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The Frequency and Length Dependence of the Target Strength of the Largehead Hairtail (*Trichiurus lepturus*) in Korean Waters

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The largehead hairtail (*Trichiurus lepturus*) is one of the most common fisheries stocks in the East China Sea and the Yellow Sea. The species is caught using a variety of fishing tools, such as a stow net or a long line, as well as jigging and trawling. Scientific investigations have been conducted throughout the world to enable evidence-based estimations for the management and protection of the main fisheries biomass. For example, inshore and offshore hydro acoustic surveys are performed annually using bottom- and mid-water trawls around the Korean Peninsula. However, to date, no acoustic survey has been conducted to estimate fish size distribution, which is necessary to construct a data bank of target strength (TS) relative to fish species, length (L), and frequency. This study describes the frequency and length dependence of TS among fishes in Korean waters for the purpose of constructing such a TS data bank. TS measurements of the largehead hairtail were carried out in a water tank (L 5 m×width 6 m×height 5 m) at frequencies of 50, 75, 120, and 200 kHz, using a tethering method. The average TS patterns were measured as a function of tilt angle, ranging from -45° (head down) to +45° (head up) every 0.2°. The length conversion constant (b_{20}) was estimated under the assumption that TS is proportional to the square of the length. In addition, *in situ* TS measurements on live largehead hairtails were performed using a split beam echo sounder.

Key words: *Ex situ* TS, Frequency, *In situ* TS, Largehead hairtail, Length dependence

Introduction

Since the United Nations Convention on the Law of the Sea (UNCLOS) convened, many coastal nations all over the world, including Japan and China, which border the sea around the Korean Peninsula, are strengthening their management of fisheries stocks in Exclusive Economic Zones (EEZ) and open sea areas. Korean fishermen experience difficulties accessing fishing areas, owing to the reduction of fishing grounds in Korea as well as overseas. Thus, the Korean government has implemented the TAC (Total Allowable Catch) system to manage and effectively use the fisheries stocks existing in the surrounding sea areas. For the effective and smooth execution of the TAC system, research is being actively conducted to analyze the development and distribution of fish using sizing echo sounders that help fishermen select only fish that are larger than a certain size and to understand fish sizing information in relation to fisheries stocks.

Currently, the National Fisheries Research & Development Institute (NFRDI), under the Korean Ministry of Food, Agriculture, Forestry and Fisheries, implements an acoustic measurement on fisheries stocks and an investigation using bottom- and mid-water trawls in the sea areas around the Korean Peninsula and other areas every year. In addition, acoustic research is being used to evaluate the fish size composition of a variety of fish species throughout the world. Korea has conducted target strength (TS) measurements on commercially important fish species among the stocks for purposes of TAC management. However, quantitative studies on the frequency and length dependence on target strength are rare for the largehead hairtail, which, with 60,086 metric tons caught in 2005, is one of the most

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commercially important fisheries stocks of Korea (NFRDI, 2006). Thus, it is necessary to study the length dependence of the acoustic target strength of the largehead hairtail stocks in neighboring waters of Korea.

Generally, a sound scattering cross-section of fish, or the TS, is almost proportionate to double the square of the fish size (Foote, 1980a) and can be used to measure the TS of fish *ex situ* and *in situ*. The *ex situ* strategy normally involve a tethered method to measure TS by locating fish in the sound axis of the transducers (Dahl et al., 1983; Foote et al., 2002; Kang et al., 2003), which is called the cage method. Conversely, the *in situ* method measures TS directly in the field using a split beam and dual beam echo sounder (Foote et al., 1986; Gauthier et al., 2001).

We measured the length and frequency dependence of the acoustic TS at 50, 75, 120, and 200 kHz in a large tank, using a tethered method for largehead hairtail caught in the waters around Jeju Island by jigging, and measured the acoustic TS of the largehead hairtail in a free swimming state using a 120 kHz split beam echo sounder in the Suyeong Man, Busan. Using the tank and field measurements, we analyzed the length dependence of the acoustic TS of the largehead hairtail.

Materials and Methods

Fish species and target strength

The largehead hairtail, *Trichiurus Lepturus* (Trichiuridae, *Perciformes*) is one of the target fish species for TAC management. Therefore, it is necessary to verify the sound scattering characteristics of this species.

