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Ex situ target strength of rockfish (*Sebastes schlegeli*) and red sea bream (*Pagrus major*) in the Northwest Pacific

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This study determined the *ex situ* target strength (TS) of rockfish (*Sebastes schlegeli*) and red sea bream (*Pagrus major*) in an artificial seawater tank as a means of helping to estimate fishery resources in coastal areas. TS experiments were conducted at frequencies of 38 kHz (split beam), 120 kHz (split beam), and 200 kHz (dual beam). The species were examined under two conditions: first, live fish confined to a small, net cage; and, second, as free-swimming fish inside a large tank. The study examined 21 rockfish and 20 red sea bream. The data were used to obtain expressions for TS against length and weight for the two species. The relationships between TS and fish length were as follows: for rockfish, $TS_{38\,kHz} = 20\log_{10}(L) - 67.7$ ($r = 0.80$), $TS_{120\,kHz} = 20\log_{10}(L) - 74.3$ ($r = 0.61$), $TS_{200\,kHz} = 20\log_{10}(L) - 72.8$ ($r = 0.41$); and for red sea bream, $TS_{38\,kHz} = 20\log_{10}(L) - 66.8$ ($r = 0.86$), $TS_{120\,kHz} = 20\log_{10}(L) - 74.0$ ($r = 0.65$), $TS_{200\,kHz} = 20\log_{10}(L) - 74.1$ ($r = 0.83$). The TS equations for rockfish and red sea bream as a function of fish weight at 38 kHz were $TS_{38\,kHz} = 6.75\log_{10}(W) - 56.0$ ($r = 0.78$) and $TS_{38\,kHz} = 4.08\log_{10}(W) - 49.9$ ($r = 0.89$), respectively. For comparison, calculations using the Helmholtz–Kirchhoff ray-approximation model based on swimbladder morphology were compared with the measured TS. When the tilt angle of the fish is zero, the mean TS from the model is 3–10 dB higher than the experimental results, although the maximum TS values were only 3–4 dB different.

Keywords: acoustic model, Helmholtz–Kirchhoff ray approximation, red sea bream (*Pagrus major*), rockfish (*Sebastes schlegeli*), target strength.

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Introduction

It is important to know the target-strength (TS) characteristics of fish for use in acoustic surveys (MacLennan and Simmonds, 1992). The TS is required so that the volume-backscattering strength (S_V) can be converted into fish biomass. Recently, there has been a concentrated effort by many researchers to measure *in situ* TS (MacLennan and Menz, 1996) or *ex situ* TS (Mukai and Iida, 1995; Iida *et al.*, 1998; Gauthier and Rose, 2001). Acoustic models using an inverse approach have also proved important for understanding fish-TS variability (Clay and Horne, 1994; Jech *et al.*, 1995). Although the *in situ* method gives TS information under natural conditions, it has inherent deficiencies when it comes to obtaining well-defined measurements. Major problems include unknown tilt angle, fishing-gear selection effects, no possibility of matching specific single-fish echoes with the corresponding single fish in the catch-by-length, and the risk of detecting multiple targets as single-fish targets, which is a problem, particularly in the case of schooling fish (Nielsen and Lundgren, 1999). *Ex situ* experiments on captive fish have been carried out on various species to provide data to supplement the *in situ* method. Although the experimental conditions are not natural, the *ex situ* method allows measurement of swimbladder characteristics with direct observation of such factors as species, tilt angle, directivity pattern, swimming speed, and depth adaptation (Mukai and Iida, 1996; Nielsen and Lundgren, 1999). Acoustic models based on fish morphology (e.g. the shapes of the body and the swimbladder) can be applied to estimate the TS at various frequencies and for comparison with the results of acoustic experiments.

