Thesis for the Degree of Master of Science

Target Strength Estimation of Juvenile Cod (*Gadus macrocephalus*) using an Acoustic Scattering Model

by

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Target strength estimation of juvenile cod (*Gadus marcrocephalus*)
using an acoustic scattering model

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Abstract

Recent years, hydro-acoustical survey has been applied to measure a small marine organism like juvenile fish or zooplankton to manage marine environment as well as fisheries abundance. In the survey, target strength (TS) of the species is used as a scale factor to convert the acoustical scattering to fish biomass or abundance. The relationship between TS and body length for the species must be established accurately, because the accuracy of TS directly and largely affect to the accuracy of fish abundance estimated by hydro-acoustical survey. Small marine organism is difficult to measure the acoustic scattering directly. Thus physical model as an alternative method can be applied to estimate the values of TS. In order to estimate acoustic scattering from small juvenile cod (*Gadus macrocephalus*) with the model, the contrast (fish body to medium ratio) of the density and the sound-speed, which are required during the calculation were measured. The results shown that the measured density contrasts of juvenile cod varied between 1.003 and 1.029 (with mean 1.014 and standard deviation (S.D) 0.01). In the other hand, sound-speed contrasts varied between 1.039 and 1.041 (mean 1.041; S.D 0.001). The relationship between averaged TS and TL in cm established by Kirchhoff-ray mode (KRM) model at 38 kHz and 120 kHz were TS = 20 log TL - 68.7 and TS = 20 log TL - 68.9, respectively.

Introduction

The Pacific cod, *Gadus macrocephalus*, is mainly found along the continental shelf and upper slopes of the North Pacific Ocean, from the Yellow Sea to the Bering Strait, along the Aleutian Islands. It is one of the most important commercial species in several countries, including Korea (Kim et al, 2010). Juvenile cod is a prospective recruitment, because they will return to the spawning area after growing up as their instinct in the certain season. Therefore, it is important to estimate the abundance of cod especially juvenile-stage to manage the abundance as well as to predict it.

Hydroacoustic is a popular method to get the information on the fish abundance estimation effectively and efficiently. And this technique has become increasingly sophisticated and useful over the years (Simmonds and MacLennan, 2005). In acoustic surveys, a quantitative echo sounder provides reflections from a fish school at various echo intensities. Field application of acoustic methods to estimate animal abundance requires information on the acoustic size, target strength or backscattering cross section of individual organisms (MacLennan, 1990; Thiebaux et al, 1991). This acoustic reflection is converted to quantitative data (e.g., number of individuals, biomass) using the target strength (TS) (Ito et al, 2011). It is a key quantity in the acoustic assessment of fish abundance (Foote, 1987).

The target strength is a logarithmic measure of the proportion of the incident energy which is backscattered by the target (Simmonds and MacLennan, 2005). Acoustic backscattering by fish depends on fish size, anatomical characteristics, morphology of the body and swimbladder, and location in acoustic beam (Foote, 1980). Fish target strength measurements are influenced by biological factors, including the length of fish (Love, 1971; Nakken and Olsen, 1977; Foote and Traynor, 1988), the presence of a swimbladder (Clay and Horne, 1994), the tilt of the fish relative to the incident acoustic wave (Love, 1971; Nakken and Olsen, 1977; Blaxter and Batty, 1990), depth in the water (Edwards and Armstrong, 1984; Mukai and Iida, 1996; Thomas et al., 2002), and physiological state (Ona, 1990).

Acoustic scattering from fish generally could be estimated by two methods. Split-beam echo sounder used to measure TS if the target is not too small in comparison with wavelength. In small zooplankton and juvenile fish, however, measurement of TS is difficult due to the weakness of their acoustic reflections. Another method is to predict TS from theoretical acoustic scattering model. Recent year, many kind of theoretical scattering model were developed and have been applied to fish (Clay and Horne 1994; Chu et al, 2003). This method can predict acoustic scattering of fish as physical model. Therefore, it can be used to predict the trend of acoustic scattering from the juvenile fish.

In order to compute TS using Kirchhoff-ray mode (KRM) model, the mass density and sound-speed contrast are two the most important factors needed. In terms of an acoustic survey, the TS should be computed with *g* and *h* values that are appropriate for the season, the location and the life-cycle stage because changes in *g* and *h* values affect the variations in theoretical TS. The objectives of this study were to (1) measure the mass density contrast *g* and sound-speed contrast *h* of juvenile cod, (2) estimate TS using KRM model with value of *g* and *h*, and (3) provide TS-length relationships of juvenile cod for acoustical abundance estimation.

Materials and Methods

KRM scattering model

The culmination of several backscatter modeling efforts are able to represent by the Kirchhoff-ray mode model. The Helmholtz-Kirchhoff integral used to develop an accurate and elaborate method to estimate backscattered sound from fish (Foote, 1985; Foote and Traynor, 1988). This approach was simplified by Clay (1991; 1992) who incorporated Stanton's (1989) finite bent cylinder equation and fluid-or- gas-filled cylinders to model fish backscatter. And has been validated for length and tilt (Jech et al., 1995; Horne et al., 2000).

The Kirchhoff-ray mode backscatter model (Clay and Horne, 1994) combines the breathing mode and Kirchhoff approximation to estimate the intensity of sound backscattered by an object based on the speed of sound and density of the fish body and swimbladder. Acoustic scattering length of fish body (L_b) and swimbladder (L_{sb}) could be estimated as fluid-filled half cylinder and gas filled cylinder.

The swimbladder in a fish body, the expression for the scattering length is

$$L_{sb} = -i\frac{R_{bc}(1-R_{wb}{}^2)}{2\sqrt{\pi}}\sum_0^{N_s-1} A_{sb}[(k_b a(j)+1)\sin\theta]^{1/2} e^{-i[2k_b v_j+\psi_p]}\Delta u_j \quad (1)$$

$$a_j \equiv [w_s(j)+w_s(j+1)]/4 \quad (2)$$

$$v_j \equiv [v_{sU}(j) + v_{sU}(j+1)]/2 \quad (3)$$

$$A_{sb} \approx \frac{ka_s}{ka_s + 0.083} \quad \text{and} \quad \psi_p \approx \frac{ka_s}{40 + ka_s} - 1.05 \quad (4)$$

$$R_{bc} = \frac{g'h' - 1}{g'h' + 1} \quad \text{, and} \quad R_{wb} = \frac{\rho_b c_b - \rho_w c_w}{\rho_b c_b + \rho_w c_w} \quad (5)$$

$$g' = \rho_c/\rho_b \quad \text{and} \quad h' = c_c/c_b \quad (6)$$

And a similar expression is derived for fish body:

$$L_b = -i\frac{R_{wb}}{2\sqrt{\pi}} \sum_0^{N_s - 1} (ka_j)^{1/2} \Delta u_j \left[e^{-i2kv_{Uj}} - \mathcal{T}_{wb}\mathcal{T}_{bw} e^{-i2kv_{Uj} + i2k_b(v_{Uj} - v_{Lj}) + i\Psi_b} \right] \quad (7)$$

where R is the reflection coefficient, subscript wb denotes the water-fish body interface, bc denotes the swimbladder-fish body interface, fb refers to the fish body, b refers to the swimbladder, and U and L refer to the upper and lower surfaces in u–v coordinates, respectively. Δu_j denotes incremental distance between cylinders. A_{sb} and ψ_p are empirical amplitude and phase adjustments for small ka. Further details of the model can be found in Clay and Horne (1994).

The scattering length from the whole fish is calculated by adding scattering amplitudes from the fish body and swimbladder coherently.

$$L_{fish} = L_b + L_{sb} \quad (8)$$

Then, target strength of fish could be computed by following equation:

$$\mathrm{TS} = 20 \log |L_{fish}| \quad (9)$$

Measurements of density and sound-speed contrasts

The density contrast (g) is defined as the ratio of the density of the animals to that of the surrounding water (Chu and Wiebe, 2005). In this measurement, we applied the density-bottle method in which fish mass density was determined by evaluating the buoyancy of each sample via a series of 500 ml beakers containing water-glycerol solution of different density, ranging from 1.026 to 1.080 g/cm³ steps (Fig. 1). We defined the value of the bottle in which the fish was neutrally buoyant as fish mass density. If the fish was not neutral in any solution, an average between the last sinking bottle and the first floating bottle was taken. The density contrast of fish body g was obtained by dividing ρ by the density of seawater (ρ_{sw}=1.025 g/cm³). The density of each bottle was confirmed using a glass aerometer and the solution in each bottle was kept at 25°C.

