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Application of sound scattering models to swimbladdered fish, red seabream (*Chrysophrys major*)

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Abstract

The acoustical response of fish depends on size and physical structure and, most important, on the presence or absence of a swimbladder. Acoustic scattering models for swimbladdered fish represent a fish by an ideal pressure-release surface having the size and shape as the swimbladder. Target strength experiments of red seabream (*Chrysophrys major*) have been conducted using 38 (split-beam), 120 (split-beam) and 200 kHz (dual-beam) frequencies. At each start of each experiment, the live fish are placed in the cage at the surface, then the cage is lowed to about 4 m depth where it remains during the measurements. To test the acoustic models, predictions of target strength based on swimbladder morphometries of 10 red seabream of fish total length from 103 mm to 349 mm ($3 < TL/\lambda < 45$)are compared with conventional target strength measurements on the same, shock-frozen immediately after caged experiments. X-ray was projected along dorsal aspect to know the morphological construction of swimbladder. and fish body. At high frequencies, Helmholtz-Kirchhoff (HK) approximation would greatly enhance swimbladdered fish modeling. Sound scattering model [HK-ray approximation model] for comparison to experimental target strength data was used to model backscatter measurements from individual fish. The scattering data can be used in the inverse method along with multiple frequency sonar systems to investigate the adequacy of classification and identification of fish

Introduction

Acoustic models of marine fish form the basis of population and biomass quantitative estimates. Therefore, modeling backscatter from fish is needed to explain measurement variability, improve the estimation of fish size and identify fish species from acoustic data [1]. The swimbladder is the dominant scattering organ in fish at typical fisheries survey frequencies (>30 kHz) [2]. A fish swimbladder has a complex and dynamic shape. Therefore, attempts to model backscatter have transformed the fish body and swimbladder to simple shapes. Foote applied an acoustic model using the HK approximation and morphology of the swimbladder [3]. Recently, Clay modified the finite bent cylinder model and applied it to anchovy measurements [4].

Clay and Horne applied the ray-mode model, using actual morphology, to Atlantic cod (*Gadus morhua*) [1]. These models are improvements in the modeling of backscatter because they allow more realistic approximations of fish body and swimbladder morphology [5], [6] [7], [8] [9]. In this study, scattering model, HK-ray approximation model, is used to construct backscatter curve for red seabream (*Chrysophrys major*) [10], [11], [12], [13], [14]. This model is based on the fish morphology. Model results are compared to measurements of backscatter from individual red seabream.

Acoustic & Morphology measurements

Acoustic data were taken in sea water tank (5 m × 5 m × 5 m). Red seabream (***Chrysophrys major***) have a physoclistous swimbladder (i. e., not connected to the throat). At each start of each experiment, the live fish are placed in the cage at the surface, then the cage is lowed to about 4 m depth where it remains during the measurements. Target strength data from 10 live red seabream were collected with a Simrad split-beam acoustic system (EK500) at 38 and 120 kHz and a Biosonics dual-beam acoustic system (DT4000) at 200 kHz [15], [16]. The two acoustic systems give the off-axis (in dB) position of the fish for each ping. Data chosen for analysis were on or near the transducer axis. The 3-dB beam width corresponds to 7.0°, 7.1°, and 6.0° off the transducer axis for 38, 120, and 200 kHz frequencies.

After caged experiments, individual fish were measured total length (TL, L, mm), body depth (mm), width (mm), and wet weight (g) and shock-frozen immediately with dry ice and ethyl alcohol (Table 1). X-ray (SOFTEX M-1005, JIRA) was projected along dorsal and ventral aspect to know the morphological construction of swimbladder and fish body. X-ray images of fish show the flesh, skeletal elements, and the swimbladder. The gas-filled swimbladder has a dark image because air absorbs the X-rays less than flesh. When the X-ray images were developed to a film, the swimbladder has a light images (Fig. 1). The film images were traced and projected to a standard length using the vertebral column as a ruler between the lateral and ventral views. The angles of the swimbladder relative to the x axis are shown. The smaller fish have larger tilts than the larger fish. The number of segments for swimbladder (N_s) and fish body (N_b) summation was chosen to give an acceptable model of the fish (Table 1). Using each segments, volume of swimbladder (Vol_s, cm^3) and fish body (Vol_b, cm^3) was calculated.

Table 1. Morphology measurements from individual Red seabream.

