atively simple and can be easily programmed. This model can be applied to almost all materials including a gaseous body such as the swimbladder and liquid body such as a fish body. The peculiar limitation of this model is that the aspect ratio should be large (approximately>5) and that the tilt angle should not be too large ($<40°$). These limitations, however, are considerably relaxed compared with the traditional finite cylinder models.[33] Our calculations are within these limitations. Estimation of the required swimbladder measurements will be discussed in the next section.

The fish body is approximated as a liquid-filled slender scatter. The reason why the fish body is modeled as liquid-filled instead of elastic material-filled are two-fold. One is that the shear properties due to the elasticity in fish flesh are usually unavailable. Second, there exist studies that support the liquid model. For example, in Ye and Farmer,[30] such a model has been used to study acoustic attenuation by different types of fish, and the results compare reasonably well with some published data (*e.g.* Furusawa *et al.*[34]).

In our computation we use the following parameters: the sound speeds in fresh water, in seawater, in the swimbladder, and in the fish body are taken as 1482, 1522, 340, and 1560 m/s, respectively; the density ratios between air and fresh water, between air and seawater, and between fish flesh and fresh water, are taken as 0.00129, 0.001259 and 1.04. These numbers are within the range widely accepted.[24]

Maximum and Average TS

The maximum TS is easily read as the peak value in the TS pattern, which is defined as the TS function against fish tilt angle. The most reasonable definition of the average TS is that given by Foote,[35] followed by Miyanohana *et al.*[4] The TS pattern is averaged for a normal distribution of tilt angle described by an average tilt angle and a standard deviation pair; for example, $(-5, 15)$ means a mean tilt of 5° head down and standard deviation of 15°. The maximum and averaged TS are derived for measured and modeled patterns and the results are compared. If the standard deviation of tilt angle is large and beam width is not too small, as in the present case, the average TS dose not vary much with the average tilt angle.[36] Therefore, the obtained average TS can be referred to for actual use.

One of the merits of modeling is the ability to predict some characteristics purely by calculation. We calculate TS patterns for wide range of frequency using DCM and deduce maximum and average TS for the frequency range.

It is convenient and reasonable to normalize the TS value by length squared; when the length is in centimeter the normalized TS in decibel is shown as TS_{cm}.

