Precise target strength pattern measurement in an indoor tank

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(Received 20 December 1996)

A precise target strength measurement system in an indoor tank is constructed. A target is rotated in pitch plane by a computer controlled stepping motor and measurements are done automatically from the start to the end. Echo data in the range between -50 and 50 degrees are stored at intervals of 1 degree on the hard disk built in an oscilloscope. Spreading loss and absorption loss are compensated for in a software to calculate precise target strength. Because all echo sounders with both output terminals of transmitting trigger signal and of echo signal are available as a transmitter and receiver of this system, precise target strength measurements are possible at any frequency for many kinds of physical models and fish. Target strength patterns of several prolate spheroidal models precisely made of expanded polystyrene are measured, and the results are compared with the exact theory of a soft prolate spheroid scattering model to ascertain accuracy and precision of the measurements. The experimental results agreed very well with the theoretical results and the correlation coefficients are almost unity.

Keywords: Target strength pattern, Prolate spheroid, Expanded polystyrene
PACS number: 43.30.Gv, 43.35.Yb

1. Introduction

It is very important to know the target strength (TS) pattern of fish both for acoustic surveys of fisheries resources and for design of quantitative echo sounders. The TS pattern is defined as a TS function of the tilt angle. There are two methods to measure TS pattern of fish: one is the echo trace analysis method\textsuperscript{1,2} used for fish in situ and the other is the controlled method\textsuperscript{3,4} used for dead, stunned or anaesthetized fish. The former analyses the echo trace which is consisted of the successive echo pulses returned from single target. By analyzing these echo traces, the TS pattern and the swimming velocity of the target can be derived.

Although a swimbladder condition, which is very important\textsuperscript{5-7} in sound scattering by bladder fish, seems to be natural in the TS measurement in situ, it is sometimes difficult to identify fish species and evaluate length of fish exactly. Moreover, signal to noise ratio becomes small when fish swims at the outer part of the main lobe of the beam because of the sharpness of the beam aiming to detect a single fish with high resolution and of the relatively longer distance compared with the controlled method. Therefore, it is difficult to get TS for the wide range of tilt angles in the TS measurement in situ.

On the contrary, fish species, length and weight are already known in the case of the controlled method. Moreover signal to noise ratio is high, because the distance is short and the central part of the main lobe of the beam can be used. However, fish condition may be different from the natural one. These two methods do not conflict but should compensate for each other.

TS pattern measurements of fish were conducted in a bay\textsuperscript{8} by our group using a raft on which a fish rotating unit was set. Sometimes it took unexpectedly long time to complete measurements because of bad weather and interference by natural fish. In
In order to conduct more exact and time effective measurements, we made an indoor tank whose size is 10 m in depth, 15 m in length, and 10 m in width. An automatic and precise TS measurement system is constructed with a target rotating mechanism for this indoor tank. In order to examine the exactness of the system, we prepared nine different prolate spheroidal physical models carved as precisely as possible with expanded polystyrene (EPS). We measured the TS patterns of the six models using this system and compared the measured results with the theoretical ones which are calculated theoretically.

2. MATERIAL AND METHOD

2.1 Measurement System

The block diagram of the system is shown in Fig. 1. The system consists of three separate but interconnected parts; a fish rotating unit, an echo sounder unit, and a data recording unit. The fish rotating unit and the data recording unit are connected with a general purpose interface bus (GP-IB). The rotation angle is controlled by a PC (HP9000 Model382, Hewlett Packard) using a stepping motor. Since the existence of two controllers is not permitted at the same time in the same GP-IB line, a router, which can communicate between the PC for data recording and the PC for controlling fish tilt angle, is used.

The target suspension and the rotation system are shown in Fig. 2. Small hooks are put in both ends of a target and a thin horizontal line locates the target between two vertical suspension lines. The top of these lines are connected to the two sides of a rotating bar that is mounted on the axis of a stepping motor. The vertical lines are tensioned by a simple weight and pulley system. A copper sphere is suspended as a standard sphere when we calibrate the acoustic system before or after the TS pattern measurement.

