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Research Article

Introduction of the Precise TS Measurement for Fisheries Acoustics

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Abstract: Two methods to measure target strength (TS) are introduced and compared with each other. One is the suspension method, and the other is the split-beam method. Each of them is representative of control and in situ methods, respectively. In addition, a morphological investigation of a swimbladder in a pressure tank, and the development of an instrumented package of acoustic and optical systems, are also introduced. The former is to reveal the degree of TS variation by the vertical movement of fish, and the latter is to obtain precise TS and fish behavior by the echo trace analysis method.

Key Words: Target strength, Suspension method, Split-beam method, Pressure tank

Balıkcılık Akustiginde Hassas Hedef Yansi Gücü (TS) Ölçümü

Özet: Balıkcılık akustigi çalısmalarında,balıklardaki akustik yansi gücünün hesaplanmasi ile ilgili olarak iki yöntem kullanılmaktadır. Bunlardan biri Kontrol Yöntemi diğeri ise In situ Yöntemidir. Her iki yöntem arastırmalarda kullanım amacına yönelik olarak oldukça yaygın olarak kullanılmaktadır. Akustik yansi gücünün hesaplanmasında balıkların yüzme keseleri önemli bir organdır. Yüzme kesesi içinin hava ile dolu olması nedeniyle gelen ses dalgalarının kuvvetli bir şekilde geriye yansıtılmasında önemli bir role sahiptir. Bu bakımdan her iki yöntemle akustik yansi gücü hesaplanırken, yüzme keselerinin durumu ve kondisyonu, bu değerin hassas olarak ölçülmesinde istenilen bir durumdur. Yapılmıs olan bu çalışmada, sözü edilen her iki yönteme değinilmiş olup, ayrıca balıkların yüzme keseleri ve bunların basınca bağlı olarak gösterdikleri değişimler gözlenmistir.

Anahtar Sözcükler: Yansı gücü, Askı methodu, Kırık-açı methodu, Basınç tankı

Introduction

Precise target strength (TS) of fish is needed in order to estimate fish abundance. There are two categories to measure TS, one is controlled measurement and the other is *in situ* measurement (1). Suspension and split-beam methods are popular representatives of the controlled and *in situ* methods, respectively.

Tethered fish, whether dead or anesthetized, are used in the suspension method (2,3). Tilt angle of fish is controlled and TS is measured as a function of its tilt angle. Therefore, fish length and species are already known in this method.

In the case of *in situ* TS measurement using the dual-beam or split-beam method, the measured target strength depends on the fish tilt angle and length distribution. Moreover, we can estimate the TS pattern and swimming velocity of fish using the echo trace analysis method (4). However, it is generally difficult to relate individual echoes and fish; hence size, species, and other characteristics of the scatterer are rarely known. Observed TS tends to become higher because of the incompleteness of the current algorithm for single echo detection when the spatial density of a fish school is high or when a fish school is deep (5).

It is important to realize the merits and demerits of both methods and to apply a suitable method depending upon the circumstances.

Over 90% of backscattering is from the swimbladder. Foote showed that a theoretical calculation of TS is possible using the exact shape of the swimbladder (6). Fish swimbladder volume will change according to Boyle's law (7), and Ona (8) reported the volume and area in three gadoids as a function of pressure. However, it was done in a high-pressure air atmosphere, and only for gadoids that are *physoclist*. We should extend his work to physostomus and live fish. According to the vacant prolate spheroid theory, TS is sensitive to the change of the major radius when compared to that of the minor radius (9). Hence, it is important to know the actual shape of the swimbladder under pressure, and to relate TS and pressure directly.

Ship motion, air bubbles generated near the sea surface and propeller noise cause serious errors not only for echo integration, but also for TS estimation.

We started two projects to understand the change of swimbladder shape, and to obtain more detailed TS data from fish schools. One was the project for swimbladder shape observation in a pressure tank, and the other was the 'Marino-Sensing' project.

In the 'Marino-Sensing' project, an acoustic system and supersensitive stereo camera system, which are small enough to be placed in an autonomous underwater vehicle (AUV), will be developed. Although the development of AUV itself is not included in this project, we designed sensors considering a prototype AUV for actual use.