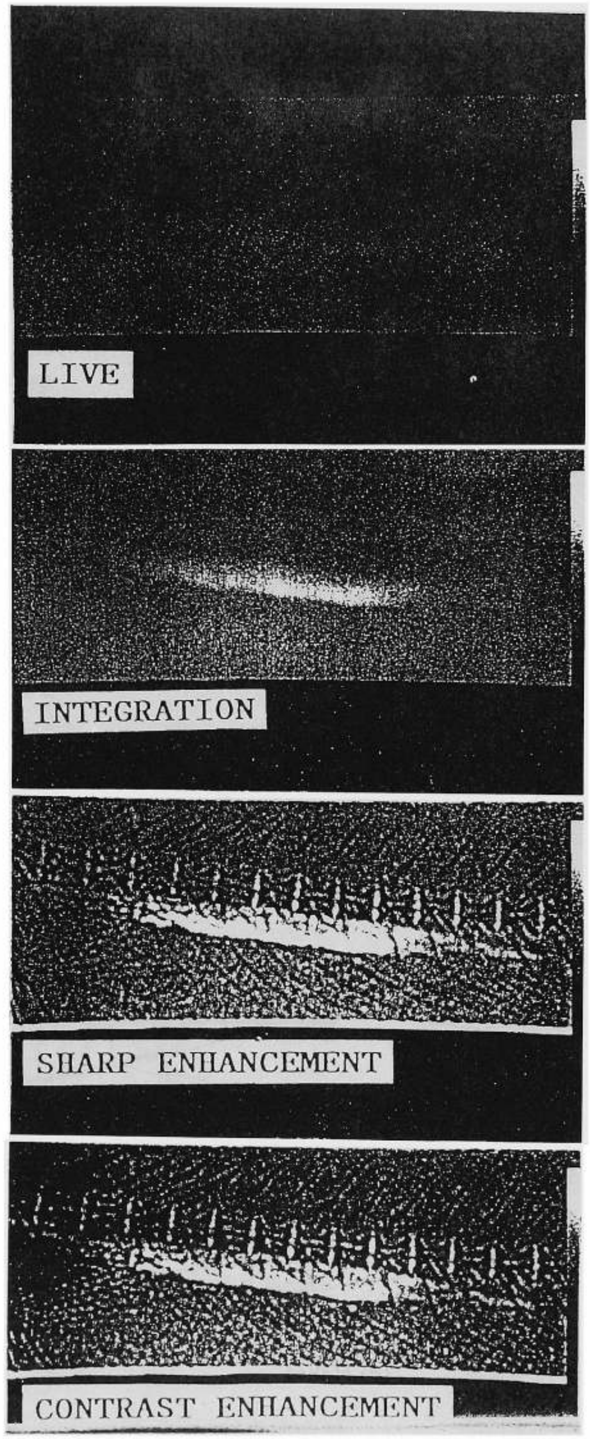


Fig. 5. Side aspect soft X-ray swimbladder image.
Three image processing procedures are compared with the live image. The fish head is to the left. Backbone, spine and swimbladder are visible.

Results

Figure 5 illustrates typical soft X-ray images of the side aspect of the swimbladder of Hake. The tail to head orientation is from right to left. The backbone and swimbladder are visible. The unprocessed or live image is compared with three image enhancement procedures.

Dorsal and side aspect swimbladder outlines are drawn from the soft X-ray images. Figure 6 gives the dorsal and side aspect swimbladder outlines for the six specimens. The X-ray images of dorsal shape for Pollock 3 were viewed but failed to record the whole shape of swimbladder, so that the heights in the side view were used for the widths. The six swimbladder outlines are quite different. This reflects natural swimbladder variability between fish,

