Paper

#### 183

### Proposal to Use Fish-Length-to-Wavelength Ratio Characteristics of Backscatter from Fish for Species Identification

Masahiko FURUSAWA (Tokyo University of Marine Science and Technology)<sup>†</sup> Kazuo AMAKASU (Tokyo University of Marine Science and Technology) (Received February 23, 2018)

### Abstract:

The multi-frequency acoustic method to identify fish species using the frequency dependence of backscatter from fish (relative frequency response) has been investigated. The method has been successfully applied to broad identification, such as distinguishing between swimbladder and nonswimbladder fishes, but it is not always possible to identify acoustically similar fish species as swimbladder fishes. To improve identification power, we, therefore, propose a method that uses the difference of fish-length-to-wavelength ratio ( $L/\lambda$ ) characteristics of backscatter among fish species (relative  $L/\lambda$  characteristic), instead of or together with the relative frequency response. We, first, theoretically confirm the rationale for using the relative  $L/\lambda$  characteristic with prolate-spheroid scattering models of fish. Second, we compute target strengths for several types of fish models, and show the advantage of using the relative  $L/\lambda$  characteristic. Third, using experimental examples in which species identification was difficult, we apply the proposed method and ascertain its effectiveness. Finally, we discuss the necessary and challenging procedure to know fish lengths and other issues.

Classification: Fisheries acoustics · Bioacoustics

Keywords: backscatter from fish, fish-length-to-wavelength characteristic, species identification

### 1. Introduction

The multi-frequency species identification method using the frequency characteristics of fish backscatter has been investigated.<sup>1–3)</sup> This method is effective for classifying broad acoustic categories such as swimbladder and nonswimbladder fishes, and as well as acoustically peculiar fish species such as Atlantic mackerel.<sup>4)</sup> It is often difficult,

† frsw@fine.ocn.ne.jp

however, to identify similar species such as swimbladder fishes.<sup>5,6)</sup> Therefore, further improvement of the multi-frequency method is needed.

Several such efforts have been made. Korneliussen *et al.*<sup>3)</sup> investigated methods to match physical and spatial characteristics as similar as possible among frequencies. Berger *et al.*<sup>7)</sup> examined a method to specify the common portion

of school echoes obtained by a multi-frequency echosounder by using the data from a multibeam echosounder which has high resolution and the capability of transducer motion compensation. Furusawa<sup>8)</sup> discussed how to reduce errors caused by a small signal-to-noise ratio and by inappropriate absorption loss compensation especially at high frequencies.

The essence of the multi-frequency method is to observe the differences among fish species of relative frequency responses that express the frequency characteristic of average volume backscattering strengths (SV) against that at the standard frequency (ordinarily 38 kHz).<sup>1)</sup> [Note that in this paper we use different terminology for acoustic scattering than that recommended by the International Council for the Exploration of the Sea (ICES).<sup>9)</sup> The correspondence between the two schemes is described in Appendix; values are the same, but symbols and units are different]. This frequency response is also the response of average target strengths (TS), so that it may be obtained from measured average TS.<sup>6)</sup>

The basic idea of the relative frequency response is that the frequency characteristics of these backscattering indices are different among fish species. Certainly, between swimbladder and nonswimbladder fishes, their scattering mechanisms are different, and indices vary in strength and frequency characteristics. Among swimbladder fishes, however, the characteristics do not generally differ much. That is because the shape and size, relative to body, of the main scattering component (i.e., the swimbladder) are similar due to similar body shapes and the need for neutral buoyancy. Also, the frequency range utilized by fishery echosounders is ordinarily at the geometrical scattering region for most fishes, where, in principle, the frequency characteristic of backscatter is flat. Therefore, it would be preferable to find a characteristic with more salient differences among species. Here we proposes using the relative fish-length-to-wavelength ratio characteristic of average SV ('relative  $L/\lambda$  characteristic') in place of or with the relative frequency response.

First, we theoretically examine the effectiveness of the relative  $L/\lambda$  characteristic using prolatespheroid modal-series (PSMS) scattering models of fish,<sup>10</sup> which are suitable for discussing the general characteristics of scattering from fish. Second, we compute backscattering characteristics using the same PSMS models for several types of fish models, demonstrate the apparent difference in relative  $L/\lambda$  characteristics among types, and show that the relative frequency response varies with fish length, even for the same type. Third, the proposed method is applied to the actual backscatter data of Atlantic herring (Clupea harengus) and Norway pout (Trisopterus esmarkii) measured by Fässler et al.,<sup>5)</sup> as well as of northeast Arctic cod (Gadus morhua), saithe (Pollachius virens), and Norway pout measured by Pedersen and Korneliussen,6 who noted that identification of fish species was difficult with only the relative frequency response. The results demonstrate that the proposed method can discriminate these species. Finally, we discuss the new method, especially how to know fish lengths that is a prerequisite for the method.