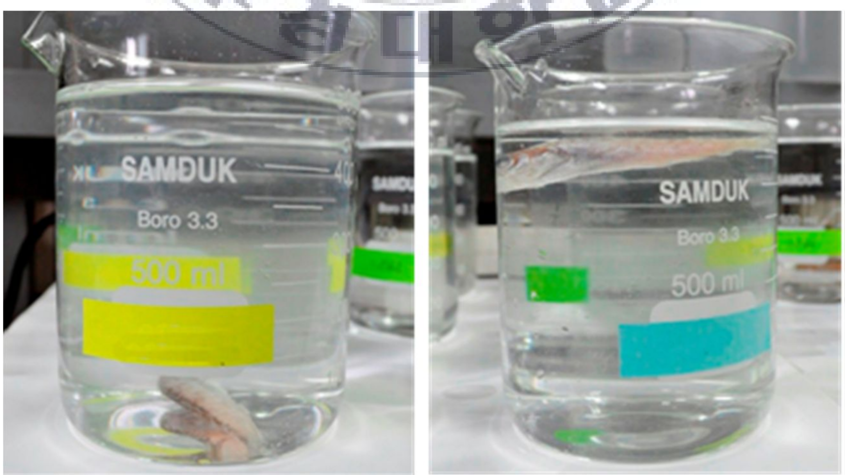

Fig. 1. Density measurement of juvenile cod by density bottle method.

The sound-speed contrast (*h*) is defined as the ratio of the sound speed in animals to that in the surrounding water (Chu and Wiebe, 2005). The sound speed through the fish body was estimated by a time-flight method (Foote, 1990). An acrylic 'T-tube' (inside diameter = 60 mm and inside length = 180 mm) was used for the measurement. A continuous, sinusoidal-wave pulse of 400 kHz, 10 μs was radiated from one side of the tube to the other by generator, and the time it took the pulse to pass through the tube containing seawater and fish was measured with a digital oscilloscope (TDS3054 Tektonik, Japan). Setting for the sound-speed measurement is shown in Fig. 2.

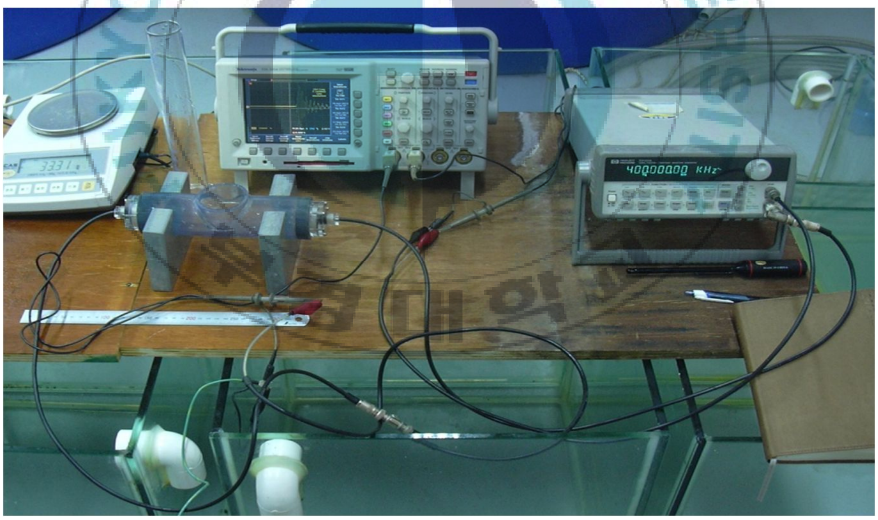

Fig. 2. Set of instrumentation for sound-speed measurement.

In the time-flight method, an empirical equation issued to relate passing time T_{total} through the mixture to the proportion of the volume filled by fishes V as

$$\mathrm{T_{total}} = (1 - V).T_{SW} + V.T_{fish} \qquad (10)$$

Where T_{sw} and T_{fish} are the ‘‘passing time’’ of sound through the seawater and through the fish body, respectively. The sound speed ratio h is given by

$$h = \frac{T_{SW}}{T_{fish}} = \frac{\mathrm{C_{fish}}}{C_{SW}} \qquad (11)$$

Where C_{sw} and C_{fish} are the speed of sound through seawater and fish body, respectively. As C_{sw} is known from T_{sw} and the measurement distance (180 mm), C_{fish} can be deduced. The fish proportion, V in previous equation was estimated by submerging a fish specimen in a graduated cylinder after the measurement. The T-tube was sunk in a temperature-controlled tank and measured between 11°C and 19°C at 2°C steps.

Figure 3 shows the example of the pulse wave data recorded by oscilloscope in the sound speed measurement. Top panel shows the pulse wave obtained from tube filled by seawater only and filled with fishes in the below. The passing time of the sound through the tube determined when the pulse wave begin drastically to changes the pattern.

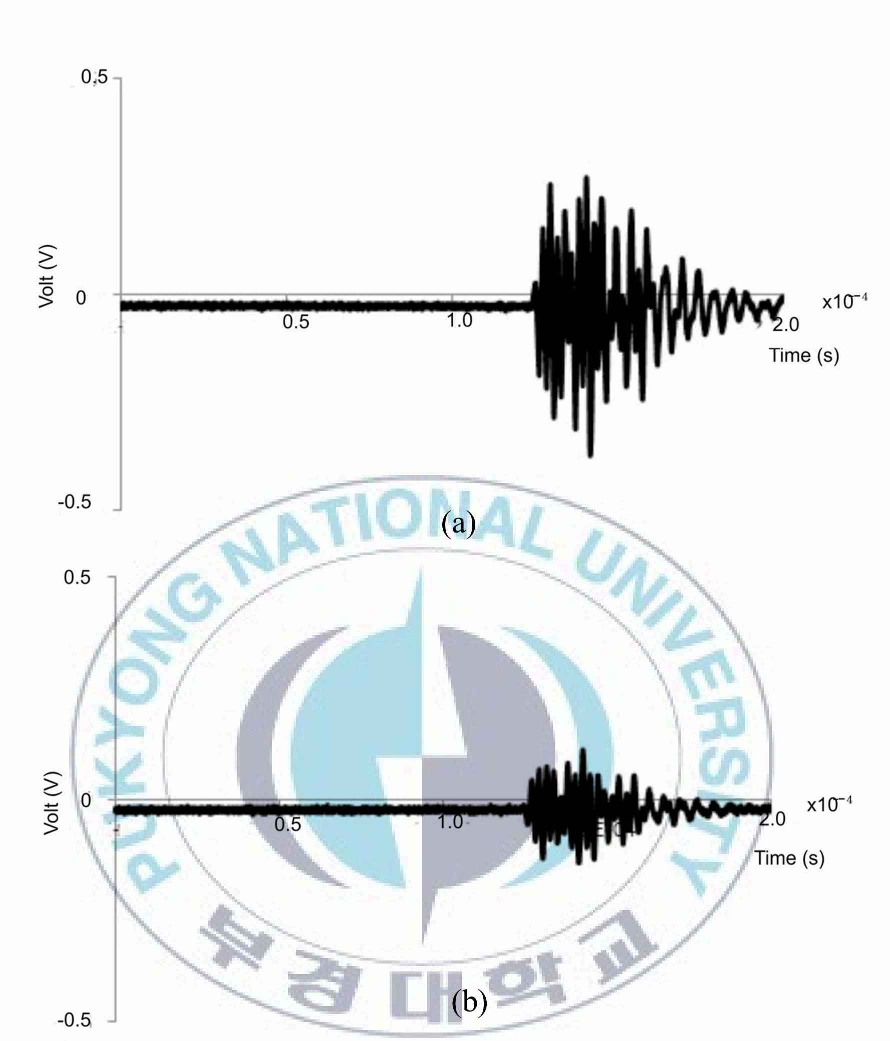

Fig. 3. Example of the pulse wave data represents the passing time of sound through the tube (a) filled by seawater (T_{sw}) and (b) filled by seawater and fishes (T_{total}).