Fig. 1(A) presents the relationship between anal length and body weight as well as the distribution of the anal lengths of largehead hairtails used to measure TS in an underwater tank in March 2005. The average anal length and body weight were 27.8 cm and 403.9 g, respectively with distribution ranges of 23.6 to 35.0 cm and 290.0 to 700.0 g, respectively. To obtain these measurements, largehead hairtails without apparent damage to their surface or internal organs were selected from those caught by jigging in the waters around Jeju Island and on the day they were caught were frozen and transported.

Fig. 1(B) shows the relationship between anal length and body weight as well as the frequency distribution of anal length of 20 largehead hairtail individuals (Fig. 2) caught using fishing hooks in the Suyeong Man, Busan in August 2005. The average anal length and weight were 15.7 cm and 51.6 g, respectively, with distribution ranges of 14.2 to 17.5 cm and 40.0 to 70.0 g, respectively.

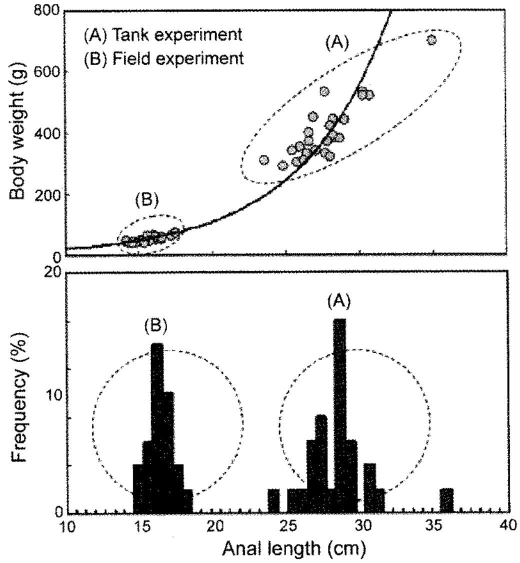

Fig. 1. Relationships between anal length and body weight, frequency distributions, and anal length for largehead hairtails.

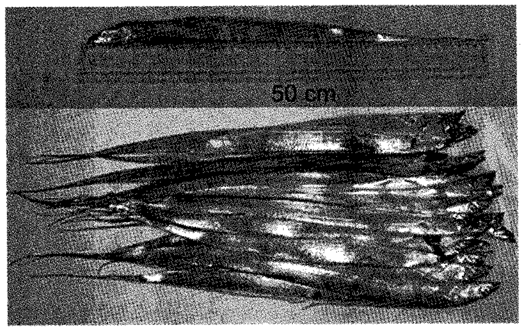

Fig. 2. Largehead hairtails caught on the fishhook in the acoustic survey area.

Ex situ TS measurements

TS measurements were performed using a tethered method for largehead hairtails in an underwater tank (L 5 m × width 6 m × height 5 m) at frequencies of 50, 75, 120, and 200 kHz using a single beam echo sounder in March 2005.

Fig. 3 shows a block diagram of the measurement system of the underwater tank used in the experiment. A moving panel was installed on the top of the underwater tank, and transducers were tethered through a 1.0 m × 0.5 m window on the top of the moving panel.

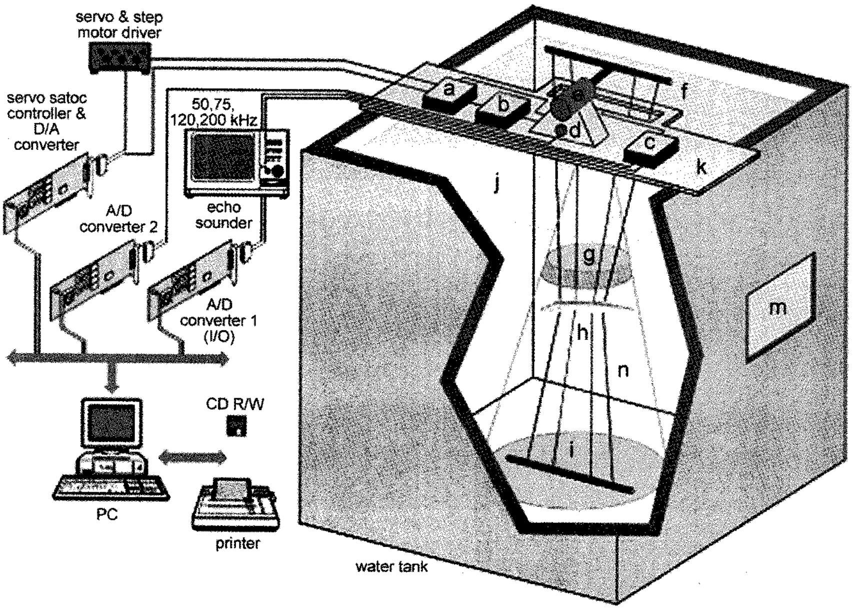

Fig. 3. Block diagram of the experimental setup developed in this study.
a, motor selector; d, potentiometer; g, sound beam; j, water surface; b, clutch controller; e, motor; h, fish; k, moving panel; c, transducer selector; f, fish support bar; i, weight; m, tank window.