Materials and Methods

Definition of TS

Target strength is defined as the ratio between the intensity of the incident wave, I_i, and the intensity of the backscattered wave, I_r, at a distance of 1m as (10)

$$T_s = \frac{I_r}{I_i} \quad (1)$$

A term, σ_{bs}, is often used and the relationship between TS and σ_{bs} is expressed as

$$\sigma_{bs} = \frac{I_r R_0^2}{I_i} = R_0^2 T_s \quad (2)$$

where R_0 is the reference range equalling to 1m.

After range compensation, the sonar equation for a single echo is expressed as

$$E_T^2 = K^2 D(\theta,\phi)^4 T_S \quad (3)$$

where K is a system parameter determined by sphere calibration and $D(\theta,\phi)$ is the pressure directivity function of the transducer. In the direct method we need to compensate for the directivity to obtain *in situ* fish TS from echo voltage, E_T.

Split-beam method and suspension method

Level beam and four phase beams are used in the split-beam method. A transducer is constructed from several sections. In our transducer, there are 15 sections made up of grouped elements as shown in Fig. 1 (11). Two level beams and four phase beams are constructed by the combination of each section. For example, sections 1,2,3,5,6,7,10 and 11 are combined and used for the 'Fore beam', and sections 1,3,4,5,6,8,9 and 13 for the 'Aft beam'. All sections are used to transmit and receive as a level beam.

If a target is not on the beam axis, phase difference occurs between the pair of phase beams such as the Fore and Aft beam. The electrical phase difference between the Fore and the Aft beam, shown as δ_x is expressed as

$$\delta_x = k(l_a - l_f) = kd \sin\theta\cos\phi \quad (4)$$

and that between Port and Starboard beam shown as dy is expressed as

$$\delta_y = k(l_p - l_s) = kd \sin\theta\sin\phi \quad (5)$$

where k is a wave number defined as $2\pi/\lambda$ and l is a distance from the target to each phase beam. The suffixes a, f, s, and p mean aft, fore, starboard, and port respectively. Here d is a distance between the pair phase sections, θ is the elevation angle and ϕ is the azimuth angle as is shown in Fig. 2.

From Eqs.(4) and (5), the angles, θ and ϕ are calculated as

$$\sin\theta = \frac{\sqrt{\delta_x^2 + \delta_y^2}}{kd} \quad (6)$$

$$\tan\theta = \frac{\delta_y}{\delta_x} \quad (7)$$

Since the directivity of the beam is known in advance from the manufacturer's calibration, directivity compensation is done using electrical phase difference.

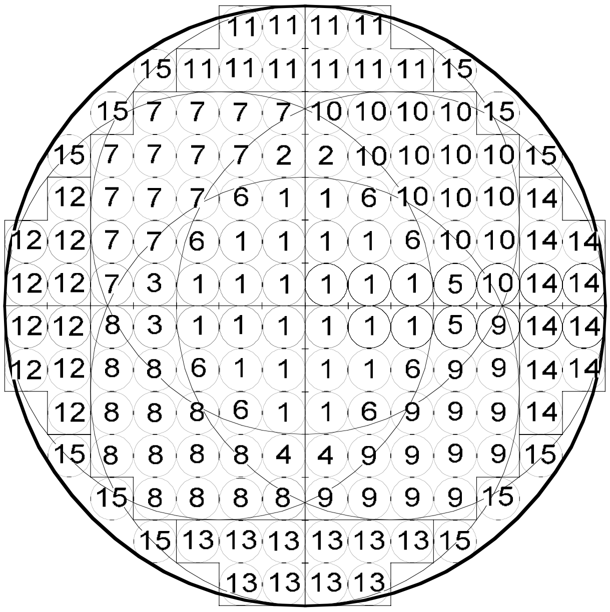

Figure 1. Alignment of elements and sections. The number of each element shows the section number. Section '1' is made up from 24 elements and used for 'Wide' beam.