#### 2. Materials and methods

### 2.1 Theoretical considerations

We used PSMS models to consider the effectiveness of the relative  $L/\lambda$  characteristic for fish species identification theoretically. Furusawa<sup>10</sup> discussed the general trend of fish target strengths using the PSMS models. Although the shape of these models is simple prolate spheroids (**Fig. 1**(a)) that cannot correspond to complex shapes, and body material cannot be varied in spheroidal bod-



Fig. 1 Modeling of fish body and swimbladder by prolate spheroids. a) Sketch of fish and modeling spheroids with definitions of fish tilt angle  $\theta_t$  and swimbladder orientation angle  $\theta_s$ . b) Modeled shapes of swimbladder and body. c) Swimbladder shapes expanded from b); labels indicate the types listed in Table 1.

ies, the PSMS models are convenient for discussing general TS characteristics.

The TS of swimbladder fish is modeled by the TS of a vacant prolate spheroid that represents the swimbladder, while the TS of nonswimbladder fish by the TS of a fluid prolate spheroid to represents the fish body. According to the model, the TS of a swimbaldder fish is expressed as

$$T_{s} = L^{2} \nu(L/\lambda, \theta_{t}; \eta, A_{s}, \theta_{s})$$
(1)

where  $T_s$  is the linear value of TS (see Appendix), L is the fish length, v is the TS normalized by  $L^2$  ('normalized TS') and is the function of the variables in the parentheses,  $L/\lambda$  is the fish-lengthto-wavelength ratio,  $\theta_t$  is the tilt or pitch angle of fish (Fig. 1 (a)),  $\eta = L_s/L$  is the swimbladder-to-fishlength ratio,  $A_s = b_s/a_s$  is the minor- to major-radius ratio when the swimbladder is assumed to be a prolate spheroid, and  $\theta_s$  is the swimbladder orientation angle relative to the fish body axis (Fig. 1(a)). The backscattering direction is  $\pi/2 - \theta_t - \theta_s$  for the swimbladder. See Ref.10 for more detail. Similarly, the backscattering cross section of a nonswimbladder fish is expressed as

$$T_{S} = L^{2} v(L/\lambda, \theta_{t}; A_{b}, g, h)$$
<sup>(2)</sup>

where  $A_b = b_b/a_b$  is the minor- to major-radius ratio when the fish body is approximated by a prolate spheroid, g is the density contrast (ratio of body density to surrounding water density), and h is the sound speed contrast (similarly the sound speed ratio). The backscattering direction is  $\pi/2 - \theta_t$  for the body (Fig. 1(a)). We assume that the variables of v in Eqs. (1) and (2) to the right of the semicolons are intrinsic to a fish species and the two

variables left to the semicolons are independent of the species. Then, including whichever expression we choose, we can combine the two expressions to introduce a 'species parameter vector',  $\vec{s}$ , as

$$T_{S} = L^{2} \nu(L/\lambda, \theta_{t}, \vec{s})$$
(3)

The relative frequency response<sup>1)</sup> is given by

$$r(f) = \frac{\langle S_V(f) \rangle}{\langle S_V(f_0) \rangle} \tag{4}$$

where  $S_V(f)$  is the raw or pixel SV (linear value; see Appendix) at a frequency f,  $f_0$  is the standard frequency (38 kHz), and  $\langle \cdot \rangle$  stands for averaging. In the original definition,<sup>1)</sup> the averaging process is not stipulated; but since the raw SV are smoothed and further averaged in an integration region or integration cell, we stipulate the averaging. Manipulating this expression using Eq. (3), we have

$$r(f) = \frac{n\langle T_{S}(f)\rangle}{n\langle T_{S}(f_{0})\rangle} = \frac{\langle T_{S}(f)\rangle}{\langle T_{S}(f_{0})\rangle}$$
$$= \frac{\langle L^{2} v (L/\lambda, \theta_{t}, \vec{s})\rangle}{\langle L^{2} v (L/\lambda_{0}, \theta_{t}, \vec{s})\rangle} \cong \frac{\langle v (L/\lambda, \theta_{t}, \vec{s})\rangle}{\langle v (L/\lambda_{0}, \theta_{t}, \vec{s})\rangle}$$
$$\equiv \frac{v_{av}(L/\lambda, \vec{s})}{v_{av}(L/\lambda_{0}, \vec{s})} = \frac{v_{av}(fL, \vec{s})}{v_{av}(f_{0}L, \vec{s})}$$
(5)

where *n* is the average distribution density of fish and  $v_{av}$  is the tilt-averaged normalized TS. In the above formulation, we assumed that *L* does not vary largely; then,  $L/\lambda$  is determined mostly by  $\lambda$ , and  $L^2$  and *v* are uncorrelated, so that in making the ratio,  $L^2$  are eliminated. The last equality tells us that r(f) is the function of f and L, and therefore, that r(f) changes not only by f but also by L to give variability in r(f).

The relative  $L/\lambda$  characteristic of average SV proposed in this paper is similarly expressed as

$$r(L/\lambda) = \frac{\langle S_V(L/\lambda) \rangle}{\langle S_V[(L/\lambda)_0] \rangle} \cong \frac{v_{\rm av}(L/\lambda, \vec{s})}{v_{\rm av}[(L/\lambda)_0, \vec{s}]}$$
(6)

where  $(L/\lambda)_0$  is the reference of  $L/\lambda$ . As can be seen, if we indicate the ratio of average SV as the function of  $L/\lambda$ , the characteristic becomes dependent only on fish species under the present theory and assumption.