TS was measured using an automatic measurement and interpretation device of acoustic TS driven through a personal computer. Transducers from a commercial fish finder (SF-7000, Samyoung ENC, Korea) that is widely used on fishing boats were modified for the device to transmit ultrasound signals to and from the water.

To obtain acoustic scattering signals over every part of the fish body, which enables proportionate measurements with regard to the overall fish length, thus providing the TS, the fish body should be completely encompassed in the main beam of the transducers. However, the largehead hairtail is long and flat, a shape that cannot be completely encompassed in a sound beam. To address the problem, we set the depth for tethering the fish body at more than 275 cm, taking into consideration the effects of reverberation in a water tank as well as side-lobe and background noise made by transducers. In addition, four piezo-electric transducers with directivity angles of 45°, 29°, 38° and 24°, each with frequencies of 50 kHz, 75 kHz, 120 kHz, and 200 kHz that can obtain a width of detection area greater than 110 cm for a -3 dB directivity angle, were customized and manufactured (Lee and Shin, 2005).

An experiment was conducted to analyze the properties of TS fluctuation by tilt angle while receiving ultrasound signals diffused from a largehead hairtail that was tethered to the main beam axis through a tethering window under the water surface. The pulse width of the transmitting signals of the fish detector was 0.5 ms, and the echo signal of the largehead hairtail after it was extracted from a detector at the end of an envelope in the receiver was put into a signal processing unit (COMI-LX201, Comizoa, Korea) with a trigger signal.

In addition, the fish location control device used to tether the fish for measurement in the water consisted of a stepping motor, an operation unit (UDK5114N, Oriental Motor, Korea), a speed reduction device (ratio, 1:30), a clutch control device, and a D/A conversion device (COMI-SD301, Comizoa, Korea). Fig. 4 shows an example of a screen display of the software modules for system control and data processing used to measure the TS of the fish.

Although in a natural habitat, the swimming pattern of a largehead hairtail can be either vertical or horizontal (Kawamura and Ohashi, 1988), we assumed a horizontal swimming position for the TS measurements. Thus, the tilt angle of the largehead hairtail was altered to reflect degrees between -45° (head down) and +45° (head up) with an interval of 0.2° for repetitive measurements of acoustic data. In addition, fluctuations in echo signals caused by a

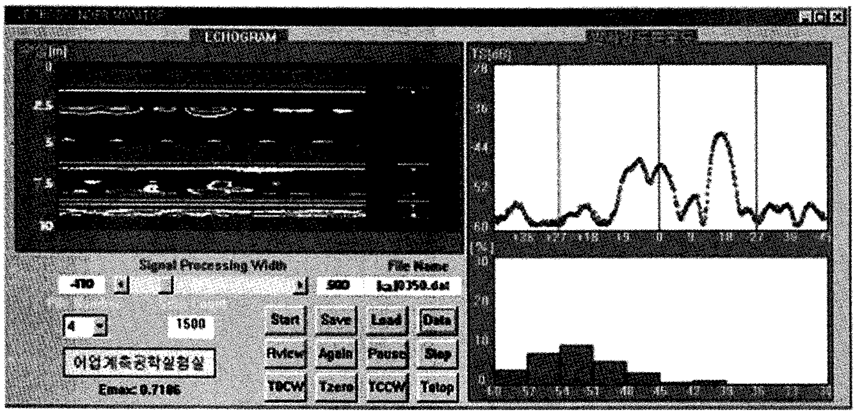

Fig. 4. Layout of the program developed for data acquisition and processing, the system parameter setting, and tilt control of fish.

change of a tilt angle were measured (Fig. 4). When problems were encountered, such as fluctuations in echo levels with each change of a tilt angle and electric noise frequency distributions of TS, the data were not used, and a new experiment was initiated. Once credible experimental data were obtained, data such as length, the number of measurements, and the echo electric pressure from each tilt angle were saved using the data recording function of the software module. Quantitative analyses were then conducted in a laboratory (Foote, 1980b).

