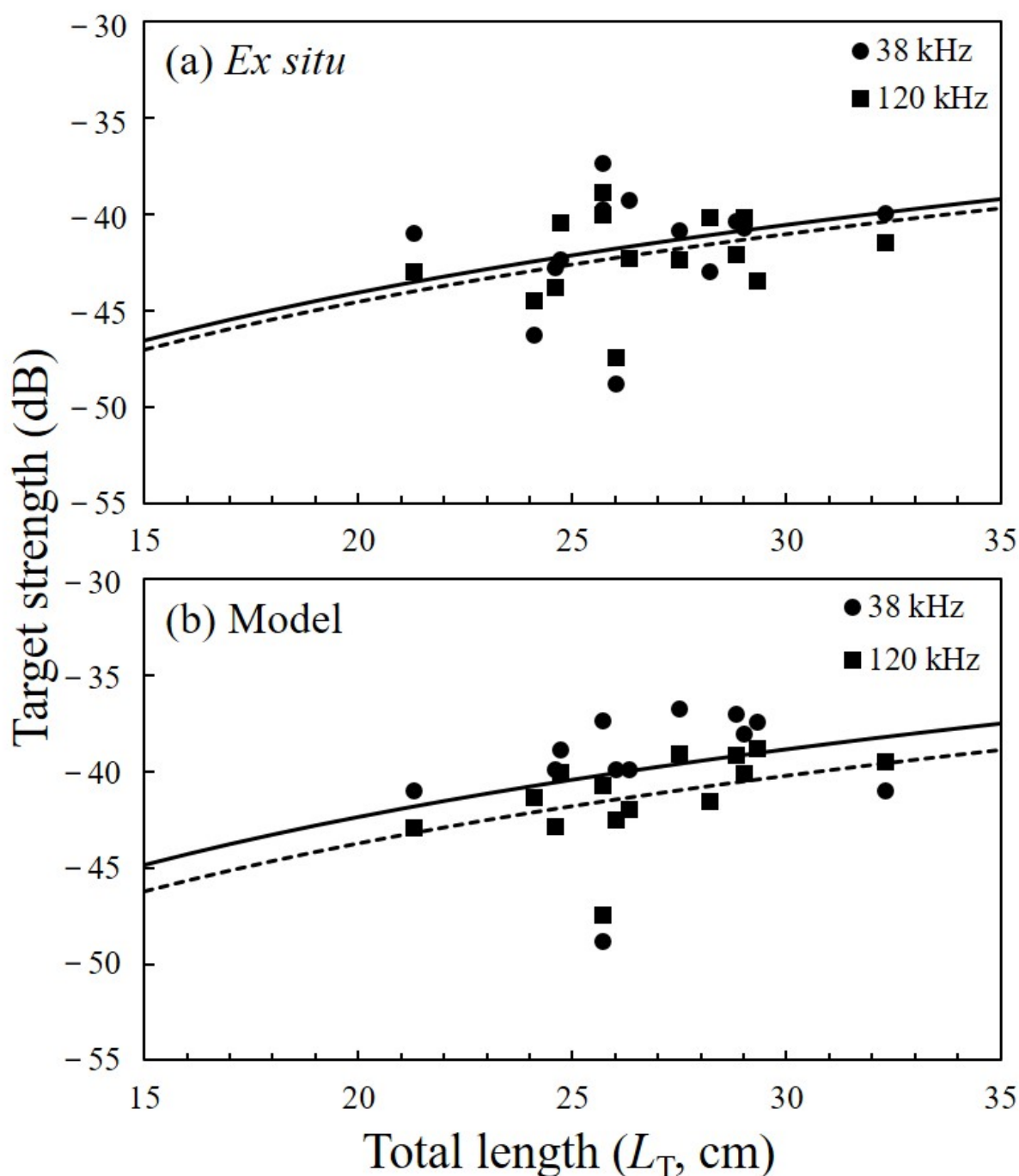


Figure 7. The TS– L_T relationships of the regression equations ($20 \log_{10}(L_T) + b_{20}$) at 38 (solid line) and 120 kHz (dashed line) using the (a) ex-situ and (b) theoretical model methods.

4. Discussion

The TS is attributed to the swim bladder (up to 90–95% of the backscatter of the swim bladder) due to the density contrast between gas and water [27–30]. The size of the Pacific herring swim bladder varies because of differences in the fat composition, gonad size, habitat, habitat depth, and season. The Pacific herring swim bladder is likely larger in the Baltic Sea than in the Norwegian Fjords because the fat content of the Baltic herring is 2–5% (owing to the lower salinity in the Baltic), whereas the fat content of the Norwegian herring is 7–19% [31]. The average fat content of Pacific herring in Korean waters is 15.1% [32]. Pacific herring observed seasonal variation in the volume of the swim bladder, which varies depending on seasonal variations in the lipid composition, gonadal development, and

stomach contents [33]. In this study, the swim bladder size decreased as GSI increased, but the correlation was non-significant. Samples in this study were only collected in summer, thus explaining the lack of correlation. The maximum observed GSI was approximately 6%, which is smaller than the values (14.5% (7.8–32.3%)) [26]. It also reported a correlation between GSI and swim bladder size [26].