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Rockfish (*Sebastes schlegeli*) and red sea bream (*Pagrus major*) occur in the coastal areas of the northwestern Pacific Ocean, especially in the East China Sea, Yellow Sea, and the coastal areas of the South Sea of Korea and Japan. In response to decreasing resources in these areas as a result of overfishing, marine-ranching programmes were introduced in Japan in the early 1980s and in Korea in 1998 to assist in the recovery and management of fishery resources. The two species studied are considered suitable for use in these programmes. In order to monitor their efficiency, however, and to manage resources, it is necessary to estimate the population biomass using acoustic surveys. However, few studies have examined the acoustic properties of the two species, and, in particular, of the respective TSs (Miyanohana *et al.*, 1986). In this article, we present empirical TS equations as a function of fish length and weight, and we compare acoustic measurements with scattering-model data.

Materials and methods

Fish species and equipment

We studied 21 rockfish and 20 red sea bream. The rockfish ranged between 9.8 and 23.9 cm in length (mean 16.15 cm) and 17.2 and 242.0 g in wet weight. The red sea bream ranged between 10.3 and 34.9 cm in length (mean 19.87 cm) and between 21.7 and 791.2 g in wet weight. The fish were taken from an artificial breeding ground and kept in a seawater holding tank for a minimum of 8 h to minimize stress and damage.

Ex situ experiments were conducted in a $5 \times 5 \times 5\ \mathrm{m}^3$ tank filled with filtered seawater (Figure 1). The nylon net cage measuring $0.5 \times 0.5 \times 0.5\ \mathrm{m}^3$ (volume $0.125\ \mathrm{m}^3$, ignoring distortion due to stretching) was made from 0.3-mm diameter twine in 1.7-cm mesh. The TS of the empty cage at all frequencies was about −73 dB; the influence of the net cage can therefore be neglected in relation to the fish echo. The net cage was lowered to about 3.1-m depth for the measurements, and most of the fish remained in good condition for the duration of the experiments.

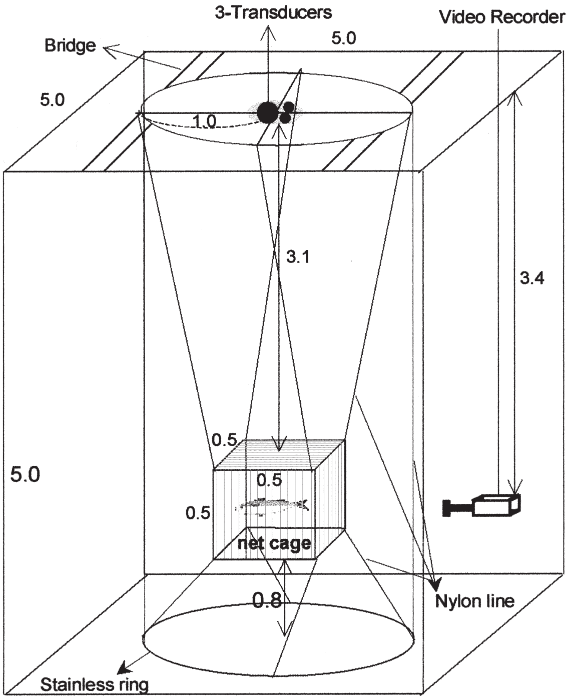

Figure 1. The apparatus for acoustic measurement of caged fish. The numbers are lengths in metres.

TS data from the rockfish and red sea bream were collected using 38 kHz (ES38_B) and 120 kHz (ES120_7) split-beam transducers (SIMRAD EK500) and a 200 kHz dual-beam transducer (Biosonics, 1997, DT5000). The 3-dB beam width corresponds to 7.0°, 7.1°, and 6.5° (narrow beam) for the transducers at 38, 120, and 200 kHz, respectively. The equipment was calibrated before the experiment with standard spheres (copper for 38, 120 kHz and tungsten carbide for 200 kHz) using the procedures described in the operator manuals (BioSonics, 1997; SIMRAD, 1997). An underwater video camera was installed outside the acoustic beam and did not produce any interfering echoes. The video camera continuously monitored the movement of the fish in the cage. After taking acoustic measurements of individual fish confined to the net cage, 80 free-swimming red sea bream were studied inside the tank, in order to compare the TS distributions of confined fish and randomly distributed targets. The lengths of these specimens ranged from 8 to ~10 cm (30 specimens) and 10 to ~13 cm (50 specimens).