Transmitting and receiving are done using echo sounder (KJ1000, KAIJO) with a split beam transducer set on the bottom of the tank. Specifications of this echo sounder are shown in Table 1. Data acquisition are done as follows and the process is shown in a flow chart in Fig. 3. One sequence of target rotation and echo level recording is done for gain setting; after reading the maximum amplitude of echo data stored on the memory of the digital oscilloscope (LeCroy 9304AM) with a gain low enough not to saturate the echo level, an optimal gain is set automatically to utilize effectively the eight bit resolution of the digital oscilloscope. Also in order to achieve a high resolution, bit resolution enhancement function of the oscilloscope is used. Due to this function the vertical resolution becomes almost the same as that of nine bits, by trading off the analogue bandwidth. We confirmed that the echo shape did not change before and after using this function. Echo data for five pings at each tilt angle are recorded on the hard disk in the oscilloscope and the echo wave forms at every fifth ping at each tilt angle are printed out to check the signal. One pair of the split beam signals are also recorded to confirm the sphere position in the beam in two dimensional plane. All measurements are automatically done from the start to the end. Target strength values are calculated by detecting the peak value in the envelope of echo pulse and by reading the echo receiving time at the front end.

Calibration was conducted before or after the measurement using a copper sphere (60.0 mm, TS = -33.6 dB) as shown in Fig. 2. Water temperature was measured at every measurement to calculate sound speed using empirical equation. The sound speed is used to obtain the accurate range.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Specifications of the echo sounder.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>38 kHz</td>
</tr>
<tr>
<td>Transducer beam width</td>
<td>6.2°</td>
</tr>
<tr>
<td>Source level</td>
<td>223 dB re 1 μPa at 1m</td>
</tr>
<tr>
<td>Pulse repetition period</td>
<td>213 ms</td>
</tr>
<tr>
<td>Pulse width</td>
<td>0.6 ms</td>
</tr>
<tr>
<td>Receiver bandwidth</td>
<td>2.5 kHz</td>
</tr>
</tbody>
</table>
from the sphere to the transducer and the wave length in the water for the theoretical calculation of the soft prolate spheroid scattering model.

After a prolate spheroidal model is attached to the rotating system (see Fig. 2), it is rotated at intervals of 1 degree from -50 to 50 degrees and echo data are recorded at each angle. In our definition minus means head down aspect for the case of fish but arbitrary for the prolate spheroidal model.

2.2 Data Processing
At first, binary data file recorded on the hard disk are converted to ASCII data file and the echo envelope is calculated using this filed data. Running average is adopted to obtain smooth envelope signal. This process is explained by the following equations. Echo signal, $w(t)$, is expressed as

$$w(t) = A(t)\sin(\omega t + \phi) \quad (1)$$
where \( A(t) \) is the envelope, \( t \) is time measured from the front of the echo, \( \omega \) is the angular frequency, and \( \phi \) is the initial phase. The echo signal at the time \( t + \Delta t \) is
\[
w(t + \Delta t) = A(t + \Delta t) \sin(\omega t + \omega \Delta t + \phi). \tag{2}\]
Setting \( \omega \Delta t = \pi/2 \), we have
\[
\sin(\omega t + \omega \Delta t + \phi) = \cos(\omega t + \phi). \tag{3}\]
Then, if the envelope signal does not change significantly during \( \Delta t \), the envelope \( A(t) \) is obtained as

\[
A(t) = \left[ w(t)^2 + w(t + \Delta t)^2 \right]^{1/2}. \tag{4}\]

The arrival time or range of the echo is derived by the cross correlation between a standard echo wave and the target echo wave. The echo signal obtained at zero degree of the rotation is used as the standard wave, as it is considered to be the typical wave.

The target strength is calculated from the range, \( r \), which is the distance between the transducer and the target, and the maximum value of echo envelope, \( E_r \), as
\[
TS = 20 \log E_r - KF + 40 \log r + 2ar \tag{5}\]
where \( TS \) is the target strength, \( a \) is the absorption coefficient, and \( KF \) is a transmitting and receiving factor obtained by the calibration. As the absorption loss is very small for near range, \( 2ar \) term is neglected in this calculation.

As some bubbles were generated near the transducer, sometimes the echoes returned from the model and those from bubbles interfered during measurements. These data are deleted in the analysis.

2.3 Prolate Spheroidal Target

Prolate spheroidal physical models are fabricated with a lathe from expanded polystyrene (EPS) by carving it. We can select the EPS material from five types\(^{11}\) classified by their density, and we used D-12 and D-16, whose density is 12 ± 1.0 kg/m\(^3\) and 16 ± 1.0 kg/m\(^3\), respectively.