To prevent the fish from moving when the tilt angle was changed, four points of the fish from the head to the tail were tethered with 0.5-mm nylon monofilament that was modified with a copper sphere before and after measurements.

In situ TS measurements

The field measurements of live largehead hairtails in a free swimming state were conducted in the Suyeong Man, Busan, in August 2005 using a 120 kHz split beam echo sounder (EY 500, SIMRAD). The directivity angle for -3 B of a 120 kHz split beam transducer used in the measurement was 7°, and the standard diameter of the copper sphere of the system was 23.0 mm (copper sphere, TS=-40.4 dB).

As shown in Fig. 5, a 120 kHz transducer was attached to the bottom of a towing body (Foil-100, SIMRAD), and three balance weights were fixed at the front end of the towing body. The towing body was then tethered in the water approximately 5 m from the right side of the survey ship. To eliminate vibration or power noise caused by the ship, a power generator that was separate from the ship was used. The ship maintained a constant speed of 4 knots, and a transducer attached to the towing body received

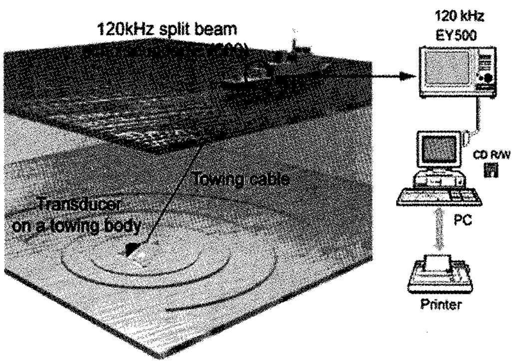

Fig. 5. Block diagram of split beam echo sounder system used in the field experiment.

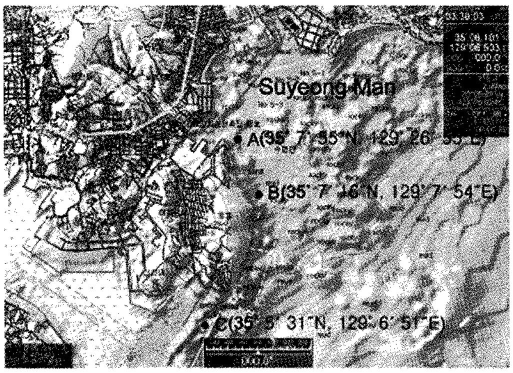

Fig. 6. Acoustic survey locations of largehead hairtail by split beam echo sounder.

echo signals from a school of fish recorded in real time. To quantitatively analyze the interrelations between the acoustic survey results and the actual catch of fish, real time videos of the largehead hairtail appearing on the echogram were recorded while drifting on the following fixed points: point A (35° 07′55″N, 129°26′55″E), point B (35°07′16″N, 129° 07′54″E) and C (35°05′31″N, 129°06′51″E) while stopping the engine of the survey ship.

Data analysis

The target strength, TS_{ref} (dB), of the largehead hairtail was measured using a single beam echo sounder in a large tank and calculated with the following equation using an indirect method with a copper sphere at each frequency:

$$TS_f = 20\log\frac{V_f}{V_{ref}} + TS_{ref} \qquad (1)$$

where TS_{ref} is the target strength of the copper sphere and V_f and V_{ref} are the voltages (V) of the echo signals for the fish used in the experiment and the copper sphere, respectively. The diameters of the copper sphere at the four frequencies of 50, 75, 120, and 200 kHz were 45.0 mm (-36.2 dB), 32.1 mm (-39.1 dB), 23.0 mm (-40.4 dB), and 13.7 mm (-45.0 dB), respectively.

The mean TS of the largehead hairtail was estimated to follow a normal distribution, assuming a probability density function on a tilt angle while the fish was swimming (Foote, 1980a).

When measuring TS by tethering the fish body on the main beam axis of the transducers, the pitch angle of the fish includes the average back scattering cross-section $<\sigma>$. If the back scattering cross-section from the direction θ is $\theta(\sigma)$, the mean TS $<TS>$ of an individual fish can be calculated with the following equations:

$$<\sigma> = \int_{-\pi/4}^{\pi/4} \sigma(\theta) f(\theta) d\theta \qquad (2)$$

and

$$<TS> = 10\log\left(\frac{<\sigma>}{4\pi}\right) \qquad (3)$$

where $f(\theta)$ is a probability density function about a pitch angle θ of the fish body.