Estimation of TS

A total 12 fish samples with total length ranged from 52 to 105 cm (Table 1) were used in TS calculation from juvenile Pacific cod. All fish were obtained from Gyeongsangnam-do Fisheries Resources Institute, Gyeongsangnam-do, South Korea. The samples were frozen rapidly, using dry ice and added with alcohol prior to take x-ray photo to keep the shape body and swimbladder of fish as actual form, after taken out of water. Examples of x-ray images of the juvenile Pacific cod are shown in Fig. 5.

Table 1.Total length (TL) and body length (BL) of juvenile cod samples

Sample No.	TL (mm)	BL (mm)
1	52	49
2	98	91
3	105	98
4	55	51
5	79	72
6	70	66
7	71	67
8	68	63
9	42	40
10	75	71
11	55	51
12	65	61
Mean	69.6	65

Fig. 4. Pacific cod (*Gadus macrocephalus*) used in this study.

Lateral and ventral images of the fish body and swimbladder were traced and then digitized at 1 mm intervals relative to the fish axis, fins and tail were not included in the trace. These digitized data were used to calculate the TS from the tilt angle and frequency using an acoustic scattering model.

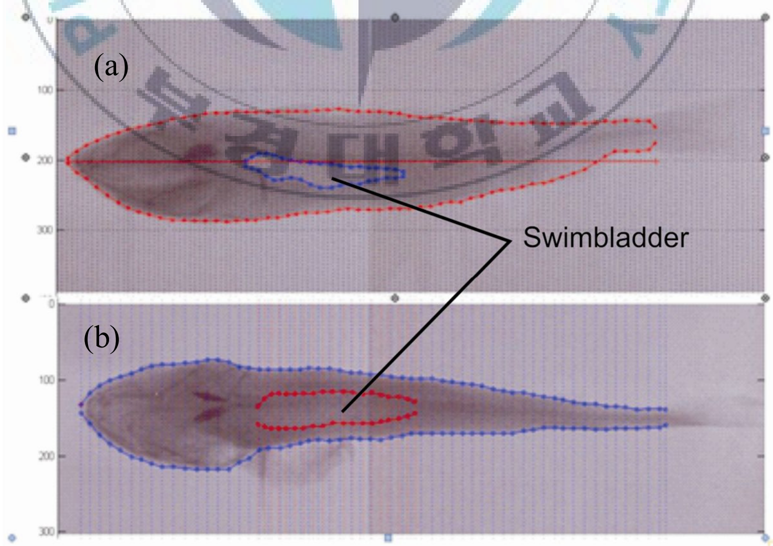

Fig. 5. Example of x-ray images to measure swimbladder and fish body from (a) lateral and (b) ventral view for using in the KRM model.

Acoustic characteristics backscatter model obtained through Kirchhoff-ray mode model, including shape of juvenile cod, density of juvenile cod (*g*), sound-speed (*h*) and frequency. The flowchart showed in Fig. 6 explained the process steps to estimate acoustic scattering characteristics of sample by KRM model.

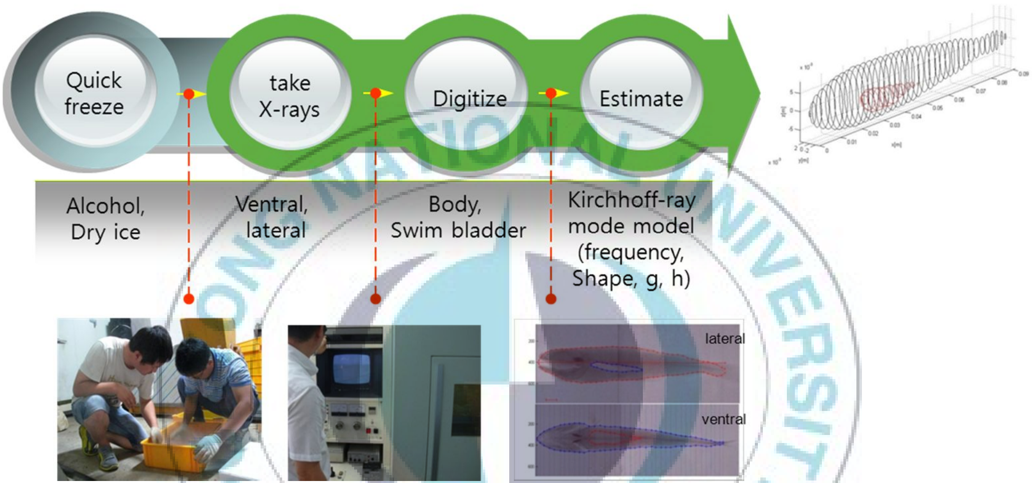

Fig. 6. Flowchart of acoustic scattering characteristics estimation using Kirchhoff-ray mode (KRM) model.

Results

Density and sound-speed contrast

Subsamples of 11 juvenile cod (58-79 mm) were used in the density measurements by density bottle method. The result showed that the value of body mass density (ρ) ranged from 1.065 to 1.067 or the density contrast (g) was 1.039-1.041, with mean value 1.066 (mean g = 1.040) and standard deviation (S.D) was 0.001. The distribution of fish samples, body mass density (ρ) and density contrast are shown in Table 2.

Table 2. Density ratio ($g = \frac{\rho_{fish}}{\rho_{sw}}$) of juvenile cod measured by density bottle method

Sample No.	Weight (g)	Length (mm)	Mass Density (g/cm³)	g
1	1.30	58	1.065	1.040
2	1.56	58	1.067	1.038
3	1.69	60	1.065	1.040
4	1.77	65	1.067	1.038
5	1.77	63	1.065	1.041
6	1.86	62	1.067	1.041
7	2.24	65	1.065	1.043
8	2.37	66	1.065	1.040
9	2.48	75	1.067	1.040
10	3.46	73	1.067	1.038
11	3.94	79	1.067	1.040
Mean			1.066	1.040
S.D				0.001

Due to the sound-speed changes according to temperature, we considered the range between 11° and 19°C for each 2°C step where the habitat temperature of cod is found. The sound-speed of fish was higher than seawater within temperature range examined. The sound-speed contrasts ranged from 1.003 to 1.029 with mean 1.014 (S.D = 0.01). The sound-speed through seawater, the sound-speed through the fish and the sound speed contrast within each given temperature are listed in Table 3. The number of fish used in the experiment was 20 individuals and the proportion of the volume V filled by fish was 0.13. The volume V denotes the ratio of the volume occupied by fishes to the volume of seawater in the tube.

Table 3. Sound-speed contrast (h) of juvenile cod measured by time of flight method

Temperature (°C)	C_{sw} (m/s)	C_{fish} (m/s)	h
11	1491	1516	1.016
13	1498	1509	1.007
15	1504	1548	1.029
17	1511	1515	1.003
19	1516	1536	1.013
Mean (S.D)			1.014 (±0.01)

According to the references (Chu et al., 2003) in most fish species, *g* ranges from 0.98 to 1.07 and *h* from 1.01 to 1.05, thus our results shown that the values are match. Furusawa (1988) analyzed published data and determined that the most common values of *g* and *h* are 1.04 and 1.02, respectively, these values are used in many models studies (Sawada et al., 1999).

TS estimation by KRM model

Typical examples of TS distribution as function of tilt angle over the range -75° to 75°, from head-down to head-up, respectively at 38 and 120 kHz obtained by Kirchhoff ray mode model are shown in Fig. 7. The tilt angle is defined as the angle between the fish axis and the horizontal plane (Foote, 1985). The average values of *g* and *h* were applied in the model calculations, 1.040 and 1.014, respectively.