### 2.2 Evaluation using several fish models

Next, assuming several fish models, we computed their relative  $L/\lambda$  characteristics using the PSMS models discussed above, and investigated whether the fish models could be identified. For the computation, the spheroidal wave functions<sup>10,11</sup> were necessary. We combined the algorithms by Zhang and Jin<sup>12</sup> and Van Buren and Boisvert<sup>13,14</sup> to develop MATLAB (Math Works, Inc.) programs, which made it possible to compute for *ka* values (product of wave-number *k* and prolate-spheroid major radius *a*) as high as *ca*. 100.

We considered the six types of models listed in **Table 1** and shown in Fig. 1(b) and its expanded version Fig. 1(c). These models were not intended to represent specific fish species, but their parameters were determined refering to the parameter ranges in Table 1 of Ref. 10. 'T-type' is a fish model that has the typical swimbladder shape, 'L-type' has a longer swimbladder than the T-type, 'R-type' has a rounder swimbladder, the swimbladder of the 'S-type' is a shrunken one of the typical swimbladder, that of the 'H-type' is horizontal (i.e., the swimbladder orientation angle  $\theta_s$  is zero), and the 'F-type' is a model without a swimbladder and with a fluid body. In Table 1 of this paper, A=b/a is the

Туре	Description	$A = b/a^{a}$	$\eta = L_s/L^{\mathrm{b}}$	$\theta_{s}[\circ]^{c}$
Т	Typical swimbladder	0.15	0.342	6
L	Longer swimbladder	0.1	0.448	6
R	Rounder swimbladder	0.2	0.282	6
S	Shrunk swimbladder	0.1	0.342	6
Н	Horizontal swimbladder	0.15	0.342	0
F	Fluid body (nonswimbladder)	0.15	$g = 1.04^{\text{ d}}$	$h = 1.02^{e}$

Table 1 Types of fish models and their parameters. The model shapes and angles are shown in Fig. 1.

Note: <sup>a</sup> Minor- to major-radius ratio of prolate spheroid; <sup>b</sup> swimbladder-length to body-length ratio; <sup>c</sup> swimbladder orientation angle; <sup>d</sup> density contrast between body and seawater; <sup>e</sup> sound speed contrast between body and seawater.

minor- to major- radius ratio of the prolate spheroids, determined around the standard value of 0.15 of the T-type model. For the L- and R-types, the swimbladder-to-fish-length ratios  $\eta$  are determined by the following equation such that the swimbladder volume is 4% of the body volume to maintain a fish at neutral buoyancy<sup>10</sup>:

$$\frac{4\pi b_s^2 a_s}{3} = 0.04 \times \frac{4\pi b_b^2 a_b}{3} \tag{7}$$

where  $a_s$  and  $b_s$  are the major- and minor-radii of the swimbladder model, and  $a_b$  and  $b_b$  are those of the body model. Therefore, we have

$$\eta = \frac{L_s}{L} = \frac{a_s}{a_b} = 0.04^{1/3} \left(\frac{A_b}{A_s}\right)^{2/3}$$
$$A_b = b_b / a_b, \quad A_s = b_s / a_s$$
(8)

where  $L_s$  is the swimbladder length. All  $A_b$  are 0.15, and by changing  $A_s$ , as shown in Table 1, the  $\eta$  of L- and R-Types are obtained. The  $\eta$  of S- and H-types are the same as that of the T-type. The swimbladder orientation angles  $\theta_s$  are 6° except for the H-types. The density contrast g=1.04, and sound speed contrast h=1.02 needed for the F-Type are determined to be the general values shown in Ref. 10.

The normalized TS, v, is averaged with normal distributions of fish tilt angle by

$$v_{\rm av}(L/\lambda, \vec{s}) = \int_{-\pi/2}^{\pi/2} v(L/\lambda, \theta_t, \vec{s}) N(\mu, \sigma) \, d\theta_t$$
(9)

where  $N(\mu, \sigma)$  is the normal probability density function with the mean  $\mu$  and standard deviation  $\sigma$ . We adopt N(-5,10), N(-5,20), N(0,10), and N(0,20) (angles are in degrees) to cover the general range, referring to McClatchie *et al.*<sup>15)</sup> and others.

We use the decibel representation of Eq. (3):

$$TS = 10 \log T_s = 10 \log v + 20 \log L$$
$$\equiv TS_{cm} + 20 \log L$$
(10)

where in the last expression L is in cm units, and  $TS_{cm}$  is the normalized TS. Similarly, the tilt-averaged TS is expressed as

$$TS_{av} = 10 \log v_{av} + 20 \log L$$
$$\equiv TS_{cm,av} + 20 \log L$$
(11)

where  $TS_{cm,av}$  is the tilt-averaged normalized TS. 2.3 Application to actual data

To examine the applicability of the present method to actual data, we used the data reported by Fässler et al.<sup>5)</sup> and Pedersen and Korneliussen.<sup>6)</sup>

The former measured SV at four frequencies (18, 38, 120, and 200 kHz) for individual schools of Atlantic herring (*Clupea haengus*) and Norway pout (*Trisopterus esmarkii*) which were difficult to discriminate by the frequency response method.