We made the models in the following way: 1) a large block of expanded polystyrene is cut to a small rectangular solid; 2) this solid is held at two end points of long axis on the chuck of the lathe; and 3) it is rotated and carved by a high speed cutter which

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### Table 2 Specifications of prolate spheroid physical model.

<table>
<thead>
<tr>
<th>Type</th>
<th>Diameter</th>
<th>Density</th>
<th>Water Temp. (°C)</th>
<th>Measurement Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2(a) (cm)</td>
<td>2(b) (cm)</td>
<td>(b/a)</td>
<td>(g/cm(^3))</td>
</tr>
<tr>
<td>A1</td>
<td>10</td>
<td>1.0</td>
<td>0.10</td>
<td>0.0133</td>
</tr>
<tr>
<td>A2</td>
<td>10</td>
<td>1.5</td>
<td>0.15</td>
<td>0.0133</td>
</tr>
<tr>
<td>A3</td>
<td>10</td>
<td>2.0</td>
<td>0.20</td>
<td>0.0133</td>
</tr>
<tr>
<td>B1</td>
<td>5</td>
<td>0.5</td>
<td>0.10</td>
<td>0.0166</td>
</tr>
<tr>
<td>B2</td>
<td>5</td>
<td>0.75</td>
<td>0.15</td>
<td>0.0166</td>
</tr>
<tr>
<td>B3</td>
<td>5</td>
<td>1.0</td>
<td>0.20</td>
<td>0.0166</td>
</tr>
<tr>
<td>C1</td>
<td>16</td>
<td>1.6</td>
<td>0.10</td>
<td>0.0133</td>
</tr>
<tr>
<td>C2</td>
<td>16</td>
<td>2.4</td>
<td>0.15</td>
<td>0.0133</td>
</tr>
<tr>
<td>C3</td>
<td>16</td>
<td>3.2</td>
<td>0.20</td>
<td>0.0133</td>
</tr>
</tbody>
</table>
moves on the trajectory of spheroid.

Their sizes and measurement conditions are shown in Table 2. We made three lengths of spheroids whose major axes, $2a$, are 10 cm (A1-A3), 5 cm (B1-B3), and 16 cm (C1-C3), respectively, and whose minor axis, $2b$, are varied so as to make the ratio $b/a$ be 0.1, 0.15, and 0.2. Type A2 was measured two times to certify the repeatability of this measuring system.

3. RESULTS AND DISCUSSION

The process of envelope derivation is shown in Fig. 4(a), (b), and (c). The dot line in Fig. 4(a) denotes the original echo data with a carrier wave, the thin line in Fig. 4(b) denotes the envelope signal before smoothing, and the thick line in Fig. 4(c) denotes the smoothed signal by the running average method. The smoothed signal agrees well to the envelope of the original wave.

![Fig. 4](image-url)  
**Fig. 4** Process of envelope derivation: (a) dot line shows original wave with carrier; (b) thin line is the envelope of the original wave; and (c) thick line shows the running average.

Measured TS patterns are shown in Fig. 5. The solid lines are theoretical curves calculated by the exact scattering function of the vacant prolate spheroid.$^7$ The parameters needed in this theoretical model are major axis, $a$, minor axis, $b$, and the wave length of the incident wave in the water.

Crosses show five original echo data at each angle and open circles show their average. Correlation coefficients are calculated to evaluate the goodness of fit between the theoretical and the averaged values and the results are also shown in Fig. 5. They are very close to one in each case. The differences between the theoretical and experimental TS patterns are found to be very small; the difference in maximum TS is only 0.04 dB in the case of A2 and even the largest difference is only 0.39 dB in B1. Generally we can see the very good agreement for a wide range of the tilt angle. There are only a slight difference even at the larger angles for two TS patterns for A2 which were measured in different days.

We see some offset between the theoretical and experimental TS patterns for B1. If we shift the experimental data so as to occur the peak TS at zero degree, the correlation coefficient becomes 0.9992. It shows that there might be some initial offset in angle when we attached the model to the vertical lines.

One of the plausible causes of slight discrepancies in the TS pattern is the difference between the actual and the ideal shape of the prolate spheroid target. Since the tip of the spheroid model is very difficult to carve because the two end points of long axis must be held, the difference may become large at the larger angles.