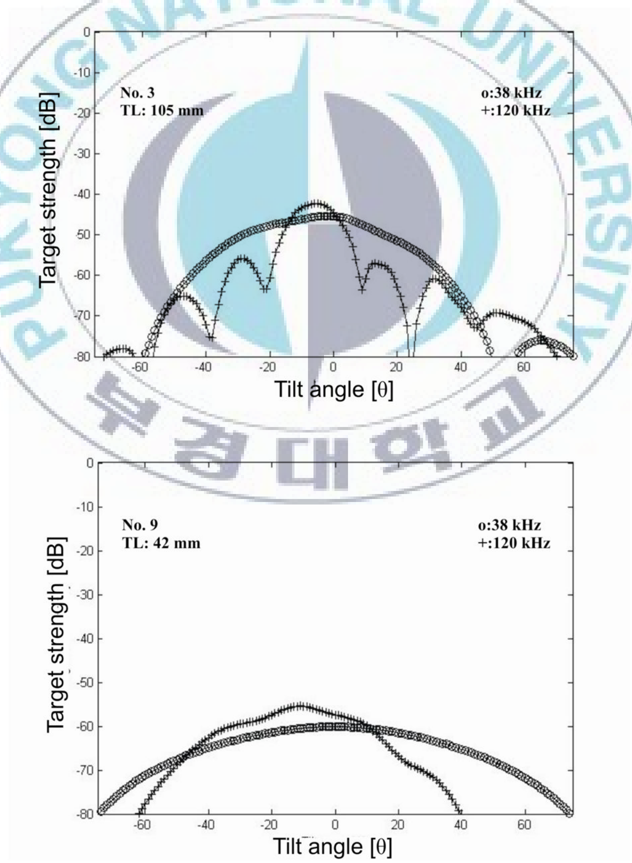

Fig. 7. Typical TS variations of juvenile cod obtained by KRM model at 38 and 120 kHz.

In general, maximum target strength (TS_{max}) obtained at tilt angles between -5° to -1° (varied from -60.14 dB to -45.37 dB) at 38 kHz and -14° to 1° (varied from -55.43 to -42.33 dB) at 120 kHz with mean value about -3° and -6° respectively. It means TS_{max} was detected when the fish head-down or near-horizontal position in both frequencies.

The values of average target strength (TS_{ave}) at two frequencies from total 12 fishes are plotted in Fig. 8 as function of total length in mm scale. The values of average TS at the frequency of 38 kHz and 120 kHz were varied between -60.42 to -46.62 and -57.83 to -49.12, respectively.

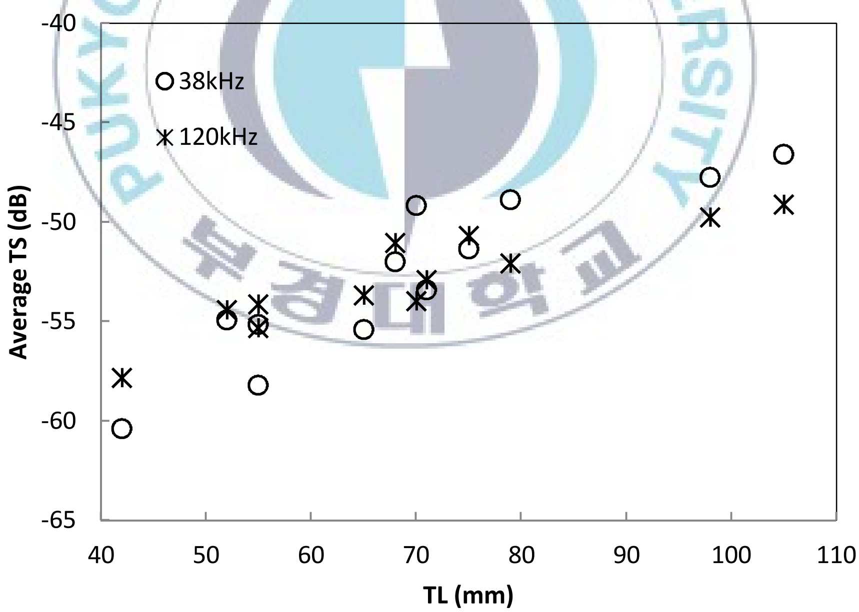

Fig. 8. The relationship between average TS and total length (TL) of juvenile cod calculated by KRM model of fish at 38 and 120 kHz.

TS-to-length regressions

In this study, the TS values for juvenile cod were estimated at two frequencies (38 and 120 kHz), where commonly used in the acoustic surveys. The average target strength for tilt angle θ' was estimated over the normal tilt angle distribution of the fish with probability density function (mean $\bar{\theta}$ = -5° and standard deviation σ_θ = 15°) obtained from the function $f(\theta') = c^{-1}\exp[-(\theta' - \bar{\theta})/2\sigma_\theta^2]\mathrm{rect}[(\theta' - \bar{\theta})/6\sigma_\theta]$ (Foote, 1980). Furthermore the ranges of maximum TS (TS_{max}) and average TS (TS_{ave}) equations of the regression lines are shown in the Table 4.

Table 4. Range of maximum TS (TS_{max}), average TS (TS_{ave}) and equations of the regression lines (TS-length equation)

Frequency (kHz)		Range	TS – length equations	R^2
38	TS_{max} (dB)	-60.14 to -45.37	TS_{max} = 37.9 log L-82.3	0.87
	TS_{ave} (dB)	-60.42 to -46.62	TS_{ave} = 35.2 log L-80.9	0.85
120	TS_{max} (dB)	-51.87 to -42.33	TS_{max}= 33.7 log L-76.0	0.87
	TS_{ave} (dB)	-57.83 to -49.12	TS_{ave} = 20.7 log L-69.5	0.86

In fisheries acoustics, the standard form of the regression is set the slope equal to 20 (Foote, 1979) because backscattering is expected to be proportional to the cross-sectional area (L^2) of a target (Love, 1971; Foote, 1979; McClatchie et al., 2003). A slope of 20 also allows populations or species to be compared using regression intercepts. As target strength-to-length regressions have been derived for more species, slopes with significant deviations from 20 have been found. Thus, by applying equation TS = 20 log [length (cm)] + b, the relation between averaged TS and length of juvenile cod were TS = 20 log L – 68.7 (R^2=0.85) at 38 kHz and TS = 20 log L – 68.9 (R^2=0.85) at 120 kHz. On these equations, the L means the total length in cm of the juvenile cod.

Discussion

Accuracy of estimated TS would be worse if density and sound-speed contrasts were not accurate. Thus, handling in making model samples is important. The frozen samples were used in the experiments for modeling. Some authors have suggested that freezing and long preservation may cause significant changes in material conditions, such as water content and tissue composition, of marine organisms (McClathie et al, 1999; Benoit-Bird et al, 2008). However, the effect of freezing on tissue compositions should be minimum if the organisms are frozen quickly to low temperatures (e.g.,<-40°C) (Pruthi, 1999). We used quick-freezing technique for making frozen samples, thus the composition and condition of material would not change. Then samples were moved and stored in fridge with temperature -40°C before used for measurement, suggest no significant differences between live and frozen fish.

Chu et al (2003) investigated material properties of North Atlantic cod on the eggs- and early-stage larvae where they obtained value of density contrasts for both of stages were nearly slightly less than unity (0.969-0.998), value of speed-contrasts were greater than unity (1.017-1.024) and TS=176.1 log L-82 at 500 kHz. The result for density contrasts shows difference with our result, where *g* in our study were greater than unity (1.039-1.041). This differ represent the fact that density contrast changed fast during early growth stage. However, the sound-speed contrast shows similar result that slightly greater than unity.

Although this study only estimate the TS by theoretical model, but there were some evidence shown the good relationship between model and measured TS. Foote and Traynor (1988) indicated that TS of Walleye Pollock, *Theragra chalcogramma,* measured in situ at 38 kHz compared well to modeled results, but modeled averages were consistently lower than measured results. Abe et al (2004) also conducted the study to compare between measured TS and modeled TS of juvenile walleye Pollock (*Theragra chalcogramma*), they obtained the good relationship results between them. Where the results show similar directivity of TS pattern however maximum values of modeled TS are larger than measured. And Clay and Horne (1994) also found a good match between their models of adult Atlantic cod and measured results from dead, tethered cod reported at 38 kHz.