Given that, when the fish was in a free swimming state, the TS values changed with tilt angle as well as with the age, length, height, width and fatness of the fish body, it was very difficult to estimate the pattern change of the TS by measuring a change in a swimming tilt angle of the fish (Lee, 1999; Lee, 2005).

We calculated the length conversion constant b_{20} from the following linear regression equation, assuming that the TS of the largehead hairtail is proportionate to double the square of anal length (AL, cm) in every case of a single beam or a split beam echo sounder:

$$<TS> = 20\log(AL) + b_{20} \qquad (4)$$

For fish species with a swim bladder, the acoustic intensity scattered by the swim bladder is approximately 90 to 95% of the total backscattered intensity from the entire fish body, such that the size and shape of the swim bladder affects the value of the TS of the fish (Foote, 1980b). Thus, to examine the relationship between the TS and the swim bladder, we took an X-ray photograph of a largehead hairtail with an anal length of 28.3 cm to compare the relationship between the tilt angle of the swim bladder and the mean TS fluctuation pattern (Fig. 8). To quantitatively analyze the average fluctuation pattern of the acoustic TS caused by the tilt angle of the largehead hairtail, TS measurements of all fish used in the experiment were averaged against the tilt angle so that the fluctuation pattern of the mean TS by frequency could be analyzed.

Results and Discussion

Average target strength pattern

Fig. 7 shows the results of the averaged TS pattern after measuring the TS values at frequencies of 50, 75, 120, and 200 kHz as they changed at intervals of 0.2° within ±45° of the tilt angle by tethering 26 largehead hairtails in an underwater tank. The average anal length $<TS>$ of the largehead hairtails was 27.8 cm, while the maximum TS was seen between -10° and 0° of the tilt angle at all frequencies in the mean TS pattern.

Fig. 8 shows the results of an X-ray photograph of the fish used for quantitative analysis of the mean TS pattern. The swim bladder of the largehead hairtail is black, and the tilt angle of the swim bladder to the horizontal direction from the head to the tail is -9.5° (Fig. 8). Thus, when the largehead hairtail aims downward -9.5°, the maximum TS of the swim bladder is observed as shown in Fig. 7. By comparing the averaged TS pattern and the X-ray photograph, we determined that whether the peak TS value in the average target strength pattern is observed at approximately -9° of the tilt angle in Fig. 7 depends on the tilt angle of the swim bladder (Mukai et al., 1993).

Length dependence of frequency TS

Figs. 9 and 10 show the results of length depen-

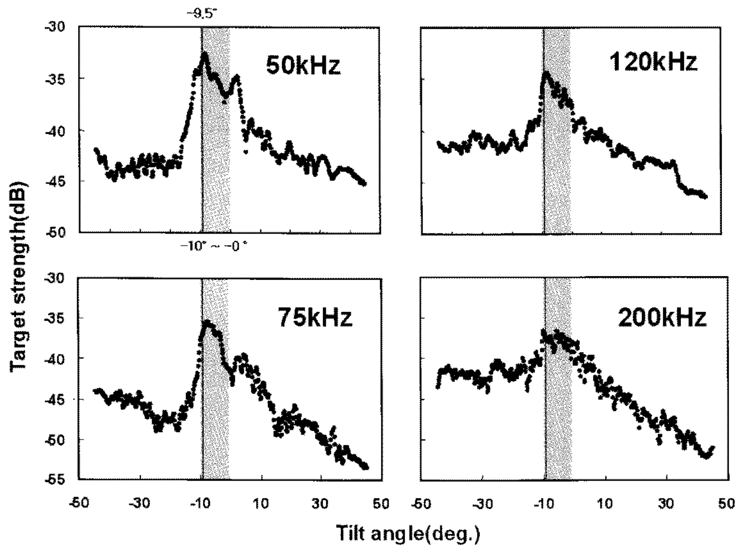

Fig. 7. Mean target strength patterns for largehead hairtail at 4 frequencies.