We use the 'eroded' SV data in Fig. 2(b) of their paper and the corresponding fish-length distribution data obtained by trawling in Table 1 to derive the relative  $L/\lambda$  characteristics. The average length of herring and pout was 26.5 cm and 10.1 cm, respectively.

Meanwhile, Pedersen and Korneliussen<sup>6)</sup> applied the relative frequency response method to three species, northeast Arctic cod (Gadus morhua), saithe (Pollachius virens), and Norway pout (Trisopterus esmarkii). Since their distributions were rather sparse, they measured TS by the splitbeam method, tracked single echoes to get the average TS from each echotrace, further averaged many single echoes, and obtained the relative frequency responses. Their results showed that although pout could be distinguished from the other two species, cod and saithe exhibited extremely similar responses, and it was difficult to distinguish these species by the relative frequency response method. From the length distributions obtained by trawl sampling in Fig. 2 of their paper, approximate lengths are read to be 75 cm for cod, 46 cm for saithe, and 18cm for pout, whereas the average TS values were presented in Fig. 3 at five frequencies, 18, 38, 70, 120, and 200 kHz. From these data, the relative  $L/\lambda$  characteristics were obtained.

### 3. Results

### 3.1 Results for T-type fish model

We first show the results for the T-type model in some detail to explain the process of obtaining the relative  $L/\lambda$  characteristic.

The normalized TS  $(TS_{em})$  as a function of fish tilt angle (TS patterns) calculated by Eqs. (1) and (10) are shown in **Fig. 2** for five  $L/\lambda$  values. As  $L/\lambda$  increases, the maximum values increase slightly, and the central lobes become sharper. The maximum values are at  $-6^\circ$ , because the given swim-

bladder orientation angle is  $+6^{\circ}$ . The maximum values for each  $L/\lambda$  are nearly the same particularly for larger  $L/\lambda$  exhibiting the geometrical scattering property.

Tilt-averaged normalized TS ( $TS_{cm,av}$ ) as a function of  $L/\lambda$  calculated by Eqs. (1), (9), and (11) for the four tilt angle distributions are shown in **Fig. 3**. Generally, they decrease with increasing  $L/\lambda$ , and the tendency is steeper for a large standard deviation  $\sigma$ . This is because, as can be seen from Fig. 2, when  $\sigma$  is large, the chance for scattering direction to deviate from the central lobe increases, and its degree is larger for a large  $L/\lambda$  for which the central



Fig. 2 Normalized TS as a function of tilt angle (TS patterns) for T-type model for five  $L/\lambda$  values.



Fig. 3 Tilt-averaged normalized TS as a function of  $L/\lambda$  for T-type model. Mean and standard deviation pairs of fish tilt angle distributions are shown.

lobe is sharper.

**Figure 4** is a modified version of Fig. 3, with the curves in Fig. 3 normalized by their values at  $L/\lambda=5$ , which is the decibel version of Eq. (6) with  $(L/\lambda)_0=5$ . The curves for N(0, 20) and N(-5,20) are almost overlapping. This figure represents what we propose in this paper, i.e., the relative  $L/\lambda$ characteristic of average SV or TS. As in Fig. 3, the curves decrease with increasing  $L/\lambda$ , and the tendency is lager for a large  $\sigma$ .

The relative frequency responses defined by Eq. (5) are shown in **Fig. 5** in decibel for the N(0,20) case in Fig. 4, changing body lengths. One curve of the relative  $L/\lambda$  characteristic in Fig. 4 varies in this way in this relative frequency response; this is why we propose the relative  $L/\lambda$  characteristic to replace the relative frequency response.

# 3.2 Comparison of relative $L/\lambda$ characteristics among fish models

**Figure 6** compares the relative  $L/\lambda$  characteristics for all models shown in Table 1 and Figs. 1(b) and (c); the derivation method is the same as for Fig. 4 but the results are arranged for each tilt-angle distribution in each panel and compared among fish types.

The undulatory characteristic of the F-type is based on deep notches due to interference between reflected waves from the dorsal and abdomen sides, and it remains at this degree even after tilt averaging; actually, the notches should be smoothed also by a slight variation of body length and we should have more smoothed curves.

Although the difference among the models, other than the F-type, are not prominent above  $L/\lambda=5$ , we can distinguish between models except for the T- and H-types. One reason for this might be the smooth and symmetrical shapes of the prolate spheroids, but this small difference should not be considered unrealistic. In fact, the examples of the relative frequency responses for several swimbladder fish species shown in Chapter 3 of Ref. 16 demonstrate that the differences of the responses are rather small. Figure 6 also shows that the difference of the relative  $L/\lambda$  characteristics is small among the tilt distributions above  $L/\lambda=5$ , and this is advantageous for actual species identification. If we assume that each model corresponds to a different species, the comparison of the characteristics can serve to enable fish species identification.



Fig. 4 Relative  $L/\lambda$  characteristics of T-type model for four tilt angle distributions. The curves for tilt distribution N(0, 20) and N(-5, 20) are almost overlapping.