Data analysis

Data for analysis were selected based on the depth and position of the targets. The depth range for echo selection was 3.1–3.6 m. The data at 38, 120, and 200 kHz were collected within ±3.5°, ±3.55°, and ±3.25° of the transducer axis, respectively.

The mean TS was calculated from the mean acoustic cross-section, since the averaging has to be done in the linear domain (Foote, 1980). For the same reason, the TS variability was calculated as the coefficient of variation (CV, %) of the acoustic-backscattering cross-section (σ_{bs}). The TS–length (L, cm) relationship was given by the best fit of the standard equation, $\mathrm{TS} = 20\log(\mathrm{L}) + b_{20}$.

Statistics of the echoes from confined and free-swimming fish, respectively, were compared so that we could study changes caused by fish behaviour. Following the terminology of Medwin and Clay (1988), the squared, mean amplitude of the backscattering length, L_{bs}, is called the "concentrated" backscattering cross-section, namely $\sigma_c = \langle |L_{bs}| \rangle^2$, and $|L_{bs}|^2 = \sigma_{bs}$. The variance, $\sigma_d = \mathrm{Var}\,|L_{bs}|$, represents random motion of the targets. The mean backscattering cross-section is the sum $\langle \sigma_{bs} \rangle = \sigma_c + \sigma_d$. In the

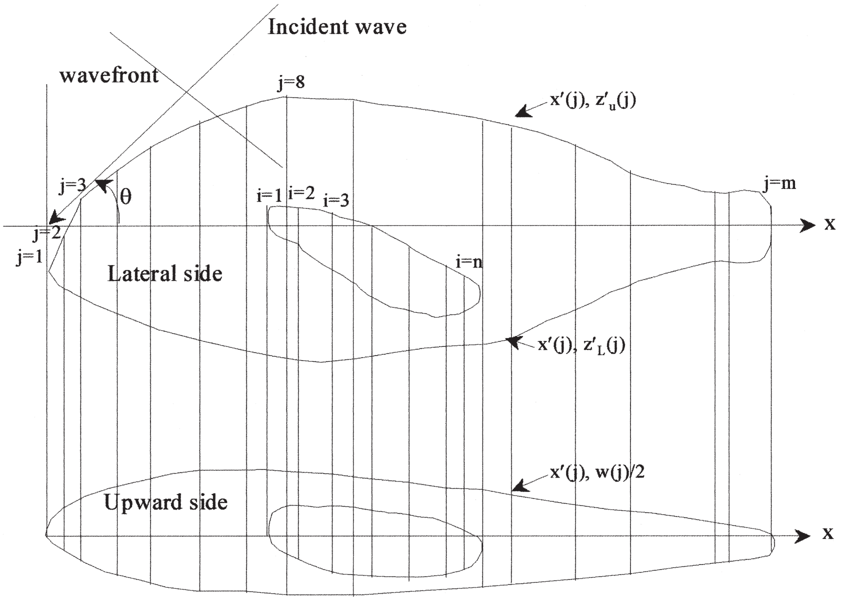

Figure 2. Digital images of fish body and swimbladder outlines of red sea bream in lateral (x, z) and dorsal (x, w) projections.

statistics of fish echoes, $\langle\sigma_{bs}\rangle$ and the ratio $\gamma \equiv \sigma_c/\sigma_d$ are convenient parameters because mean values are measured directly and the ratio is easy to calculate from measurements.

After the experiments, the total length (cm) and wet weight (g) of each fish were measured and the fish were immediately shock-frozen using dry ice and ethyl alcohol. X-ray pictures (SOFTEX M-1005, JIRA) were taken of the dorsal and lateral views of the fish to quantify their morphology. The film images were traced and lengths were compared using the vertebral column as a ruler (Figure 2).

The Helmholtz–Kirchhoff (HK) ray-scattering model represents the fish body as a set of fluid-filled cylinders surrounding the swimbladder modelled as a set of gas-filled cylinders (Clay and Horne, 1994; Horne and Jech, 1999). Theoretical TS predictions in this study were calculated using the HK ray-scattering model based on digitized images of dissected rockfish and red sea bream. The number of segments for the swimbladder (N_s) and fish body (N_b) were chosen to give an acceptable model for each species, taking account of their different length distributions (Table 1).