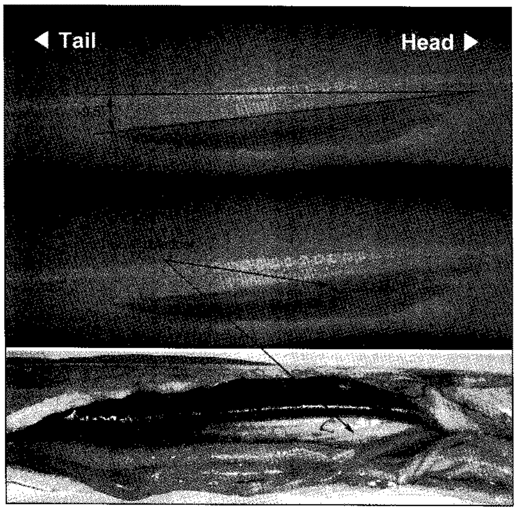

Fig. 8. X-ray photographs of the swimbladder of a largehead hairtail.

dence of the TS of the largehead hairtail in an experimental underwater tank. Fig. 9 presents the frequency distribution of TS data measured for 26 largehead hairtails with a total of 12,348 counts at 50 kHz, 12,378 counts at 75 kHz, 12,482 counts at 120 kHz, and 12,430 counts at 200 kHz. The mean TS values calculated on the basis of the data at these frequencies were -39.78, -43.32, -40.36, and -42.26 dB, respectively. Assuming that TS is proportionate to double the square of the length, the length conversion constants b_t were calculated using the mean TS <*TS*> and the averaged anal length <*AL*> as -68.65 dB at 50 kHz, -72.18 dB at 75 kHz, -69.23 dB at 120 kHz, and -71.13 dB at 200 kHz.

Meanwhile, the mean TS values of the 26 tethered largehead hairtails were estimated assuming a normal distribution whereby the average and standard deviations of tilt angles, which is the swimming pitch angle of the fish (Mukai et al., 1993), to the TS pattern for each largehead hairtail were -5° and 15°, respectively.

Fig. 10 shows the relationship between TS and anal length. Circles indicate TS measurements and the solid line indicates the regression line under the assumption that TS is proportionate to double the square of the anal length. The length conversion constants b_{20} for each frequency calculated in the experiment were -66.60, -69.53, -67.85, and -69.57.

TS in a free-swimming state

An echogram of a largehead hairtail in a free-swimming state was recorded at the Suyeong Man, Bussan, in August 2005. The *in situ* TS of the largehead hairtail was measured using software that interprets the TS values acquired by a split beam echo sounder (EP500, Simrad). The mean TS was derived from the frequency distribution of the TS values to analyze the length dependence of the TS of the largehead hairtail.

Fig. 11 shows an example of an echogram recorded while drifting at the time of the experiment. The mean

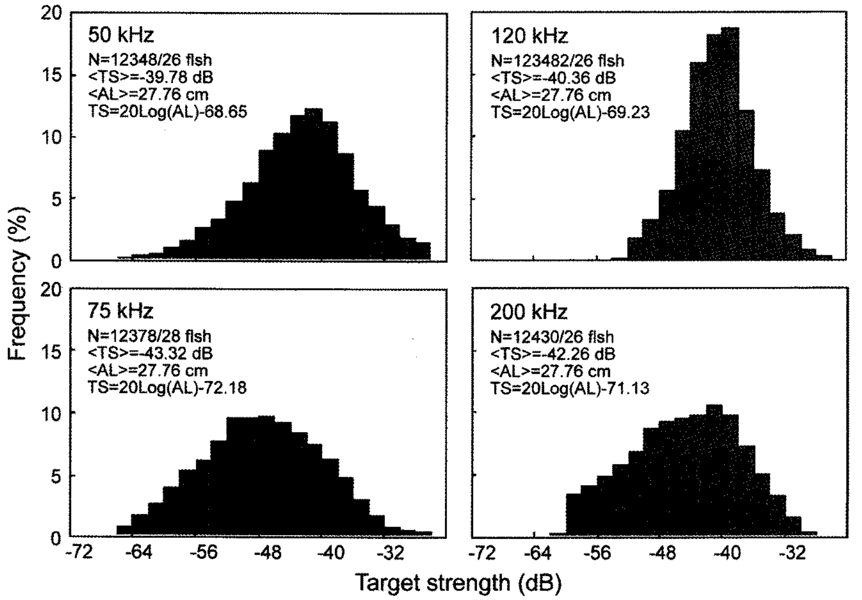

Fig. 9. TS frequency distributions for largehead hairtails at 50, 75, 120, and 200 kHz.