Num	N_s	N_b	TL	weight	Vol_s	Vol_b
A	11	17	109.4	19.26	0.96	21.22
B	13	17	115.4	30.11	1.72	31.73
1	14	20	103.1	21.65	1.03	22.42
2	13	23	112.2	23.24	1.18	22.89
3	13	23	106.3	23.60	1.22	23.30
4	15	30	237.2	197.35	9.24	206.22
5	12	22	243.5	270.60	13.63	371.07
6	15	22	313.7	578.65	25.89	735.85
7	18	27	349.2	791.19	39.89	999.93
8	13	17	253.1	278.46	15.51	382.26

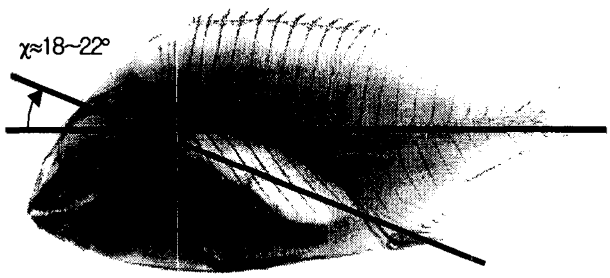

Fig. 1. Lateral X-ray of red seabream (*Chrysophrys major*). The swimbladder is light and its angle relative to the horizontal axis is about 18 - 22°.

HK scattering model

To demonstrate how the HK-ray approximations for the scattering of sound by finite length cylinders can be used for high frequencies, consider the scattering geometry at a fish in Fig. 2 [1], [2], [7]. We considered scatter from the swimbladder, the fish body, and whole fish.

The sum of the scattering length ($\mathcal{L}_s$) of a swimbladder at each segment is

$$\mathcal{L}_s \approx -i\frac{R_{bs}(1-R_{wb}^2)}{2\sqrt{\pi}}\sum_{j=0}^{N_s-1} A_{sb}\times[(k_b a_j+1)\cos\chi]^{1/2}$$
$$\times\exp[-i(2k_b v_j+\psi_p)]\cdot\Delta u_j \quad (1)$$

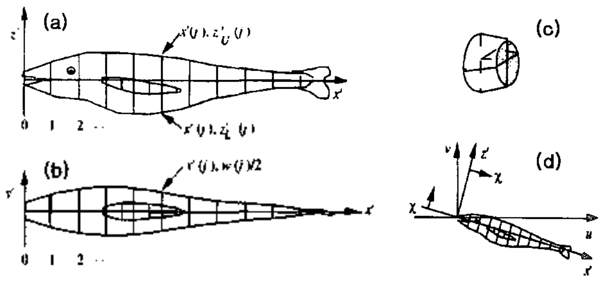

Fig. 2. Geometrical construction of an acoustic fish model. Length of fish body and swimbladder are digitized at a set of x'(*j*) and z'(*j*). The width of the fish body and swimbladder is w(*j*). (a) Lateral view in the x'-z' plane. (b) Ventral view in the x'-y' plane. (c) *j*-th element. (d) Rotation of x'-z' to ***u-v*** coordinate. Coordinate ***u*** is parallel to the incident wavefront, and ***v*** is parallel to the incident ray.

where,

$$a_j=[w_s(j)+w_s(j+1)]/4,$$
$$v_j=[v_{sU}(j)+v_{sU}(j+1)]/2,$$
$$A_{sb}\approx\frac{ka_s}{ka_s+0.083},\quad \psi_p\approx\frac{ka_s}{40+ka_s}-1.05,$$
$$v(j)=-x'(j)\sin\chi+z'(j)\cos\chi$$
$$\Delta u_j=[x'(j+1)-x'(j)]\cos\chi.$$

The sum of the scattering length ($\mathcal{L}_b$) of a fish body at each segment is

$$\mathcal{L}_b \approx -i\frac{R_{wb}}{2\sqrt{\pi}}\sum_{j=0}^{N_b-1}(ka_j)^{1/2}\Delta u_i\times[\exp(-i2kv_{Uj})$$
$$-T_{wb}T_{bw}\exp\{-i2kv_{Uj}+i2k_b(v_{Uj}-v_{Lj})+i\psi_b\}]. \quad (2)$$

R_{wb} is reflection coefficient at water-fish body interface. T_{wb} and T_{bw} are transmission coefficient at water-fish body and fish body-water interface.

The scattering length functions for the swimbladder and fish body were computed individually. Whole fish scatter ($\mathcal{L}_{wf}$) can be computed from the $\mathcal{L}_s$ and $\mathcal{L}_b$. Coherent scatter is assumed and thus $\mathcal{L}_s$ and $\mathcal{L}_b$ add as the complex functions (i.e., with real and imaginary terms added separately)

$$\mathcal{L}_{wf}=\mathcal{L}_s+\mathcal{L}_b \quad (3)$$

The backscattering cross-section (σ_{bs}) can be computed from the complex $\mathcal{L}_{wf}$ by $\sigma_{bs}=|\mathcal{L}_{wf}|^2$ and target strength (TS) is $20\times\log_{10}|\mathcal{L}_{wf}|$. The relative scattering length is $\mathcal{L}_{wf}(L/\lambda)/L$ and relative target strength is $20\times\log_{10}|\mathcal{L}_{wf}(L/\lambda)/L|$. Acoustical and physical parameters used in the backscatter model are given in Table 2.