To demonstrate the use of the HK ray-approximations for the scattering of sound by finite-length cylinders at high frequencies, we considered the scattering geometry of a fish described by Clay and Horne (1994). Coherent scattering is assumed. The scattering length of the whole fish (L_{wf}) is the sum of those due to the swimbladder (L_s) and the fish body (L_b), respectively, and both are added as complex functions. The backscattering cross-section is $\sigma_{bs} = |L_{wf}|^2$ and TS is $20 \log_{10} |L_{wf}|$. Further details of the calculation formulae can be found in Clay and Horne (1994).

Results and discussion

Eighteen of the 21 rockfish and 19 of the 20 red sea bream were judged to have remained in good condition throughout the experiment. The sample size (i.e. number of acoustic measurements) for each species and the frequencies used in individual cases varied with the measurement time and the positions of individual fish in the net cage.

The percentage CV for rockfish in the net cage ranged from 13.2 to 82.1, 34.4 to 254.3, and 71.3 to 224.3 for the measurements at 38, 120, and 200 kHz, respectively. The corresponding results for red sea bream were 30.1–105.5, 64.8–260.9, and 78.3–154.4. Of the three frequencies, the CV for both species was lowest at 38 kHz, indicating that the backscattering cross-section at 38 kHz is more stable because of the lower directivity. This might result from the fish's behaviour (Love, 1977) or the pattern of scattered waves reflected from the fish (Haslett, 1962).

The CV of free-swimming red sea bream was higher than that of the fish in the net cage, i.e., 119.3 vs. 31.3–77.3 (38 kHz), 205.3 vs. 72.4–193.4 (120 kHz), and 195.5 vs.

Table 1. The number of segments for swimbladder (N_s) and body (N_b) of rockfish (*S. schlegeli*) and red sea bream (*P. major*) used in the model computations.

Species	TL (cm)	Weight (g)	N_s	N_b
Rockfish	10.61	20.00	18	27
	19.95	133.70	13	17
Red sea bream	10.63	23.60	13	23
	23.70	197.35	15	30

80.1–138.4 (200 kHz). The comparison of the backscattering cross-section indicates that the mean TS of free-swimming red sea bream is about 6 dB lower.

A Rician probability density function (PDF) was fitted to each measurement set to quantify the behavioural effects (Jech *et al.*, 1995). Generally, γ is below 12 under natural conditions. For the caged fish, $\gamma = 23(\mathrm{CV} = 40.3)$ at 38 kHz and $\gamma = 4.1(\mathrm{CV} = 112.8)$ at 200 kHz. At 120 kHz, the bimodal PDF ($\gamma = 3.5$, $\mathrm{CV} = 72.4$) indicates that the fish behaviour changed abruptly from motion to stillness during the experiment (Figure 3, upper-middle). For randomly distributed, free-swimming fish, the PDF shows a Rayleigh distribution with a higher CV (lower γ) at all frequencies (Figure 3, below). The behaviour of free-swimming fish was erratic compared with a similar length class (8–13 cm) in the net cage. The free-swimming fish moved rapidly at a large orientation angle, just as they do *in situ*, although they were in a seawater tank. This indicates that the *ex situ* results must be interpreted carefully before applying them under natural conditions.

Acoustic experiments with caged fish have shown that the variation in TS correlates well with the tilt angle of the fish. The greater variability at high frequency is associated with the directivity pattern of the fish (MacLennan and Simmonds, 1992). Although we monitored the tilt angle of the fish with an underwater camera, we experienced difficulty in synchronizing the acoustic and video data and were unable to relate the TS variation to the tilt angle of individual fish. Further analysis of these data will be done in a future study.