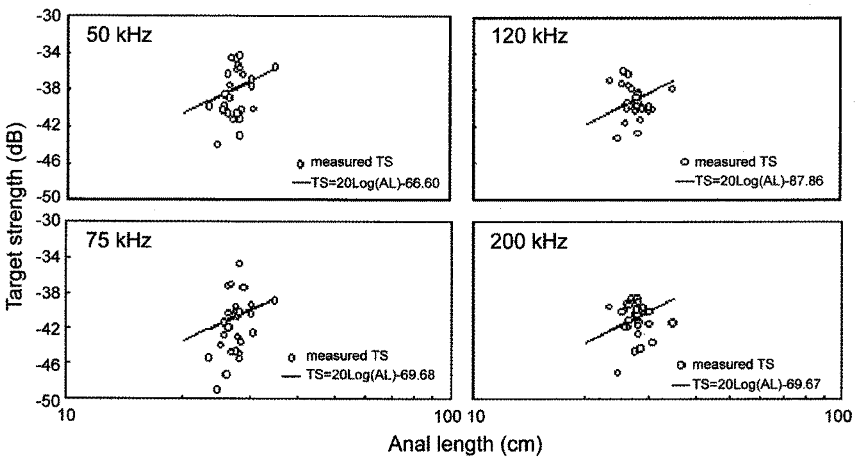

Fig. 10. Fish length dependence on TS of largehead hairtail at 4 frequencies.

TS was calculated from the frequency distri-bution of the TS for an individual largehead hairtail, one of 118 counts in total, which was obtained from the echogram shown in Fig. 11. Then, under the assumption that the mean TS is proportionate to double the square of the anal length, the length conversion constants were calculated as shown in Fig. 12.

The mean TS of 118 largehead hairtails was -45.9 dB, and the length dependence of the TS based on the data was calculated as TS=20log(AL)-69.82. The length conversion constant b_t was -69.82 dB, thus reflecting a difference of 0.59 dB when compared to the length conversion constant, and -69.23 dB at 120 kHz in the *ex situ* TS experiment (Fig. 12).

Length and frequency dependence of TS

We analyzed the frequency and length dependence of the TS of the largehead hairtail by combining the two, which was achieved by evaluating the experimental relationship between the ratio (AL/λ) of anal length (AL) to wavelength (λ) and the ratio (σ/λ^2) of a sound scattering cross-section (σ) to double the

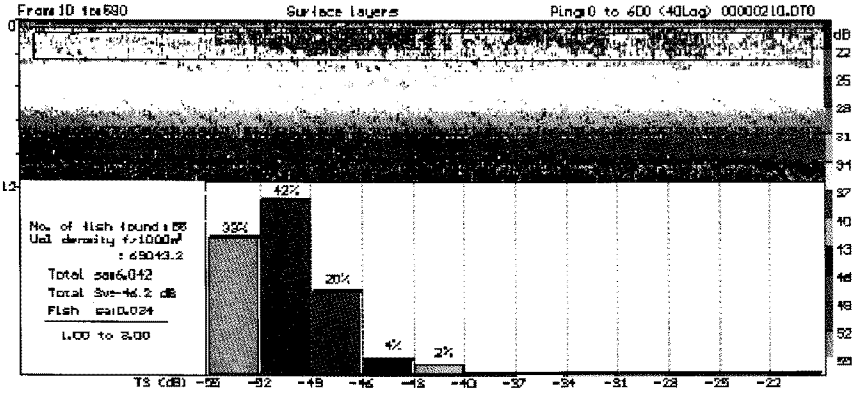

Fig. 11. An echogram of the largehead hairtail by split beam echo sounder.

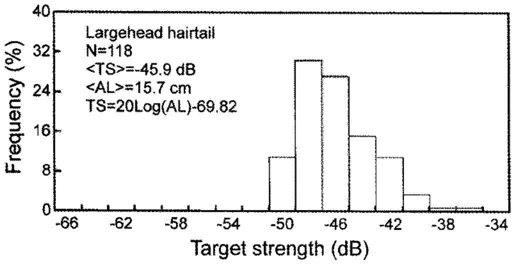

Fig. 12. TS frequency distribution for largehead hairtails at 120 kHz.

square of the wavelength (λ^2) (Love, 1971).
The experiment was conducted using the length dependence of the TS measured at four frequencies, including 50, 75, 120, and 200 kHz, for 26 largehead hairtails with 104 counts in total. Fig. 13 shows the results of the linear regression analysis of the ratio of anal length to wavelength and the ratio of the sound scattering cross-section to double the square of the wavelength. The following regression equation was established to determine the relationship between anal length and frequency:

$$\sigma/\lambda^2 = 0.032042(AL/\lambda)^{1.75101},\ r^2=0.67 \quad (5)$$

The following equation is derived if each side of the equation is decoupled:

$$TS = 17.51\log(AL) + 2.49\log(\lambda) - 12.4842 \quad (6)$$

The equation represents the anal length and frequency (λ) dependence of the largehead hairtail. It can be used to estimate the temporary anal length dependence of the target strength of the largehead hairtail inhabiting the waters surrounding the Korean peninsula.