This is the first study report which provides the two important material properties and target strength of juvenile Pacific cod (*Gadus macrocephalus*). However there are only few studies can be found for related species, especially Atlantic cod (*Gadus morhua*). Rose and Porter (1996), they reported that TS-length relationship of adult Atlantic cod were TS=20log L(cm)-66 at 38 kHz and TS=20 log L(cm)-65 at 120 kHz measured by *ex-situ*. Nielsen and Lundgren (1999) reported the ex-situ TS measurements of live juvenile cod (*Gadus morhua* L.) and their results shown the relationship of mean TS and log L of juvenile cod at 120 kHz was 20 logL-68.0. And previously, Ona (1994) performed in situ target strength measurements of juvenile cod in size 30 to 80 mm at 120kHz obtained the TS- length relationship: TS=20 log L-70.

Though there are many difficulties to perform measurement of TS by ex-situ with dual or split beam method, such as the unavailability of the water tank with appropriate volume, difficulty of controlling tethered anesthetized fish to adjust tilt angles due to the fish size, or even to provide the seawater with cold temperature for live fish, perhaps other scientists or researchers will able to conduct the experiment in the future to compare with our TS model estimation as guideline.

Conclusion

This study conducted to estimate the length dependence on TS and analyze the density and sound-speed contrasts of juvenile cod. The physical parameters are important acoustic material properties to estimate theoretical target strength. Results shown the value of the density contrast (*g*) was 1.039-1.041, with mean was 1.040 (S.D = 0.001). On the other hand, the value of sound-speed contrasts (*h*) ranged from 1.003 to 1.029 with average 1.014 (S.D = 0.01).

The distribution of the target strength for respective sample are shown in figure 7 and appendix, where varied due to fish tilt angle. The average TS calculated by assuming the normal tilt angle distribution of the fish with a mean of -5° and a standard deviation of 15°. The TS – length (total length, cm) equations at the frequency of 38 kHz and 120 kHz were TS = 20 log L – 68.7 and TS = 20 log L – 68.9, respectively, are recommended for use in acoustic surveys to estimate juvenile cod abundance.

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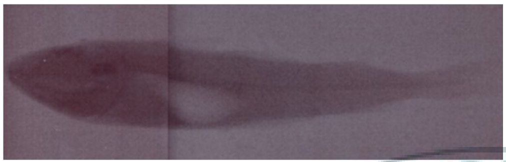
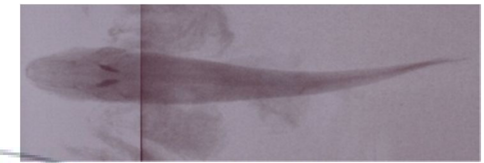
thank God, who has given me guidance and power to encounter the difficulties of life, and without His blessing this life would be meaningless.

Appendix

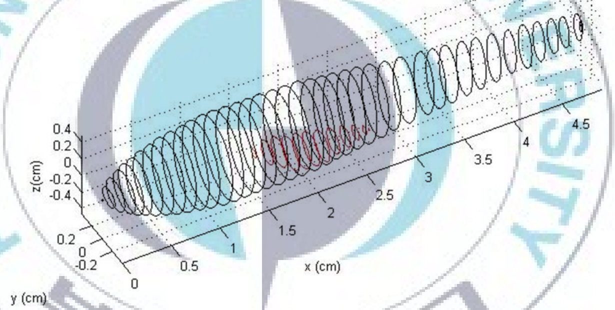
Fish sample no. 1



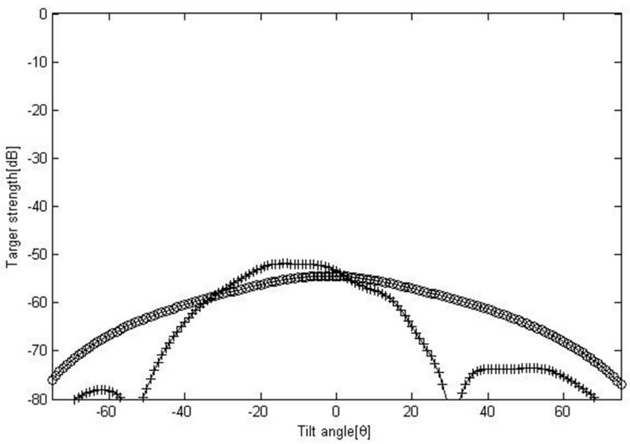
(a) Lateral



(b) Ventral

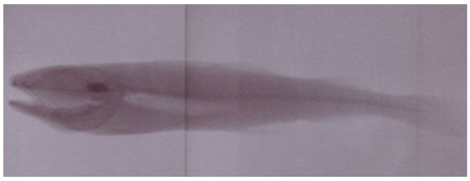


(c) 3D shape

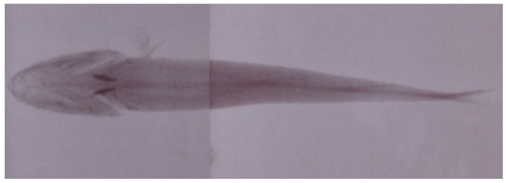


(d) Acoustical scattering pattern (o : 38kHz and + : 120kHz)

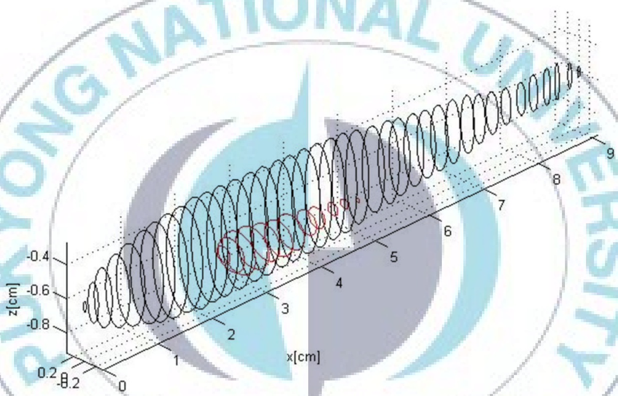
Fish sample no. 2



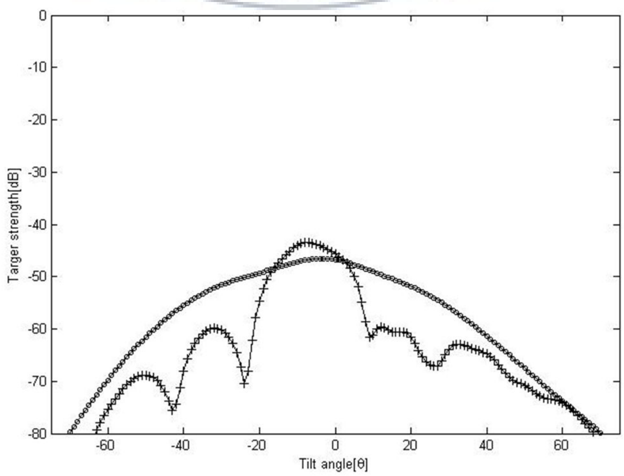
(a) Lateral



(b) Ventral

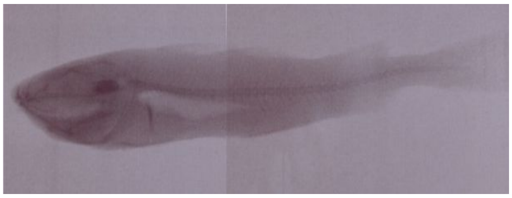


(c) 3D shape

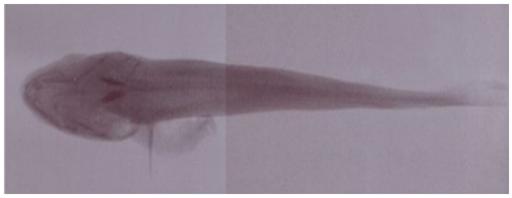


(d) Acoustical scattering pattern (o : 38kHz and + : 120kHz)