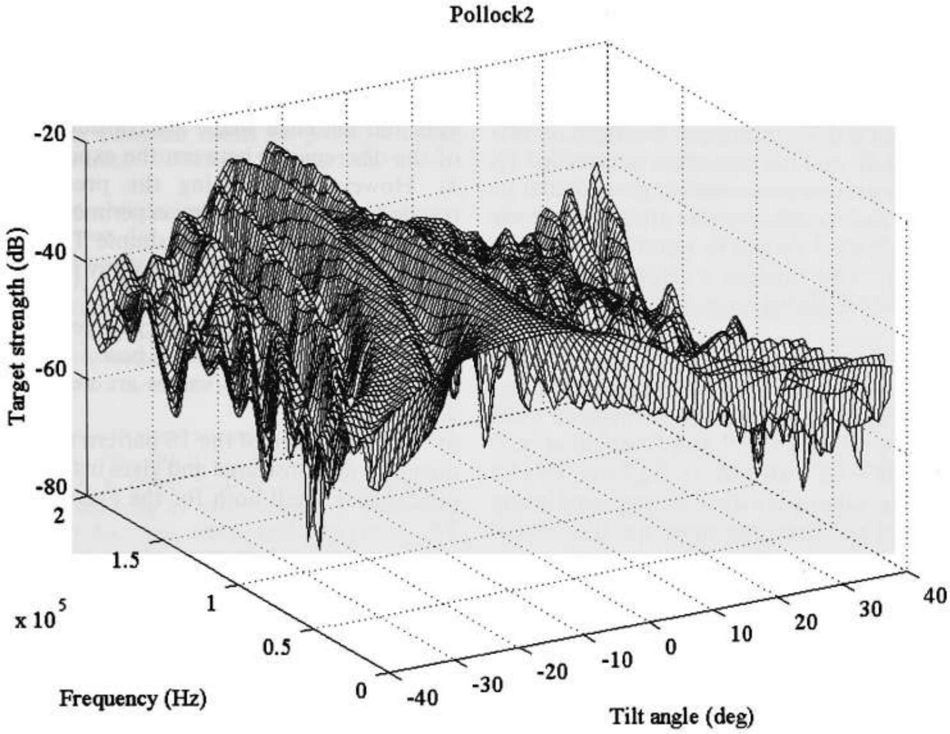


Fig. 12. Calculated TS pattern of Pollock 1 over a broad frequency range.

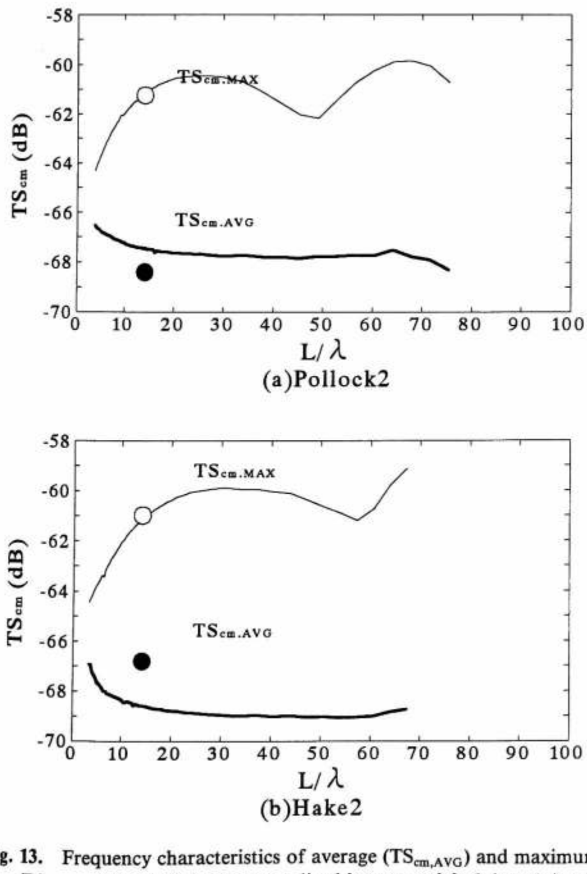


Fig. 13. Frequency characteristics of average ($TS_{cm,AVG}$) and maximum ($TS_{cm,MAX}$) target strength normalized by squared fork length in cm for Pollock 2 (upper) and Hake 2 (lower).
Circles show measurements.

own merits and demerits. Therefore, we could not judge the models from one aspect. We have used PSM and DCM.

The PSM is exact, is applicable to a broad parameter range, and needs few parameters. Therefore, it is suitable to elucidate general trends of TS of marine animals[15] and also can be a standard in developing other more theoretically approximate model.[21] One example of the outcomes is shown in Fig. 11 and Fig. 13 where the normalized TS are shown as a function of L/λ. If f in Eq. (2) is divided by the length ($L=2a$), then k in the right side becomes ka or L/λ eliminating pure length dependency and establishing the similarity law. This double normalization scheme is thus theoretically justified by PSM and very effective in processing and displaying data. In regeneration of the individual TS pattern for individual shape, however, this model gives a poorer result than other more detailed models such as the present DCM. In Fig. 10, however, we can confirm how well the PSM expresses the general trend of the DCM.

The DCM model[21] we have used is more suitable for individual fish and better for the present study than PSM as shown in Fig. 10. This model can predict scattering characteristics for rather complicated shapes by moderate number of parameters and is applicable to a wider range of parameters, as shown in Fig. 12. This model, however, could not predict scattering properties at large tilt angle and cross sections along the axis need to be circular. We believe that the present DCM model is useful for fish TS prediction by X-ray and modeling technique, if a good quality X-ray photo is obtained.