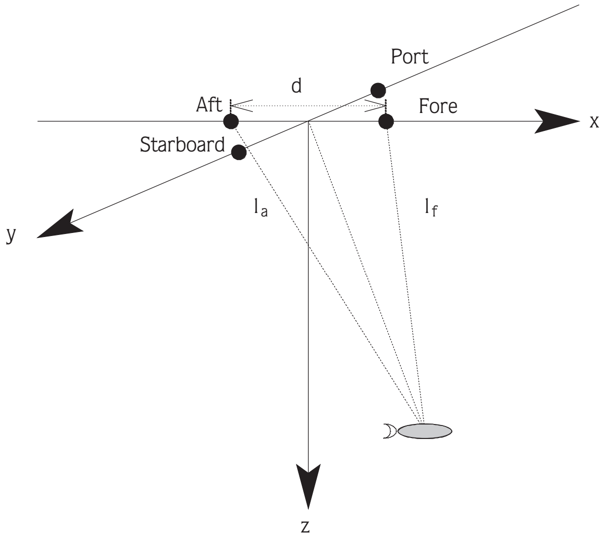

Figure 2. Coordinate system. Vessel direction is x-axis. 'Fore' means the center of the fore beam. 'lf' is the distance from fish to the fore beam. 'la' is that from fish to the aft beam. 'd' is the distance between the two phase beams.

In our system, a reference table between (δx, δy) and the directivity function is used to lessen the processing time for online directivity compensation.

Figure 3 shows the suspension system at the National Research Institute of Fisheries engineerin (NRIFE). The fish is attached between two vertical lines in the suspension method. The ends of two lines are attached to the rotating bar and the other sides are attached to small weights. A computer controlled stepping motor rotates bar by one degree increments. A transducer is mounted on the bottom of the tank. A more detailed description is shown in Sawada et al. (12). TS patterns are easily and precisely measured using this system.

Observation of the swimbladder shape under pressure

A pressure tank, which could be used in a soft X-ray system installed at the NRIFE site, was constructed and the performance was tested. The shape of the pressure tank is a circular piston 40cm in diameter and 12cm in height. A thermometer and pressure sensor are attached to the pressure tank. Figure 4 shows the schematic diagram of the pressure tank and the soft X-ray system. Nitrogen gas (N_2), provided by the cylinder (D in Fig. 4), is used to press the piston (7) in the cylinder (C). Water in the cylinder (C) is compressed, and the pressure inside of the tank (A) becomes the same as the pressure inside the cylinder (C). The valve (10) is the main valve the Nitrogen cylinder (D), while valves (8, 9) are used to adjust the pressure. The safety valve (6) is attached to the cylinder (C). The valve (5) is used to release N2 gas pressure. A fish is put inside of the pressure tank (A). X-ray permeable acrylic glasses (2) are used on both sides the pressure tank (A). A soft X-ray is emitted from the X-ray tube (1), and detected by the lower X-ray camera (4). Water is provided through the valve (11) and released from the valve (12). Both valves are closed during measurement.

The performance test was conducted as follows.

1. Fill the pressure tank with water.
2. Drain water (about 200ml) from the cylinder and set the piston free in the cylinder.
3. Set the pressure inside the pressure tank to about 9kg/m^2.
4. Close the pressure circuit and observe the pressure change every minute for 30 minutes.
5. Repeat procedures 3 and 4 at the pressure of 8, 7, 6, 5, 4, 3, 2, 1kg/m^2, respectively.

Table Comparison between suspension method and direct method. The symbols 'G', 'M','NG', and '!' denote good, medium, no good, and caution respectively.

	Suspension method	In situ direct method
S/N	G High	M Depends on condition
Biological information (Species,Length,Weight)	G Already known	M Needs sampling
Fish condition (biological properties like swimbladder)	NG Not natural	G Natural
Average TS	M Tilt angle and fish length distributions are needed.	G! Several biases
Tilt angle	G Already known	M Needs special analysis as ETA*1.

*1ETA is echo trace analysis.

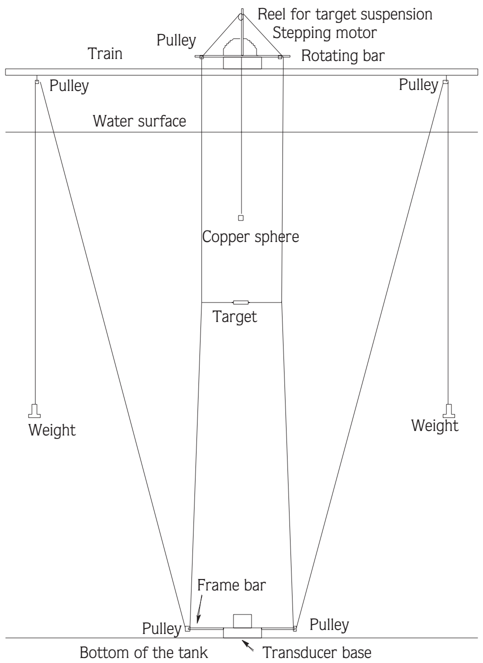

Figure 3. A suspension and rotating mechanism of a target.