Fig. 5 Relative frequency response of T-type model for tilt distribution of N(0, 20) and fish lengths L=10, 20, and 40 cm.



Fig. 6 Comparison of relative  $L/\lambda$  characteristics among all model types. Tilt angle distributions are shown in each panel, and line labels in the upper left panel indicate the fish models types (see Table 1). The curves for T- and H-Types are almost overlapping.



Fig. 7 Relative  $L/\lambda$  characteristics of Atlantic herring and Norway pout. Data from Table 1 and Fig. 2 (b) of Ref. 5.

### 3.3 Application to actual data

The relative  $L/\lambda$  characteristics computed using data from Ref. 5 are shown in **Fig. 7**. The reference value of  $L/\lambda$  is set at 5 as above, and the values at this  $L/\lambda$  are obtained by interpolating the nearest



Fig. 8 Relative  $L/\lambda$  characteristics of Atlantic cod, saithe, and Norway pout. Data from Figs. 2 and 3 of Ref. 6.

data in terms of decibels. This figure demonstrates that the two species, whose relative frequency responses almost overlapped (Fig. 2(b) of Ref. 5), are well discriminated.

The results for the data in Ref. 6 are shown in

**Fig. 8**; the data at  $L/\lambda=5$  are obtained as above but extrapolation is used for cod and saithe data. The three species are well discriminated particularly between cod and saithe whose relative frequency responses almost overlap (Fig. 3 of Ref. 6). The curve for pout is considerably different from that of Fig. 7 at  $L/\lambda$  smaller than 5; the cause is not clear but one possibility is the difference of the survey areas (i.e., the North Sea<sup>5)</sup> and Norwegian Sea<sup>6)</sup>).

### 4. Discussion

### 4.1 Reasonability to use PSMS scattering model

Since prolate spheroids can realize bodies from the spherical to the cylindrical, and the prolatespheroid modal-series (PSMS) scattering model is genuinely theoretical and exact, this model is appropriate for a discussion of general scattering properties as in the present study. As described earlier, it allows a fish TS to be normalized by the squared length of the fish, and it claims that the normalized TS depends upon  $L/\lambda$ , not upon frequency or wavelength itself. This has also been confirmed by the TS data measured by a controlled method for six fish species around Japan.<sup>17)</sup> Therefore, if we observe the relative  $L/\lambda$  characteristic of average SV or average TS instead of the relative frequency response, we can eliminate one cause of variability, i.e., body length, and identification becomes easier and more accurate. This is the main point of this paper.

In the derivation of Eqs. (5) and (6), we assumed that the distribution of fish length *L* is narrow, and that the parameters included in the species parameter vector  $\vec{s}$  do not depend on fish length. There are likely to be cases in which these assumptions deteriorate, however. To obtain the results in Fig. 8, the approximate mean lengths were estimated from the size distribution by trawling in Ref. 6; but since the length distributions were not particularly narrow for cod and pout, the results in Fig. 8 must be seen with some grains of allowance. If an approximate fish length is estimated by data from in situ TS measurement, as will be discussed later, and a length distribution is wide judging from the TS distribution, it should be noted that the discriminatory capability of the relative  $L/\lambda$  method would be reduced. However, this situation will be similar for the relative frequency method as seen in Fig. 5. If some element(s) in the species parameter vector  $\vec{s}$  shown in Table 1 change substantially with fish length, the vector could not be species specific. In such a case, we must proceed as if each size or age class belonged to a different species, even if they are the same species. Studies on age or length dependent changes in morphology and/or body material of target species would be necessary.

There may be an objection to normalizing fish TS by length squared.<sup>18)</sup> This normalization, however, is reasonable theoretically, as discussed above, and experimentally, as shown in Refs. 17, 19, and 20. The problem is to assume the normalized TS to be a constant. For example, in the Rayleigh scattering region the normalized TS is proportional to  $(L/\lambda)^4$ . Figures 2–4, 6–8 demonstrate such variable characteristics of the normalized TS. In the geometrical region, however, the tilt-averaged normalized TS is nearly constant, and then caution must be exercised due to the fact that difference in scattering characteristics is small. Figure 6 reinforces this fact.

### 4.2 Relative $L/\lambda$ characteristics

Among the fish models tested above (other than the F-type), since TS properties do not differ significantly, relative  $L/\lambda$  characteristics also do not differ much among the model types and they decrease slightly with increasing  $L/\lambda$ . In the small  $L/\lambda$  region, however, the characteristics change considerably according to the difference of the standard deviations of tilt angle,  $\sigma$ . We consider this phenomenon

referring to the TS patterns in Fig. 2. When  $\sigma$  is as small as 10°, the characteristics around the central lobe become important and the following two phenomena cancel out each other to result in the rather small change in the tilt-averaged normalized TS: 1) the TS pattern becomes sharper with increasing  $L/\lambda$ and the contribution from the small level portion of the TS pattern increases as a result; 2) the maximum value becomes somewhat large with increasing  $L/\lambda$ . Meanwhile, when  $\sigma$  is as large as 20°, the above first phenomenon overwhelms the second, and the tilt-averaged normalized TS decreases more rapidly. For both  $\sigma$ , since the sharpness of the central lobes does not differ much, as  $L/\lambda$  becomes somewhat large the characteristics decrease only gradually.