Variance of measured values is rather high for A3 and B3. We could not find the exact reason, but it may be explained by the bubbles in the tank. We sometimes observed bubbles produced near the transducer. The frequency of bubble generation might have increased from a certain time during experiments. The TS pattern measurement of A3 and B3 were conducted in July 11 and July 12, respectively(see Table 2). The other measurements were conducted before July 10. It shows us the possibility that more bubbles were generated between July 10 and July 11 than before.

There is a linear relationship$^{11,12}$ between Poisson's ratio and the density and also between Young's modulus and the density of EPS within the elastic
Fig. 5 Measured TS patterns and theoretical patterns. Refer to Table 2 about the scattering model specification. (a) Type A2, 31 May, 1996. (b) Type A2, 2 June, 1996. (c) Type A3, 11 July, 1996. (d) Type B1, 19 June, 1996. (e) Type B3, 12 July, 1996. (f) Type C3, 10 July, 1996. (+ five data obtained at each angle, ◦ average of the five data at each angle excepting bubble interfered echoes, —theoretical values).

Table 3 Typical acoustic properties of EPS.

<table>
<thead>
<tr>
<th>Density (kg/m³)</th>
<th>Poisson's ratio</th>
<th>Young modulus $\times 10^3$ (N/m²)</th>
<th>Sound speed (compressional wave) (m/s)</th>
<th>Sound speed (shear wave) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.07</td>
<td>2.23</td>
<td>438.5</td>
<td>298.2</td>
</tr>
<tr>
<td>16</td>
<td>0.09</td>
<td>4.07</td>
<td>509.9</td>
<td>342.3</td>
</tr>
</tbody>
</table>

Limit. These values, Young’s modulus and Poisson’s ratio, are referred from Fig. 2.4.1 and 2.8.1 of Ref. 11), respectively. Sound speed is calculated from the density, the Poisson’s ratio, and the Young’s modulus of EPS. The sound speed of compressional wave is 438.5 m/s for type A and C and 509.9 m/s for type B as listed in Table 3. Since these sound speeds are close to that of the air, approximately 350 m/s, and their densities are much smaller than water, acoustic characteristics of the present EPS models may be thought to be close to the vacant prolate spheroid whose scattering pattern can be calculated exactly.

The demonstrated general good agreement between theory and measurements shows that 1) the exactness and precision of the present measuring
method and system and 2) correctness of the theoretical scattering model of prolate spheroid and its calculation. In this study we find a very good agreement between the measurements and the theory. Generally, this kind of agreement does not assure both measurement and theory, and either which is validated assures the other. But we think that the present study is not the case, and that the exactness of both the measurement and the theory are confirmed. The reasons are: 1) the measurement and the theory are completely independent, 2) we applied very precise measurement method, and 3) the theoretical model is not an approximate but exact.

Since the theory of the soft prolate spheroid scattering model is an exact model and the prolate spheroid is similar in shape to fish swimbladder, it is useful to predict general TS patterns of fish. It, however, becomes difficult to calculate the TS for higher frequencies and larger targets. In the present case, we could not calculate theoretical patterns for type C (Fig. 5(f)). Moreover, the theory can predict TS pattern analytically only for simple shape target. On the other hand, deformed cylinder model can treat relatively complicated shape target as some kinds of fish swimbladder. It, however, only can predict TS pattern for restricted range of the tilt angle. Measurement of TS of a finite cylinder EPS model will be used for the certification of the deformed cylinder model or other approximate theories. Also, it may be possible to exactly reproduce the TS pattern of fish by measuring the TS of EPS model with swimbladder shape.

4. CONCLUSION

A precise TS pattern measurement system was constructed. In this system, we can measure TS at the tilt angle of −50 to 50 degrees at intervals of 1 degree automatically. We made nine different spheroidal models by expanded polystyrene and measured their TS patterns. The results of the measurement and theory of the soft spheroid scattering model agreed very well in the wide range of tilt angle. The measurement system can be used for precise experimental studies of TS pattern. The soft prolate spheroid scattering model is certified by the experiments using the physical models.

ACKNOWLEDGMENTS

The authors thank Mr. Tsuchida, the president of TSUCHIDA SEISAKUSHO, for making the spheroid models, Dr. Masahiko Furusawa of Tokyo University of Fisheries for his detailed comments, and Mr. Yoshimi Takao of National Research Institute of Fisheries Engineering for his help in the experiments. Anonymous referees provided valuable comments on the manuscript.

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