Fish sample no.3



(a) Lateral



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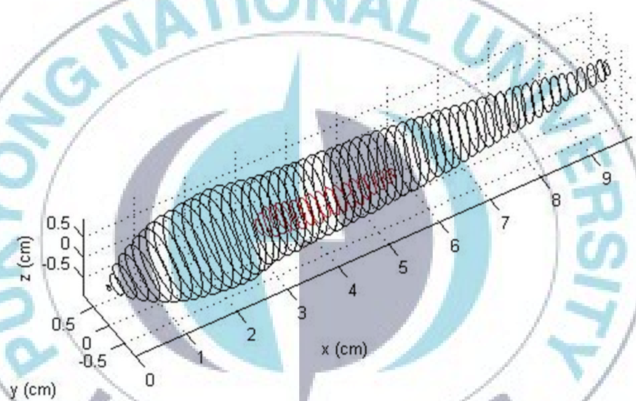
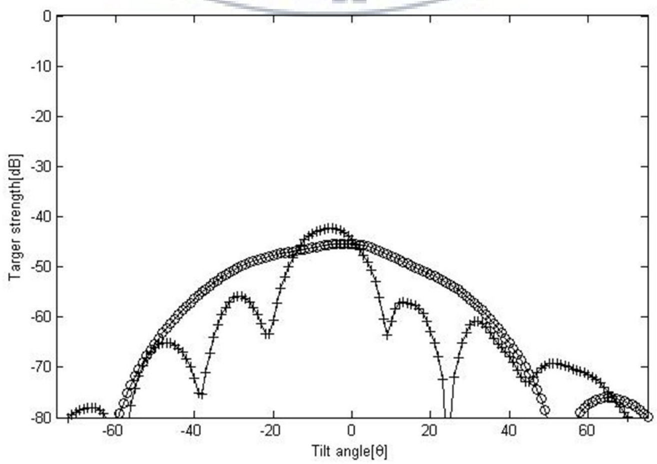


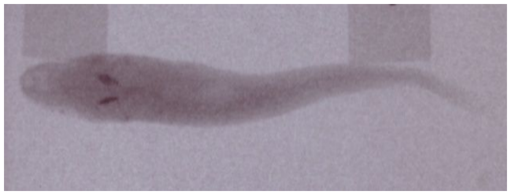
(c) 3D shape



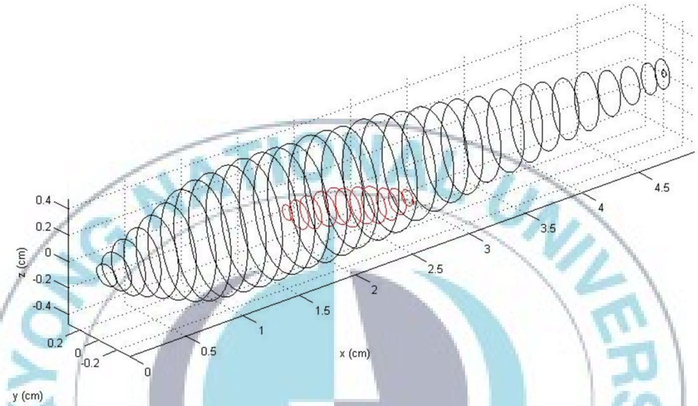
(d) Acoustical scattering pattern (o : 38kHz and + : 120kHz)

Fish sample no.4

(a) Lateral



(b) Ventral



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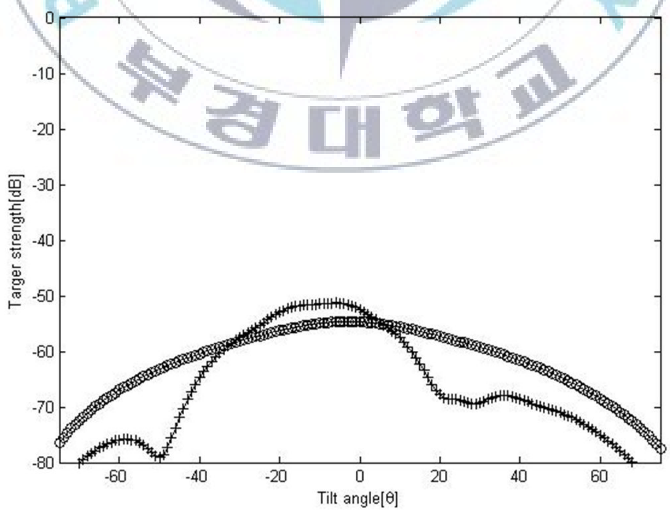
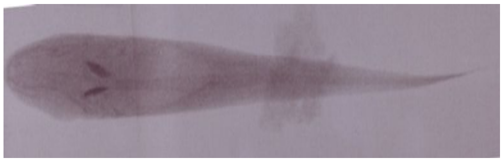


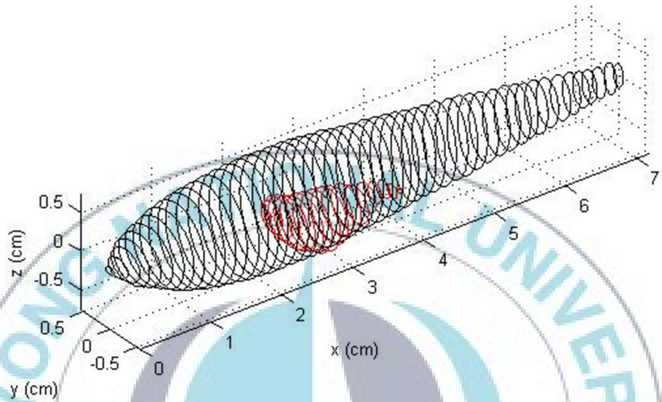
(d) Acoustical scattering pattern (o : 38kHz and + : 120kHz)

Fish sample no.5

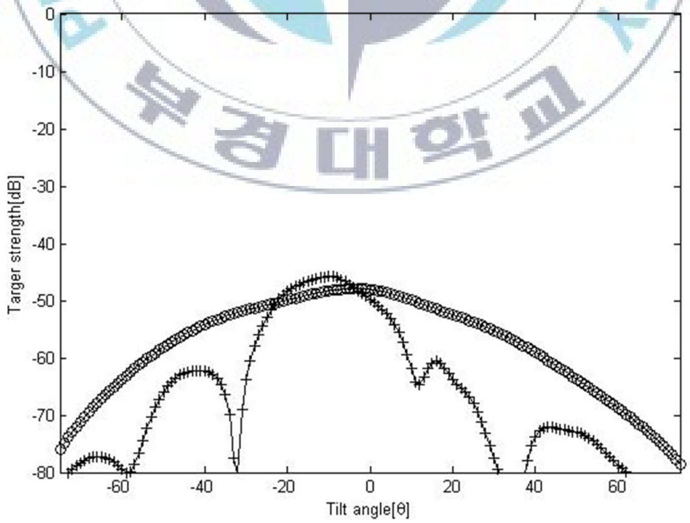
(a) Lateral



(b) Ventral



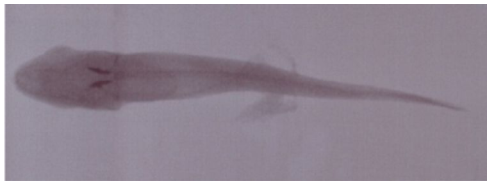
(c) 3D shape



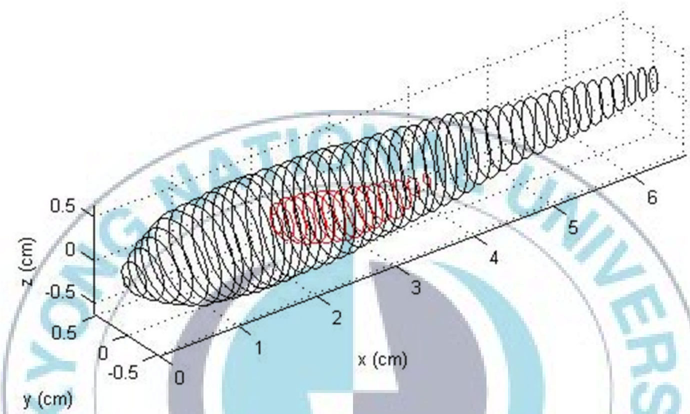
(d) Acoustical scattering pattern (o : 38kHz and + : 120kHz)