As the reference value of  $L/\lambda$ , we adopted  $(L/\lambda)_0 = 5$ . The selection of this value considerably changes the relative  $L/\lambda$  characteristic, so that careful selection is needed. We can see from Fig. 6 that if we selected 10 for the reference, differences among types would become small. Meanwhile, judging from Fig. 3, if we selected a value considerably smaller than 5, the effect of tilt distribution would become larger. The reference frequency of the relative frequency response is 38 kHz, and the body length computed from  $L/\lambda=5$  and 38 kHz is about 20 cm; this body length is medium, and also in that sense the reference of  $(L/\lambda)_0=5$  is appropriate.

The relative  $L/\lambda$  characteristics in Fig. 8 decrease with  $L/\lambda$  rather steeply compared with curves in Fig. 6. This trend is also too large compared with the relative frequency response curves for several swimbladder fishes in Chapter 3 of Ref. 16. The reason is not clear, but plausible explanations includes that the actual swimbladder is not so simply shaped as the prolate spheroid, and that these three fish species might have a rather peculiar swimbladder. Incidentally, Sand and Hawkins<sup>21)</sup> reported that cod has a somewhat peculiar swimbladder.

Referring to the characteristics in Fig. 6 and the relative frequency responses in Ref. 16, even if we employ the relative  $L/\lambda$  characteristic instead of the relative frequency response, the difference among fish species is not prominent, so that to discriminate the differences the measurement accuracy and precision of average SV must be as high as 0.2 dB. In particular, at high frequencies, since measurement with high accuracy and precision is not easy,<sup>8)</sup> attention must be paid to ensure appropriate absorption coefficients and low noise.

### 4.3 How to determine fish length

To realize the proposed method, it is necessary to know the length of fish. Since an acoustic method is preferable, it would be best to measure an average TS in situ and then convert it into an average length by Eq. (11) using well scrutinized average normalized TS  $(TS_{cm av})$  data (We here use the term 'average normalized TS' instead of 'tilt-averaged normalized TS', because the results of in situ TS measurements should be averaged not only for tiltangle, but also for other in situ conditions such as swimbladder states). As fish species, however, are not known beforehand, we must use an approximate average normalized TS value. Foote<sup>19)</sup> derived -67.5 dB as the average normalized TS (his notation is  $b_{20}$ ) of physoclistous fish from many reliable in situ TS data. Ona<sup>20)</sup> measured TS of physostomous fish, herring (Clupea harengus), by several methods at various depths and established a depth dependent TS formula that gives average normalized TS values at 38kHz: -65.4dB at 0m, -67.8dB at 100m, and -68.4dB at 200m. Referring to these values, we can use -67 dB as the approximate value of the average normalized TS of swimbladder fish. Incidentally, the average

normalized TS value of six species of fish around Japan is approximately  $-67 \,\text{dB}$  at  $L/\lambda = 10$ , and does not change significantly with  $L/\lambda$ .<sup>17)</sup>

Since nonswimbladder fishes have rather peculiar frequency characteristics of TS (for example, see Fig. 6, F-type), and much smaller TS values, discrimination from swimbladder fish is possible.<sup>1)</sup> There have not been sufficient data on the average normalized TS of nonswimbladder fish and further studies are needed, but the following value can be a reference for the time being. Foote<sup>22)</sup> compared the TS of swimbladder fish, gadoids, and nonswimbladder fish, Atlantic mackerel, and deduced the 'percentage swimbladder contribution.' From Fig. 5 in his paper the contribution for average TS at 38kHz is about 90%, which means that the gadoid TS is about 10 dB larger than the mackerel TS. Thus, from the above average normalized TS of -67 dB for the swimbladder fish, -77 dB will be a reference for the average normalized TS of nonswimbladder fish. Once a target species is successfully discriminated by means of several identification methods, including the proposed method, we will be able to obtain a more accurate average normalized TS value, and by using it a more appropriate species specific relative  $L/\lambda$  characteristic will be obtained, which will serve for later species identification.

TS values or body lengths themselves are very important information for species identification. Pedersen and Korneliussen<sup>6)</sup> cited above reported that although cod and saithe were difficult to discriminate by the relative frequency response, the large difference in TS values made discrimination possible. As this example shows, there will be cases in which large difference in TS values or fish lengths of target species can serve for species identification. Moreover, simultaneous observation of average SV and TS will make near real-time density measurement possible, which has been a long-cherished dream in fisheries acoustics. When such measurement is realized, the problem related to TS variability will be largely resolved.

In order to get relative  $L/\lambda$  characteristics and to address the abovementioned challenges, it will be necessary to develop a quantitative or scientific echo sounder able to simultaneously measure both SV and TS even for dense or deep schools. Although the *in situ* TS measurement method has been greatly advanced by the introduction of the split-beam method, TS measurement is sometimes difficult due to considerably strict conditions such that single echoes with negligible noise and interference from other fish echoes must be fulfilled. The most effective solution will be to increase the resolution of echosounders.