Table 2. Acoustical parameters.

	ρ (kg/m³)	c (m/s)	g	h
Sea water	1030	1541	-	-
Fish body	1070	1570	1.04	1.02
Swimbladder	1.24	345	0.001	0.22

Comparison of Acoustic model and Acoustic measurements

Example results of calculations of the target strength using the morphology for swimbladder, fish body, and the whole red seabream 1 are shown in Fig. 3 and 4 as a function of the frequencies. From results of the acoustic model, the target strength of whole fish without regard to fish length is depended on variations in swimbladder morphology than fish body morphology. The oscillatory modulations of target strength are due to the contributions of the fish body.

The effects of target strength with incident angle at this study don't to be considered. All incident angle to horizontal axis of the fish, therefore, is assumed to be 0 degree. In case of small red seabream, variations of the target strength with frequencies have a tendency to monotonic decrease. But, for large red seabream, the curves of target strength are shown to oscillate about an average trend of target strength. Data points in Fig. 3 and 4 are mean and maximum target strength values for any orientation angle from individual acoustic measurements (see Table 3). The upper points were indicated maximum target strength and lower points mean target strength. The limit of the acoustic measurement data at three frequencies was placed on the curve of the model except higher frequency.

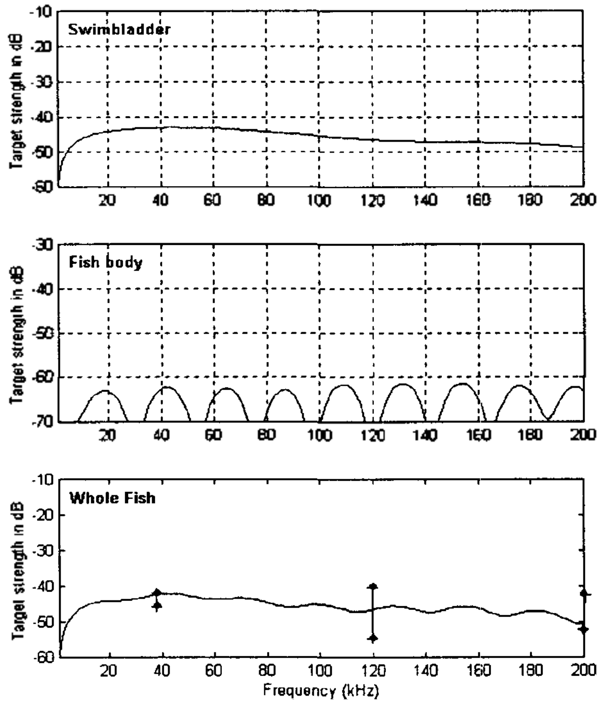

Fig.3. Target strengths for an acoustic model of a red seabream (*Chrysophrys major*). Total length of the fish is 103.1 mm, and incident angle 0 degree.

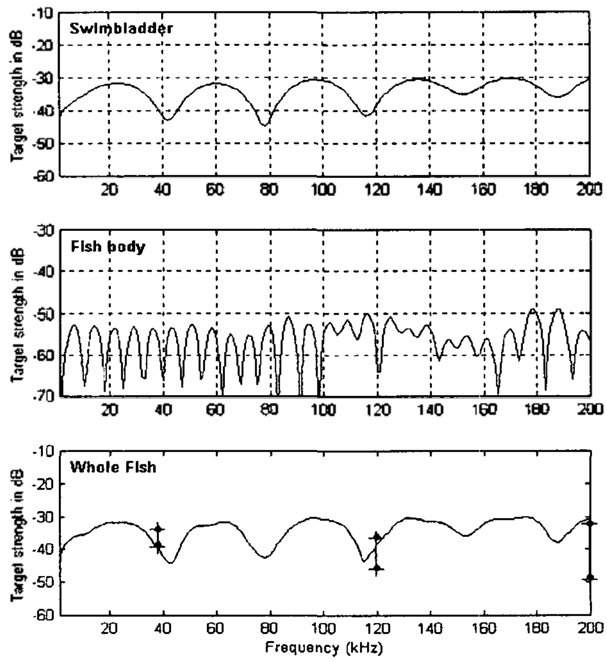

Fig.4. Target strengths for an acoustic model of a red seabream (*Chrysophrys major*). Total length of the fish is 313.7 mm, and incident angle 0 degree.