Marino-Sensing project

'Marino-Sensing' is a four-year project that began in 1996. One of the objectives is to obtain detailed information, such as species, length, behavior, and the distances between fish in a fish school, using a quantitative echo sounder as the 'ears' and a stereo camera as 'eyes' with an approaching fish school. First, research vessel conducts a rough survey and the AUV will be launched where a significant fish school is observed. The AUV follows a trajectory programmed in advance, and records acoustic and optical data. The AUV is retrieved at a certain position that is also programmed before launch. We assume an AUV that can operate up to 200m in depth, 3 kt in maximum speed and 3 hours in durable time. The transducer and the stereo camera are installed on the AUV in both an upper and the lower looking state. It is useful to conduct a survey for a close by surface fish school with the upper looking installation. This work can not be done by a general research vessel because of fish avoidance from the ship and the limitations of the hull-mounted transducer. It is impossible to search for fish shallower than the depth of the hull-mounted transducer.

We developed a small size quantitative echo sounder, a transducer with an operating frequency of 70kHz, a highly sensitive stereo camera system, and a test bed for these instruments. The test bed is designed to be a part of the AUV in the future and its size is about 533mm in diameter and 500mm in length for the acoustic instrument, and 370mm in length for the optical instrument. The optical unit and the acoustic unit form the top end of the AUV. A special transducer was designed for this project. Requirements for this transducer are as follows:

1. Transducer must be as small as possible and also utilize both split-beam and dual-beam.
2. Signal to noise ratio must be greater than 10 dB for a single fish whose TS is –40dB at 200m from the transducer.

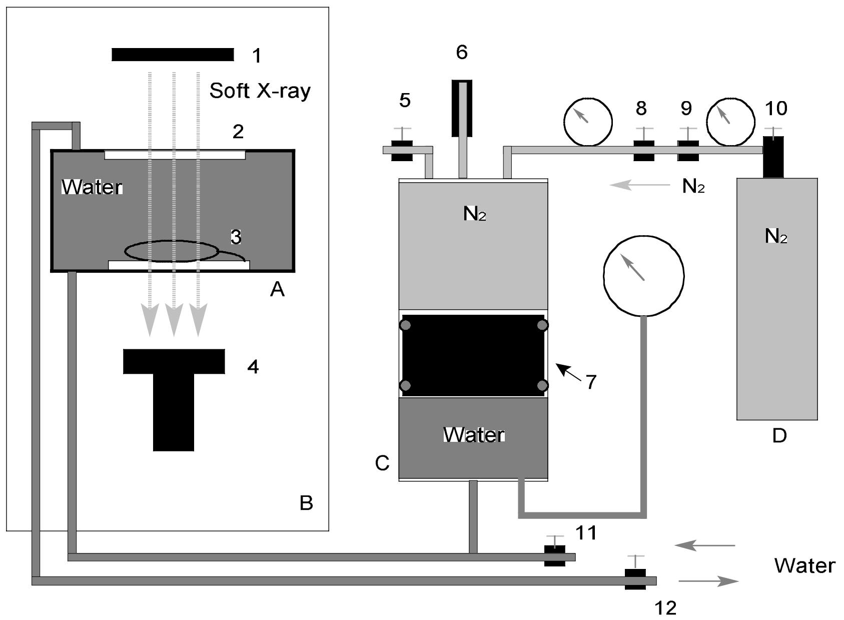

Figure 4. Soft X-ray system and the pressure tank. Diameter is 40cm and the height is 12cm. A thermometer and pressure sensor, seen on the left side, are attached to the pressure tank. An outlet tube is seen behind these sensors. The details are explained in the text.

3. Select adequate frequency and beam width to lessen any errors.

The split-beam method is useful in combination with echo trace analysis, because we can estimate single fish behavior and TS patterns. This information helps us to identify fish species. The dual-beam echo integration technique is valid for judging the precision of obtained data (13,14). Hence, we adopted the transducer with functions of both split-beam and dual-beam.