Here, as an example of such an idea, we introduce a quantitative echosounder aimed at species identification.<sup>23)</sup> This sounder operates at 38 and 120 kHz, and has an 'SV mode' and 'TS mode.' In the SV mode, the beamwidth is 11.8° and pulse duration is 1.2 ms for both frequencies; measured raw SV are averaged in a small integration cell (such as 2-s horizontally and 1-m vertically) and the difference between the average SV at the two frequencies are obtained and displayed in near real-time. In the TS mode at 38kHz, a split-beam system with a sharp main beamwidth of 5.9° and a short pulse duration of 0.4 ms realizes TS measurement for rather high density or deep schools and provides average fish lengths using Eq. (11) with the appropriate average normalized TS data discussed above. Combining the SV difference and the average body length, we can realize the proposed method (although only two frequencies are used in this system).

In order to further improve such capability, it would be better to have a special channel in which

the main aim is TS measurement. The channel has functions of multiple narrow beamwidths (e.g., 3.5, 7, and 14°) and a short pulse width (e.g., 0.2 ms, range resolution 15 cm). If we use a broadband system, we can realize a further short pulse width such as 0.1 ms. Since transducer motion error becomes large for sharp beams,<sup>24)</sup> an electrical or mechanical stabilizer will be necessary for the transducer. Also, since the narrow beamwidths make the transducer size too large at 38 kHz, a higher frequency such as 70 kHz is preferable. Such a 'medium' frequency realizes a sufficient signal-to-noise ratio even for targets at 400-m depth.<sup>8)</sup>

### 5. Conclusions

- 1) Introduction of the relative fish-length-towavelength ratio  $(L/\lambda)$  characteristic of average SV, instead of or together with the relative frequency response, is necessary to obtain discernible information for fish species identification.
- 2) To that end, a fish-length measurement technique by acoustics should be evolved. The technique will also serve to offer powerful information for species identification and to realize real-time density measurement.
- Even if the relative L/λ characteristics are employed, differences among species are not particularly conspicuous, so that high accuracy and precision in SV measurement will still be necessary.

## Appendix: Symbols, units, and nomenclature of scattering indexes

The symbols, units, and nomenclature of scattering indexes used in this paper are shown in **Table A1**, compared with those recommended by the ICES.<sup>9)</sup> Our definition of the target strength is based on the intensity ratio, in accord with the traditional definition in Refs. 25–27, and other scattering indexes are systematically derived from it. The symbols of decibel equivalents follow the rule of 'two or three capital letters.<sup>28)</sup> We use the same name for each linear and decibel scattering index for simplicity, but calculations such as averaging are done for linear values, if not otherwise stated. Values are the same but the units are different between our system and that of the ICES.

The volume backscattering strength (SV) is intrinsically defined for multiple scatterers distributed approximately homogeneously and broader than beam spreading. Squared '20 log r TVG' outputs compensated for the multiple echo coefficient,<sup>27)</sup> including the equivalent beam angle and pulse width, do not often meet the above condition, and should be called 'raw SV' or 'pixel SV.' Only if the above condition is satisfied, the raw SV can be the 'intrinsic SV.' Averaging or echo integration makes the condition equivalently hold, and the result should be called the 'average SV', for which we use the symbol $\langle S_V \rangle$ . For a more detailed explanation, see Ref. 29.

This paper				ICES		
Name	Abbre- viation	Definition	Unit	Name	Definition	Unit
Target strength	TS	$T_S = I_r / I_i$		Backscattering cross section	$\sigma_{bs} = r_0^2 I_r / I_i$	m <sup>2</sup>
		$TS=10 \log T_S$	dB	Target strength	$TS=10 \log \sigma_{bs}$	dB
Volume	s sv	$S_V = nT_S$	1/m <sup>3</sup>	Volume backscattering coefficient	$s_v = \sum \sigma_{bs} / V$	1/m
strength		$SV=10 \log S_V$	dB	Volume backscattering strength	$S_{\nu}=10\log s_{\nu}$	dB
Area	C A	$S_A = \int S_V dr$	1/m <sup>2</sup>	Area backscattering coefficient	$s_a = \int s_v dr$	
strength	SA	$SA = 10 \log S_A$	dB	Area backscattering strength	$S_a = 10 \log s_a$	dB
$I_i$ : Incident inte $I_r$ : Scattered int r : Range [m]	nsity [W/m <sup>2</sup> ] ensity at 1 m	[W/m <sup>2</sup> ]	Nautical backscattering coefficient	$s_A = 4 \pi \ 1852^2 s_a$	m²/nmi²	
<ul> <li>r<sub>0</sub> : Reference range (1 m)</li> <li>n : Distribution density [1/m<sup>3</sup>]</li> <li>V : Volume occupied by scatterer [m<sup>3</sup>]</li> </ul>				Nautical backscattering strength	$S_A = 10 \log s_A$	dB

Table A1. Nomenclature for scattering indexes.