The coefficient b_{20} in the equation, $\mathrm{TS} = 20 \log_{10}(\mathrm{L, cm}) + b_{20}$, is determined by a least-squares fit of the mean TS against the individual fish lengths. The TS functions at the three frequencies are, for rockfish (Figure 4(a), Table 2):

$$\mathrm{TS}_{38\,\mathrm{kHz}} = 20 \log_{10}(\mathrm{L}) - 67.7 \ (\mathrm{r} = 0.80)$$

$$\mathrm{TS}_{120\,\mathrm{kHz}} = 20 \log_{10}(\mathrm{L}) - 74.3 \ (\mathrm{r} = 0.61)$$

$$\mathrm{TS}_{200\,\mathrm{kHz}} = 20 \log_{10}(\mathrm{L}) - 72.8 \ (\mathrm{r} = 0.41)$$

and, for red sea bream (Figure 4(b), Table 2):

$$\mathrm{TS}_{38\,\mathrm{kHz}} = 20 \log_{10}(\mathrm{L}) - 66.8 \ (\mathrm{r} = 0.86)$$

$$\mathrm{TS}_{120\,\mathrm{kHz}} = 20 \log_{10}(\mathrm{L}) - 74.0 \ (\mathrm{r} = 0.65)$$

$$\mathrm{TS}_{200\,\mathrm{kHz}} = 20 \log_{10}(\mathrm{L}) - 74.1 \ (\mathrm{r} = 0.83)$$

The overall mean TS, calculated from the average length of all the sampled fish and the derived TS function, is given in Table 2 for each species and frequency. For both species, there was little difference in the overall mean TS at 120 and 200 kHz, while at 38 kHz, it was about 6–8 dB higher. Similar tendencies have been seen in the TS functions of gadoid fish at 38 and 120 kHz (Nielsen and Lundgren, 1999; Gauthier and Rose, 2001). Although rockfish and red sea bream are both demersal species, the coefficients (b_{20}) at 38 kHz are similar to those of pelagic species (MacLennan and Simmonds, 1992).

The correlation of mean TS with fish length was best at 38 kHz. The variability was much greater at the higher frequencies. Miyanohana *et al.* (1986) made *ex situ* measurements of tethered sea bream to determine the tilt-angle dependency of TS at 50 and 120 kHz. The tethered fish had a maximum TS of −34 dB at 50 kHz. Comparing fish of similar length, the maximum TS of free-swimming fish was lower (−34.1 to ∼−39.8 dB). There are two explanations

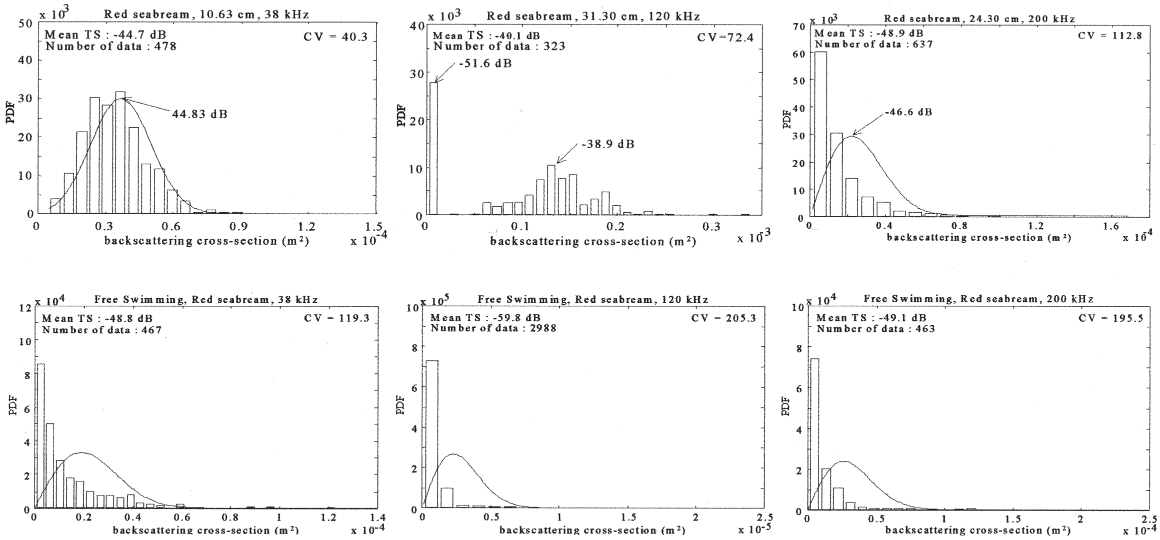

Figure 3. Examples of the PDFs of the backscattering cross-section for encaged fish (above) and for free-swimming fish (below). The curves are fitted Rician distributions. CV is the percentage coefficient of variation.