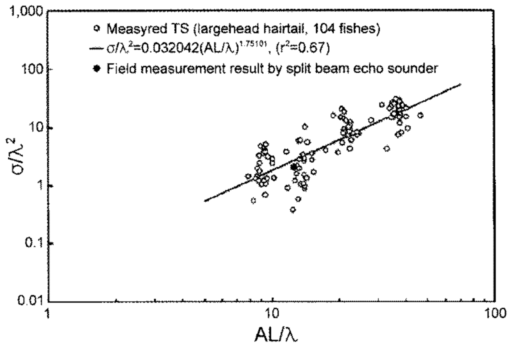

Fig. 13. Length dependence for largehead hairtail derived from ex situ TS by single beam system (○) and in situ TS by split beam system (●), respectively. The backscattering cross-section (σ) is normalized to the square of wavelength (λ) and plotted against the anal length (AL) to wavelength ratio.

The black circle in Fig. 13 represents the *in situ* measured TS values of the largehead hairtails in the Suyeong Man, Busan, whereas the white circles represent the *ex situ* measured TS values of largehead hairtails in an underwater tank. When the two types of measurements were compared, the TS values obtained in the field experiment did not differ significantly from the estimates derived from the regression line of the *ex situ* TS values measured in the experimental underwater tank. Table 2 presents a comparison between the length conversion constants b_{20} and b_t, derived from the four frequencies using the tethered method, and the length conversion constant b_t of live largehead hairtails in a free-swimming state at 120 kHz. The values of the length conversion constants in Table 2 are approximately 1.5-3.7 dB smaller than those previously reported for the largehead hairtail [-68.3±0.2 dB (Zhao, 2006) and 66.1 dB

Table 1. Biological composition of the largehead hairtail, *Trichiurus Lepturus* used in TS measurement

Frequency (kHz)	Anal length Range (cm)	Weight range (g)	No. of fish
50/75/120/200	23.6-35.0	290.0-700.0	26
120	14.2-17.5	40.0-70.0	20

Table 2. Values of length conversion constants derived from the relationship between mean TS and length of the largehead hairtail at 50, 75, 120, and 200 kHz in underwater tank and field experiments

Length conversion constant (dB)		Frequency (kHz) 50	75	120	200
tank	b_{20}	-66.60	-69.53	-67.85	-69.57
	b_t	-68.65	-72.18	-69.23	-71.13
field	b_t	-	-	-69.82	-

(Ona, 1987)]. This may have been caused by changes in the tilt angle resulting from varied swimming behavior patterns when the largehead hairtails are mixed with other fish species for feeding in the field. Thus, further studies should be conducted to determine whether the TS changes when measure-ing a single fish species or mixed fish species in an ecosystem setting. In addition, to improve the reliability of fish length estimation, further *ex situ* TS and *in situ* TS experiments should be conducted using live fish. We measured the length dependence of the TS of largehead hairtails inhabiting the waters surrounding the Korean Peninsula in an underwater tank at frequencies of 50, 75, 120, and 200 kHz (single beam system), using a tethered method, and in a field experiment at 120 kHz (split beam system). The length conversion constants, which were rounded up to double the square of the length at each frequency, were 66.60 dB at 50 kHz, -69.53 dB at 75 kHz, -67.85 dB at 120 kHz, and -69.57 dB at 200 kHz. To estimate the relationship between σ/λ^2 and AL/λ for a total of 104 largehead hairtails at 50, 75, 120, and 200 kHz, the following regression line equation was obtained: $\sigma/\lambda^2=0.032042(AL/\lambda)^{1.7501}$, with ($r^2$=0.67). The mean TS of a total of 118 largehead hairtails evaluated *in situ* using a split-beam echo sounder at 120 kHz was -45.9 dB. As estimated, the length conversion constant b_t was b_t=-69.82 dB, using the relationship of the average anal length of 15.7 cm of the largehead hairtail caught on fishing hooks in the same area. The *in situ* TS (-45.9 dB) was 1.1 dB lower than the *ex situ* TS (-44.8 dB) derived by the regression analysis.

Acknowledgments

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