### References

- R. J. Korneliussen and E. Ona, "An operational system for processing and visualizing multi-frequency acoustic data," ICES J. Mar. Sci., 59, 293–313 (2002).
- R. J. Korneliussen and E. Ona, "Synthetic echograms generated from the relative frequency response," ICES J. Mar. Sci., 60, 636–640 (2003).
- R. J. Korneliussen, N. Diner, E. Ona, L. Berger and P. G. Fernandes, "Proposals for the collection of multi-frequency acoustic data," ICES J. Mar. Sci., 65, 982–994 (2008).
- R. J. Korneliussen, "The acoustic identification of Atlantic mackerel," ICES J. Mar. Sci., 67, 1749–1758 (2010).
- 5) S. M. M. Fässler, R. Santos, N. Garcia-Nunez and P. G. Fernandes, "Multi-frequency backscat-

tering properties of Atlantic herring (*Clupea haengus*) and Norway pout (*Trisopterus esmarkii*)," Can. J. Fish. Aquat. Sci., **64**, 362–374 (2007).

- G. Pedersen and R. J. Korneliussen, "The relative frequency response derived from individually separated targets of northeast Arctic cod (*Gadus morhua*), saithe (*Pollachius virens*), and Norway pout (*Trisopterus esmarkii*)," ICES J. Mar. Sci., 66, 1149–1154 (2009).
- L. Berger, C. Poncelet and V. M. Trenkel, "A method for reducing uncertainty in estimates of fish-school frequency response using data from multi-frequency and multibeam echosounders," ICES J. Mar. Sci., 66, 1155–1161 (2009).
- M. Furusawa, "Effects of noise and absorption on high frequency measurements of acoustic-

backscatter from fish," Int. J. Oceanography, vol. 2015, Article ID 589463, 1–11 (2015).

- D. N. MacLennan, P. G. Fernandes and J. Dalen, "A consistent approach to definitions and symbols in fisheries acoustics," ICES J. Mar. Sci., 59, 365–369 (2002).
- M. Furusawa, "Prolate spheroidal models for predicting general trends of fish target strength," J. Acoust. Soc. Jpn. (E), 9, 13–24 (1988).
- C. Flammer, Spheroidal Wave Functions (Stanford University Press, Stanford, 1957).
- S. Zhang and J. M. Jin, Computation of Special Functions (John Wiley & Sons, New York, 1996).
- A. L. Van Buren and J. E. Boisvert, "Accurate calculation of prolate spheroidal radial functions of the first kind and their derivatives," Quart. Appl. Math., 60, 589–599 (2002).
- A. L. Van Buren and J. E. Boisvert, "Improved calculation of prolate spheroidal radial functions of the second kind and their derivatives," Quart. Appl. Math., 62, 493–507 (2004).
- S. McClatchie, J. Alsop and F. Coombs, "A reevaluation of relationships between fish size, acoustic frequency, and target strength," ICES J. Mar. Sci., 53, 780–791 (1996).
- Anon., "Species identification methods from acoustic multi-frequency information (SIMFAMI)," Final Report, EU Contract Q5RS-2001-02054, 1–486 (2006).
- Y. Miyanohana, K. Ishii and M. Furuswa, "Measurements and analyses of dorsal-aspect target strength of six species of fish at four frequencies," Rapp. P.-v. Reun. Cons. Int. Explor. Mer, 189, 317–324 (1990).
- 18) S. McClatchie, G. J. Macaulay and R. F. Coombs, "A requiem for the use of 20 Log10 Length for acoustic target strength with special reference to deep-sea fishes," ICES J. Mar.

Sci., 60, 419-428 (2003).

- K. G. Foote, "Fish target strengths for use in echo integrator surveys," J. Acoust. Soc. Am., 82, 981–987 (1987).
- E. Ona, "An expanded target-strength relationship for herring," ICES J. Mar. Sci., 60, 493–499 (2003).
- O. Sand and A. D. Hawkins, "Acoustic properties of the cod swimbladder," J. Experiment. Biol., 58, 797–820 (1973).
- 22) K. G. Foote, "Importance of the swimbladder in acoustic scattering by fish: A comparison of gadoid and mackerel target strength," J. Acoust. Soc. Am., 67, 2084–2089 (1980).
- Anon., "Report on developing quantitative echo sounder for fish species identification," Fishing Boat and System Engineering Association of Japan, 1–75 (2003) (in Japanese).
- 24) M. Furusawa and K. Sawada, "Effects of transducer motion on quantifying single fish echoes," Nippon Suisan Gakkaishi, 57, 857– 864 (1991).
- 25) J. Saneyoshi, Y. Kikuchi and O. Nomoto, *Chouonpa gijyutsu binran* (Handbook of ultrasonic technology), 2nd ed. (Nikkan Kougyo Shimbun Sha, Tokyo, 1966), (in Japanese).
- R. J. Urick, *Principle of Underwater Sound* (McGraw-Hill, New York, 1975).
- M. Furusawa, "Designing quantitative echo sounders," J. Acoust. Soc. Am., 90, 26–36 (1991).
- 28) R. Kieser, "Standard notation for the hydroacoustic assessment of biological parameters," Meeting on Hydroacoustical Methods for the Estimation of Marine Fish Populations, Cambridge, MA, USA, 25–29 June, 1979.
- M. Furusawa, "Section and Total Scattering Strengths of Individual Fish School," J. Mar. Acoust. Soc. Jpn., 38, 177–194 (2011).