Results and Discussion

Comparison between the split-beam method and suspension method.

An example of the measured TS pattern is shown in Fig. 5. In this case, we verified both the system accuracy and the vacant prolate spheroid scattering theory itself using an artificial target (9). The cross correlation between theory and measurement is 0.9996. *in situ* method, fish condition is natural and the measured TS reflects the tilt angle distribution and the size distribution. However, it is difficult to relate a received echo to the individual fish. Although we need biological samples to identify fish species and length distribution, they may contain some sampling errors. Moreover, the current algorithm of single echo isolation is imperfect and causes several biases when the fish school is dense or deep. On the other hand, fish condition is not natural in the suspension method, and tilt angle information is needed to estimate average TS.

There are several merits and demerits of both the *in situ* direct method and the suspension method. The comparison of these two methods is shown in Table. In the case of the average TS measurement, the *in situ* method is superior to the suspension method with regards fish condition. However, the suspension method is necessary to confirm the scattering theory by comparing a theory with measurements. Both methods should compensate for each other.

Performance check of pressure

Results of the performance test show that the pressure variation was less than 1% of the set pressure over 30 min up to 9 atm by one atm increments. We will try the continuous soft X-ray measurement for live fish. A theoretical model such as the deformed cylinder model (15) or prolate spheroidal model, will be adequate to calculate TS from soft X-ray images.

Marino-Sensing project

According to the design index of transducers for general acoustic surveying shown by Furusawa (10), the upper limit of the frequency for fish is 70 kHz, and beam width is from 5 to 20 degrees. We chose 70 kHz to keep the signal to noise condition high and to make the transducer small. Beam width is about 6 degrees. We show the design point of our transducer on the general design map shown in Fig. 6 as a white circle.

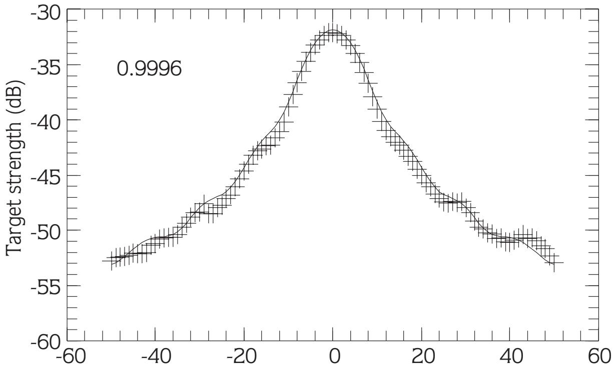

Figure 5. Target strength pattern of an artificial target. The shape is a prolate spheroid made of expanded polystyrene. Solid line shows theoretical calculations using prolate spheroidal model. Crosses show the average of the five sets of data at each tilt angle. The diameter of this target is 10cm as a measure axis, and 1.5cm as a minor axis.

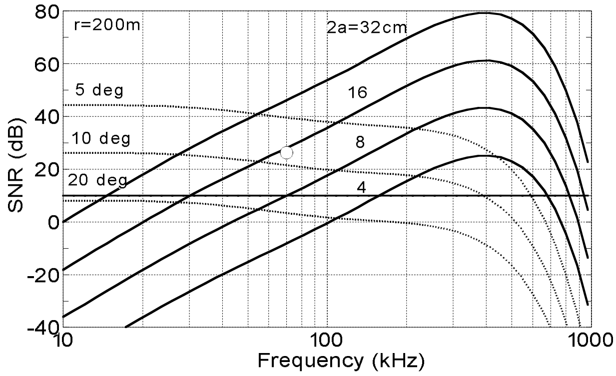

Figure 6. Universal diagram for the basic design of quantitative echo sounders. Horizontal axis shows frequency, and vertical axis shows signal to noise ratio. Two parameters, a diameter and a beam width of the transducer, are used to design the transducer. The diameter of the transducer (2a) and beam widths are on the figure.

The signal to noise ratio is about 27dB. It measure –57 dB in TS at 200m. This TS correspond to about 3cm in the case of bladdered fish.

Raw digital data sampled every 7.5cm is recorded by this system. Detailed analyses, such as echo integration and TS analysis, are possible on computer through software compiling the raw data after the AUV is retrieved on deck.

We will verify these instruments in both a fresh water tank and at sea.

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