Fish sample no.6

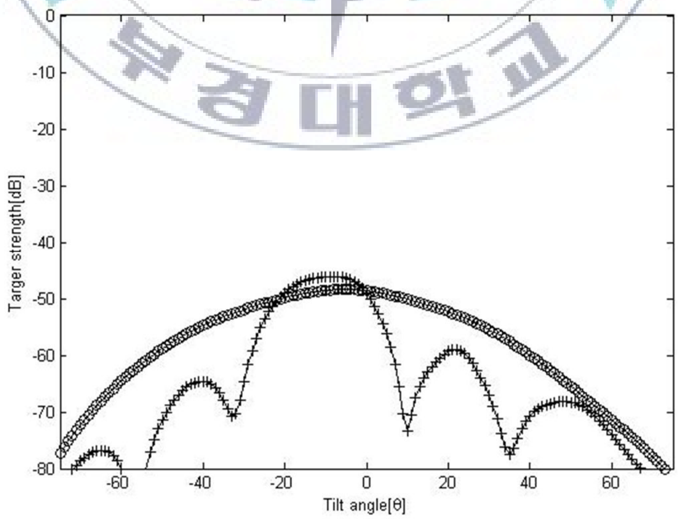
(a) Lateral



(b) Ventral



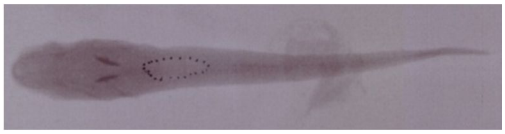
(c) 3D shape



(d) Acoustical scattering pattern (o : 38kHz and + : 120kHz)

Fish sample no.7

(a) Lateral



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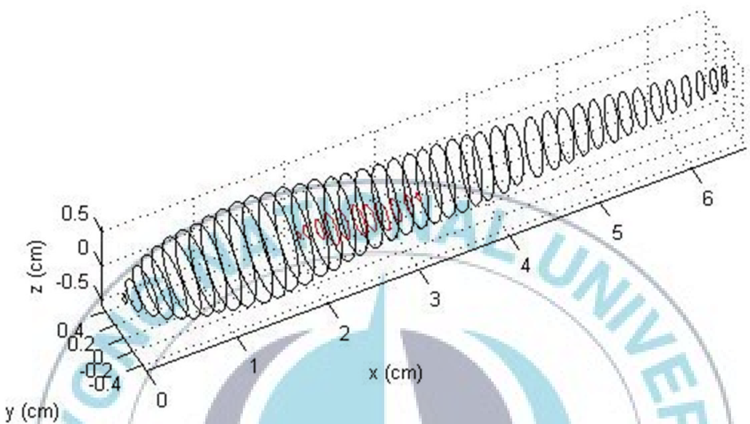
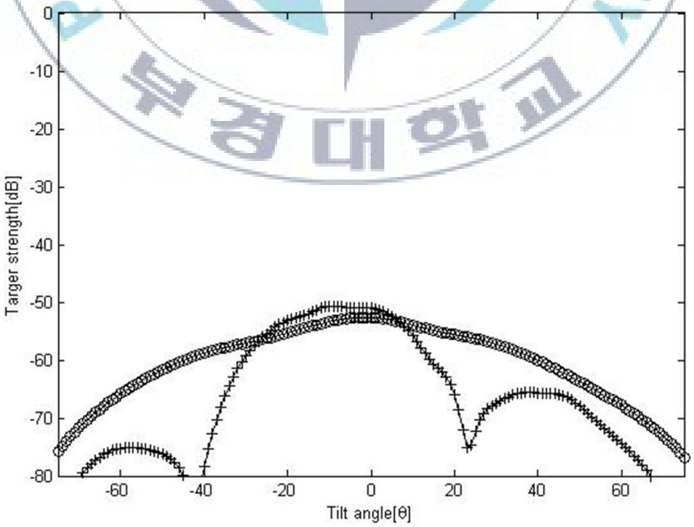


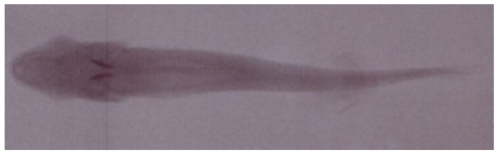
(c) 3D shape



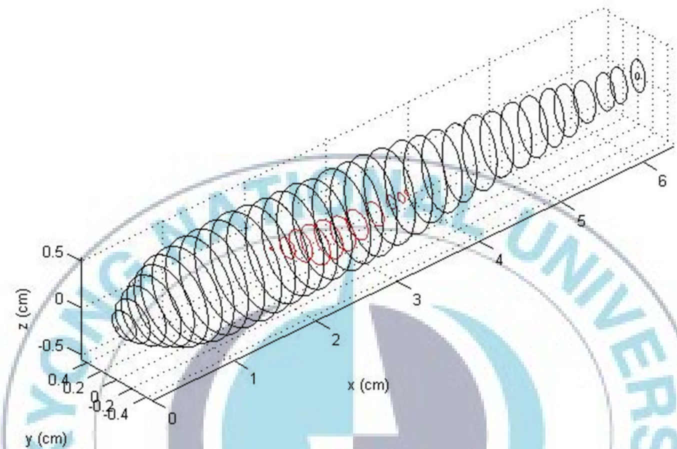
(d) Acoustical scattering pattern (o : 38kHz and + : 120kHz)

Fish sample no.8

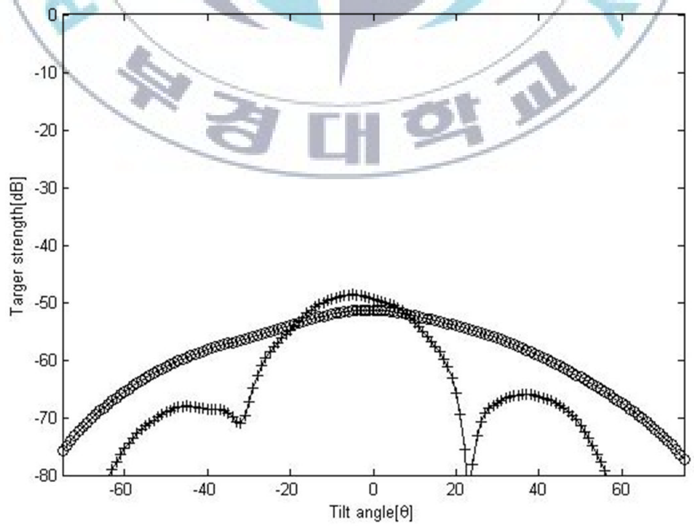
(a) Lateral



(b) Ventral



(c) 3D shape

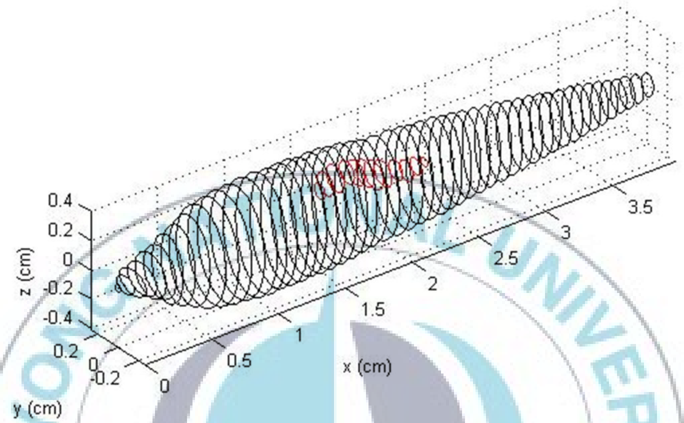


(d) Acoustical scattering pattern (o : 38kHz and + : 120kHz)