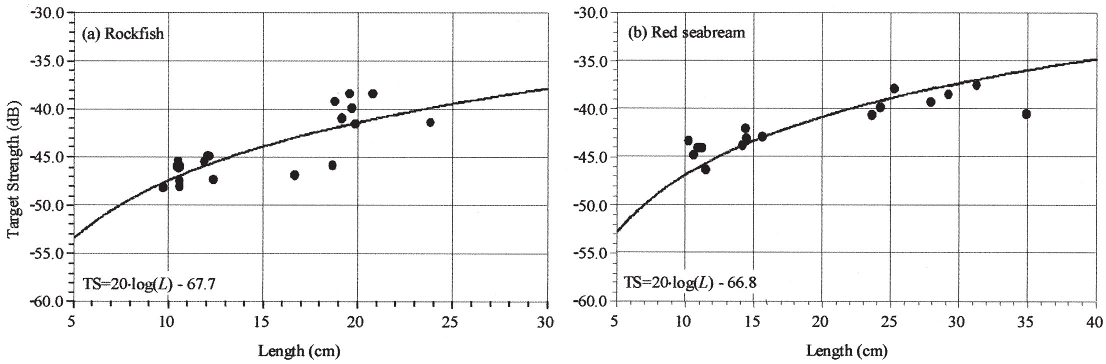

Figure 4. Mean TS of rockfish (a) and red sea bream (b) at 38 kHz plotted against fish length. The curves are fitted standard functions $TS = 20\ \log(L,\ cm) - b_{20}$.

for the higher TS of the tethered fish: first, the density of the fish body may change, and, second, exposure to air during treatment may leave bubbles attached to the fish's skin.

The mean TS in dB for wet weight W in grams is determined by the coefficients a and b in the equation $TS = a\log_{10}(W) + b$. The following results were obtained by linear regression of the 38 kHz data. For rockfish, $TS_{38\ kHz} = 6.75\ \log_{10}(W) - 56.0$ with 95% confidence intervals (a: ±3.0, b: ±5.5). For red sea bream, $TS_{38\ kHz} = 4.08\ \log_{10}(W) - 49.9$ with 95% confidence intervals (a: ±1.2, b: ±2.4).

The tilt angles used in the HK model ranged from 20° to 160°, which means incident angles of −70° to 70° with respect to the fish body. Negative and positive angles represent head-down and head-up orientations, respectively. Disregarding fish size, the results show that the whole-fish TS is dominated by the swimbladder contribution with oscillatory modulations associated with the fish body (Figure 5). The maximum TS occurs at a body tilt around −20° when the long swimbladder axis is roughly perpendicular to the incident beam. The TS is high over a broad range, 30° to −50°, of tilt angles. As far as frequency dependence is concerned, the TS is maximum between 50 and 100 kHz for small fish and below 50 kHz for large fish. In an *ex situ* study of black sea bream (*Acanthopagrus schlegeli*), a species similar to red sea bream, Iida and Mukai (pers. comm.) studied the reflectivity of the bony skull. Their preliminary results indicate that it produces relatively strong echoes. These differences in body components should be considered in future work on fish TS.

The theoretical and experimental results have also been compared. When the tilt angle of the fish is zero, the model TS is 3–10 dB higher than the measurements. The maximum TS values obtained by the two methods, however, were only 3–4 dB different at all frequencies.

Our results suggest that further work is needed to enhance TS information on red sea bream and rockfish. In particular, the *in situ* dependency of TS on depth and tilt angle should be examined. The methodology for this is well established from previous work on other physoclistous species (e.g. Mukai and Iida, 1996; Gauthier and Rose, 2001).