Fish used for empirical measurements of target strength ranged from 103 - 349 mm TL ($3 < TL/\lambda < 45$). The ranges of small size fish (Number A, B, 1, 2, and 3) are $3 < TL/\lambda < 14$, and the ranges of large size fish are $\sim 6 < TL/\lambda < 45$. In Fig. 5, relative scattering length of small fish computed finite cylinder model using HK ray approximation. Data points are mean relative scattering length of small each red seabream at the three frequencies. Average curve of the relative scattering strength at the range, $3 < TL/\lambda < 14$ range, has a tendency to monotonic decrease with similar to Fig. 3 curve. Data of mean relative scattering length from acoustic measurements includes effects of all swimming angle of the fish. Because the incident angle for model calculation is assumed to be 0 degree, target strength due to model calculations is possible to different from that of acoustic measurements.

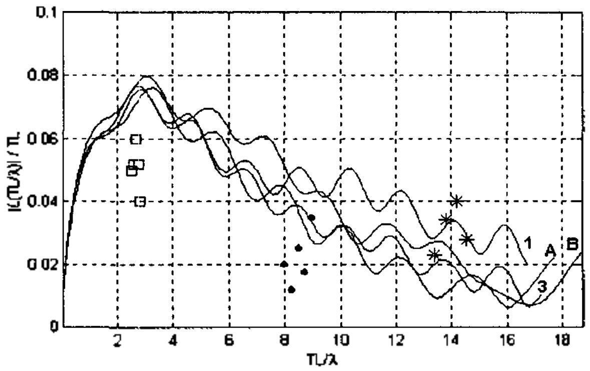

Fig.5. Small fish relative scattering length curve computed finite cylinder model using HK ray approximation. Data points are mean relative scattering length of small each red seabream at the three frequencies: 38 (squares), 120 (circles), and 200 kHz (asterisk). See Table 3.

Conclusions

Acoustic scattering model [HK-ray approximation model] for comparison to experimental target strength data using caged method was used to model backscatter measurements from individual fish. The target strength of whole fish without regard to fish length is depended on variations in swimbladder morphology than fish body morphology. In case of small red seabream, variations of the target strength with frequencies have a tendency to monotonic decrease. For large red seabream, the curves of target strength are shown to oscillate about an average trend of target strength. The limit of the acoustic measurement data at three frequencies was placed on the curve of the model except higher frequency. The scattering data can be used in the inverse method along with multiple frequency sonar systems to investigate the adequacy of classification and identification of fish

Table 3. Backscatter measurements from individual red seabream.

Num	Freq. (kHz)	$\overline{\sigma_{bs}}$ (m^2)	$\overline{TS}$ (dB)	$\frac{\overline{\lvert L \rvert}}{\overline{TL}}$	Max TS (dB)
A	38	3.64e-5	-44.38	0.055	-40.60
	120	7.00e-6	-51.55	0.024	-45.98
	200	2.07e-5	-46.83	0.042	-38.22
B	38	2.29e-5	-46.40	0.041	-43.80
	120	1.59e-5	-47.98	0.035	-42.01
1	38	2.82e-5	-45.50	0.052	-41.90
	120	3.44e-6	-54.64	0.018	-40.15
	200	5.78e-6	-52.38	0.023	-40.28
2	38	3.39e-5	-44.70	0.052	-40.42
	120	3.87e-6	-54.12	0.018	-41.66
	200	9.75e-6	-50.11	0.028	-40.04
3	38	3.08e-5	-45.12	0.052	-42.43
	120	1.57e-6	-58.02	0.012	-43.75
	200	1.27e-5	-48.95	0.034	-41.84
4	38	7.47e-5	-41.26	0.036	-34.35
	120	1.52e-6	-58.16	0.005	-38.05
	200	6.92e-6	-51.60	0.011	-39.95
5	38	5.00e-5	-43.00	0.029	-32.50
	120	2.90e-6	-55.35	0.007	-37.55
	200	5.14e-6	-52.89	0.009	-38.33
6	38	1.36e-4	-38.64	0.037	-33.70
	120	2.86e-5	-45.43	0.017	-36.24
	200	1.35e-5	-48.68	0.012	-32.18
7	38	7.69e-5	-41.14	0.025	-32.65
	120	9.12e-6	-50.40	0.086	-35.85
	200	1.02e-5	-49.91	0.009	--32.89
8	38	1.31e-4	-38.81	0.045	-34.37
	120	1.49e-5	-48.24	0.015	-36.43
	200	1.04e-5	-49.85	0.013	-34.21

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