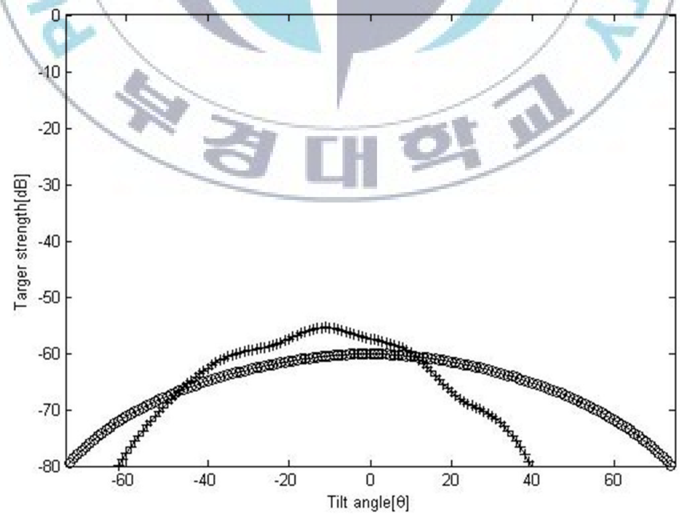
Fish sample no.9


(a) Lateral


(b) Ventral



(c) 3D shape

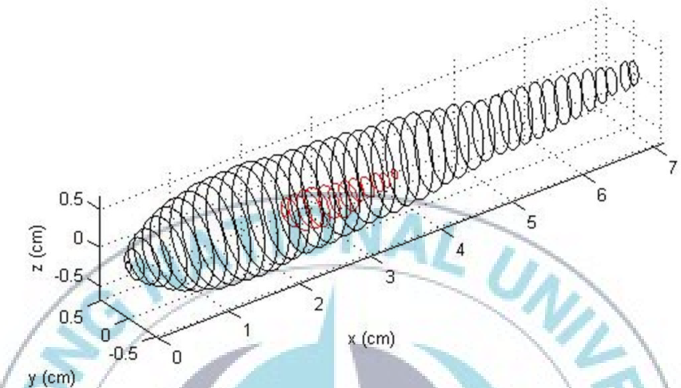


(d) Acoustical scattering pattern (o : 38kHz and + : 120kHz)

Fish sample no.10

(a) Lateral

(b) Ventral



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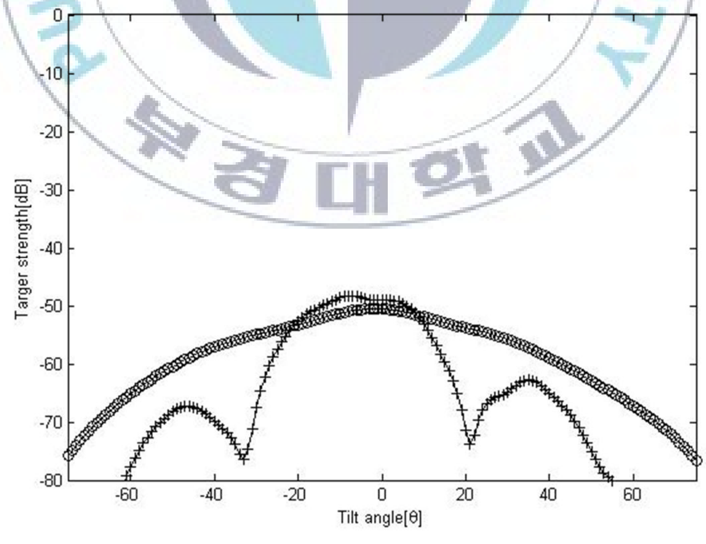
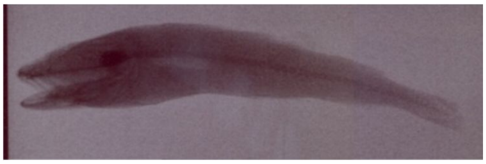
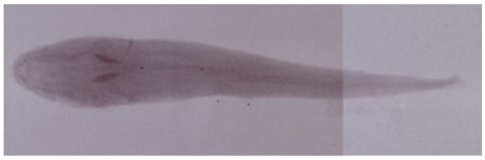


(d) Acoustical scattering pattern (o : 38kHz and + : 120kHz)

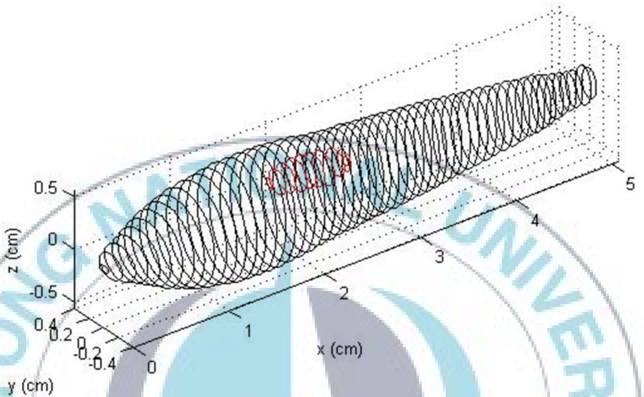
Fish sample no.11



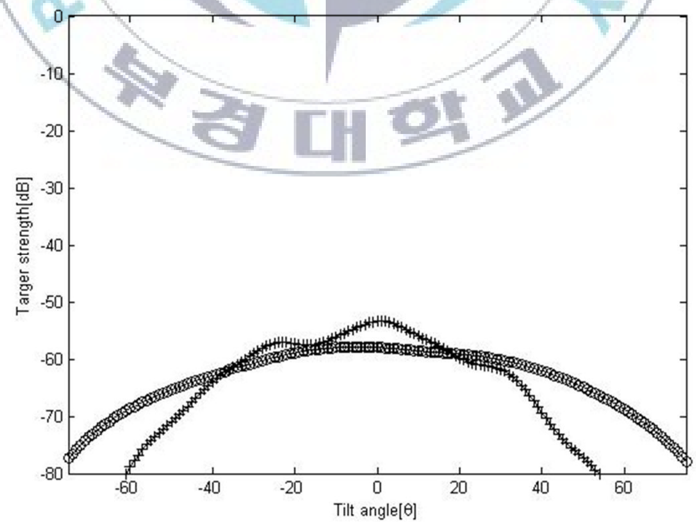
(a) Lateral



(b) Ventral

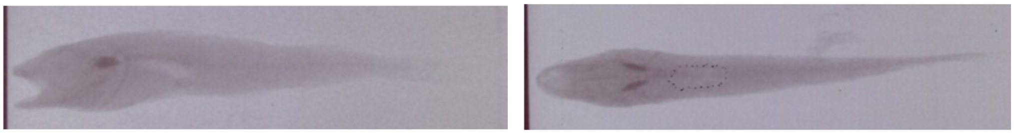


(c) 3D shape

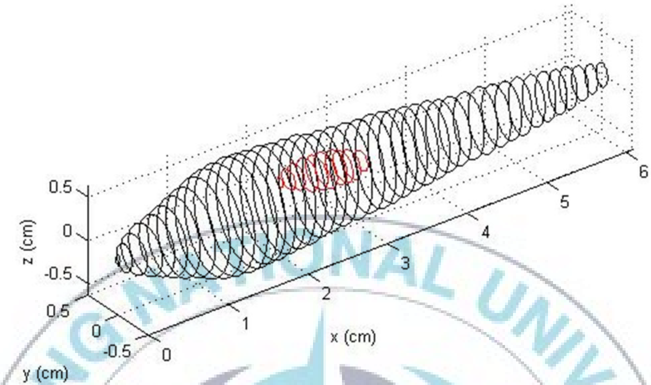


(d) Acoustical scattering pattern (o : 38kHz and + : 120kHz)

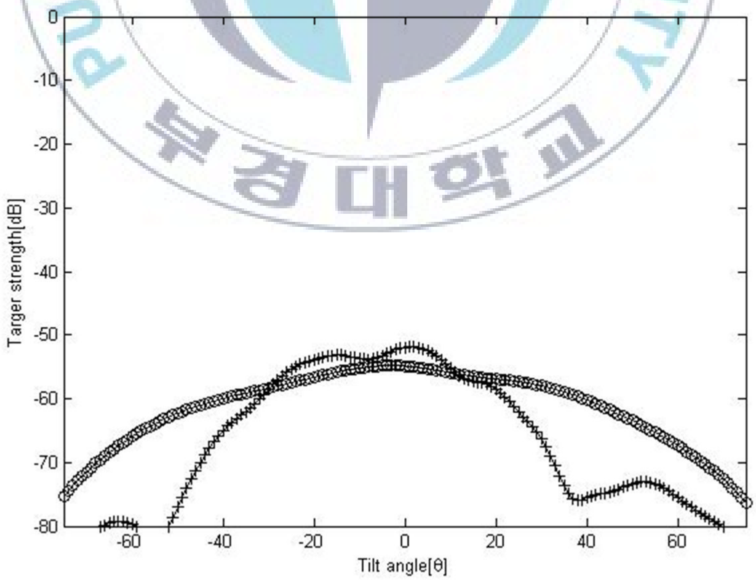
Fish sample no.12



(a) Lateral (b) Ventral



(c) 3D shape



(d) Acoustical scattering pattern (o : 38kHz and + : 120kHz)