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Table 2. The results of TS experiments on rockfish (*S. schlegeli*) and red sea bream (*P. major*) based on fitted equations $TS = 20\ \log(L) + b_{20}$, where r is the correlation coefficient.

		Length (cm)						
Species	Frequency (kHz)	Range	Mean	b_{20} (dB)	99% CI (lower, upper)	Mean TS (dB)	Method	r
Rockfish	38	9.8–23.9	16.15	−67.7	(−68.8, −66.6)	−43.5	Split	0.80
	120	9.8–23.9	16.15	−74.3	(−75.8, −72.8)	−50.1	Split	0.61
	200	9.8–23.9	1–48.6				Dual	0.41
Red sea bream	38	10.3–34.9	19.87	−66.8	(−67.8, −65.8)	−40.8	Split	0.86
	120	10.3–34.9	19.87	−74.0	(−76.0, −71.9)	−48.0	Split	0.65
	200	10.3–34.9	19.87	−74.1	(−76.5, −71.8)	−48.1	Dual	0.83

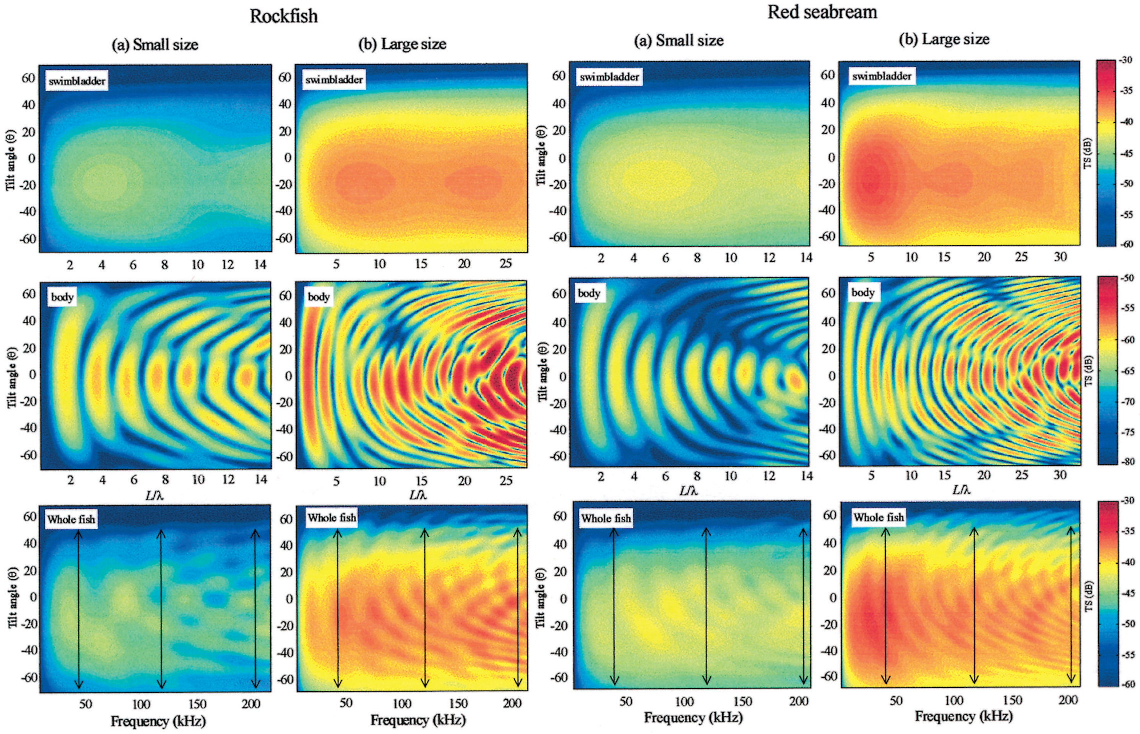

Figure 5. The variation of TS with frequency and tilt angle for rockfish (left side) and red sea bream (right side) from the HK ray-scattering model. In the bottom figures, the arrow lines show the frequencies used and the corresponding L/λ. The lengths of the small and large fish are shown in Table 1.

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