Pacific herring are mostly found offshore, but in late winter and early spring, they migrate to coastal areas to spawn [6]. Their habitats vary in depth. According to Boyle's Law, the volume of the swim bladder decreases as the water depth and pressure increase [27]. A pressure change from 1 to 7 bar (equivalent to a depth range of 0–60 m) results in a decreased swim bladder volume, calculated as $V = 4.20 (1 + z/10)^{-0.92}$. The dorsal cross-sectional area also decreases, calculated as $A = 7.01 (1 + z/10)^{-0.36}$ [34]. Herring TS reported decreased herring TS as the depth increased, showing a -7 dB decrease at 100-m depth [33]. Herring TS relative to water depth is expressed as $20 \log L - 2.3 \log(1 + z/10) - 65.4$ [26]. Water depth should also be incorporated into the TS estimates of Pacific herring.

The relationship between TS and the tilt angle is also important [28,35]. The TS range of the ex-situ measurements with variable tilt angles (-20° to 20°) was 7.7–20.2 dB at 38 kHz and 11.0–20.6 dB at 120 kHz. The mean TS was calculated at a tilt angle of $3.8^\circ (\pm 6.0^\circ)$ for *Clupea harengus*: A tilt angle of $3.8^\circ (\pm 6.0^\circ)$ was used for daytime and $-3.2^\circ (\pm 13.6^\circ)$ was used for nighttime [23]. Norwegian spring-spawning herring aggregate during the day; the average swimming angle is approximately horizontal, and positive swimming angles up to 40° were recorded at night [36]. For herring measured at 1.5- and 4-m depths: The tilt angles were $-3.9^\circ (\pm 12.8^\circ)$ and $0.2^\circ (\pm 11.9^\circ)$, respectively [37]. The tilt angle of Pacific herring has not yet been reported in situ.

The b_{20} value estimated by ex-situ measurements and KRM model calculation were -70.10 dB and -68.39 dB at 38 kHz and -70.59 dB and -69.74 dB at 120 kHz. In this study, the b_{20} value was not as high as those of previous studies (Table 2). Herring has a higher fat content than other fish species. The TS of a fish with high-fat content, the orange roughy (*Hoplostethus atlanticus*), was measured in live and dead individuals. The TS of the dead fish was 1.9 to 9.8 dB higher than that of the live fish owing to the attached bubble and changes in the body tissues [38]. This study used dead fish, which could introduce post-mortem influences, including rigor mortis and denaturation of body components [39]. In the present study, to delay such reactions, samples were transferred to plastic bottles containing seawater and quick-frozen. However, in a few samples, the reactions might have influenced the swim bladder conditions. The TS measurements in dead Pacific herring indicated the possibility that the morphological characteristics of the swim bladder changed compared to the attached bubble.

The TS–length relationship in herring has been studied (Table 2). The b_{20} of Pacific herring was reported to be -71.5 dB at 75 kHz [40] and -64.3 dB at 120 kHz [33] (Thomas et al., 2002). The b_{20} values at 120 kHz were higher in previous studies than in this study. The b_{20} of Baltic Sea herring was -70.8 to -63.9 dB at 38 kHz [31,41–46], -69.9 dB at 70 kHz [47], and -73.4 dB at 120 kHz [41]. The b_{20} of Norwegian spring-spawning herring was -73.6 dB at 18 kHz [48], -71.9 and -71.1 dB at 38 kHz [48,49], -73.5 dB at 120 kHz [48], and -73.1 dB at 200 kHz [48]. The herring b_{20} values vary because the swim bladder volumes differ across seasons and environments. Herring TS depends on the fish length, swim bladder morphology, and habitat depth.

We investigated TS of a small range of L_T using dead fish. For accurate acoustic estimates of Pacific herring density, future studies will need to improve the TS vs. $\log L_T$ relationship that is valid for a wide range of L_T using live fish. To increase the reliability of TS results it is necessary to compare the TS of dead vs. live fish. In the present study, fish were sampled only in summer. As the GSI of Pacific herring changes by month, monthly observations of the GSI and swim bladder size are necessary. In addition, knowledge of Pacific herring ecology under their natural conditions is essential to contribute to Pacific fishery management in the future.

Table 2. Summary of target strength (TS)–length (*L*) relationship of this study and previous studies.

Species	Frequency (kHz)	Method	b_{20} (dB)	Reference
Pacific herring (<i>C. pallasii</i>)	38	ex-situ model	−70.10 −68.39	This study
	120	ex-situ model	−70.59 −69.74	
	75	ex-situ	−71.5	[40]
	120	ex-situ	−64.3	[33]
Baltic sea herring (<i>C. harengus</i>)	38	in situ	−70.8	[41]
	38 and 70	in situ	−67.8	[31]
	38	model	−63.9	[42]
	38	model	−65.1	[43]
	38	in situ	−67.55	[44]
	38	in situ	−67.55	[45]
	38	in situ	−67.1	[46]
	70	in situ	−69.9	[47]
	120	in situ	−73.4	[41]
Norwegian spring-spawning herring (<i>C. harengus</i>)	18	in situ	−73.6	[48]
	38	in situ	−71.9	
	120	in situ	−73.5	
	200	in situ	−73.1	
	38	in situ	−71.1	[49]

5. Conclusions

We reported the relationship between the TS and L_T ($TS = 20 \log_{10}(L_T) + b_{20}$) for 14 Pacific herrings using ex-situ measurements and the KRM model at 38 and 120 kHz. The b_{20} values at 38 and 120 kHz were −70.10 and −70.59 dB, respectively, using ex-situ measurements, and −68.39 and −69.74 dB, respectively, using the KRM model. The difference in b_{20} value between ex-situ measurements and KRM model was 1.71 dB at 38 kHz and 0.85 dB at 120 kHz. The results of the present study provide basic data for future Pacific herring density and biomass estimations, which are key to evaluating the impact of their exploitation and establishing the necessary management measures.

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Informed Consent Statement: Not applicable.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

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