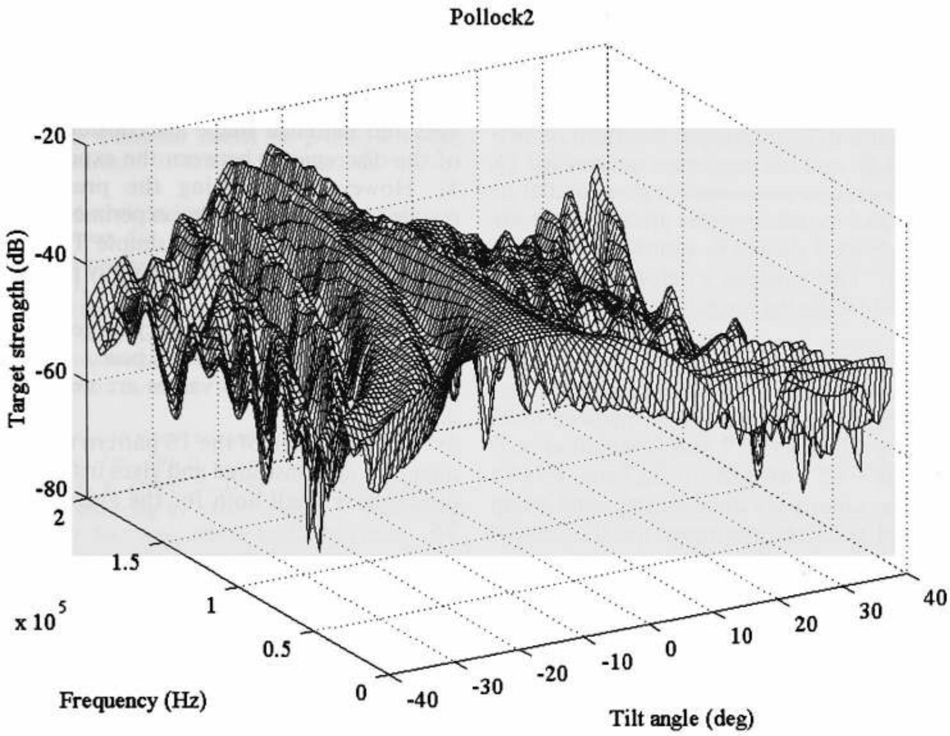
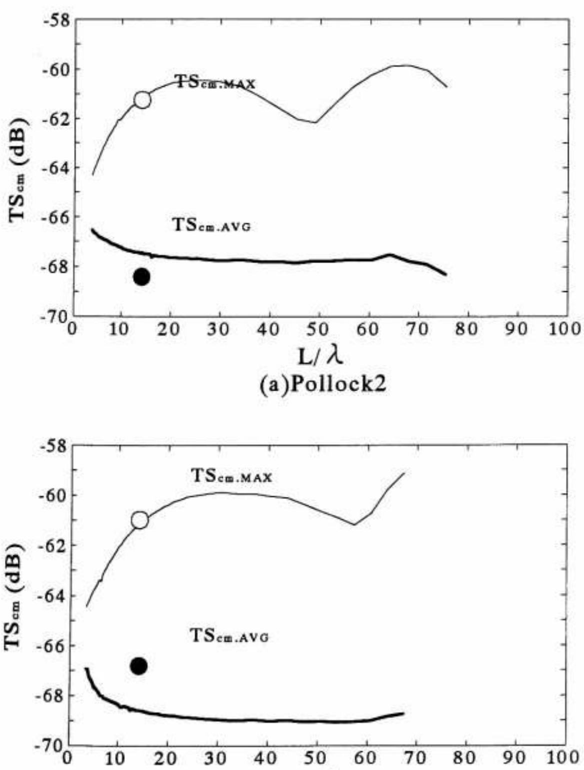


Fig. 12. Calculated TS pattern of Pollock 1 over a broad frequency range.



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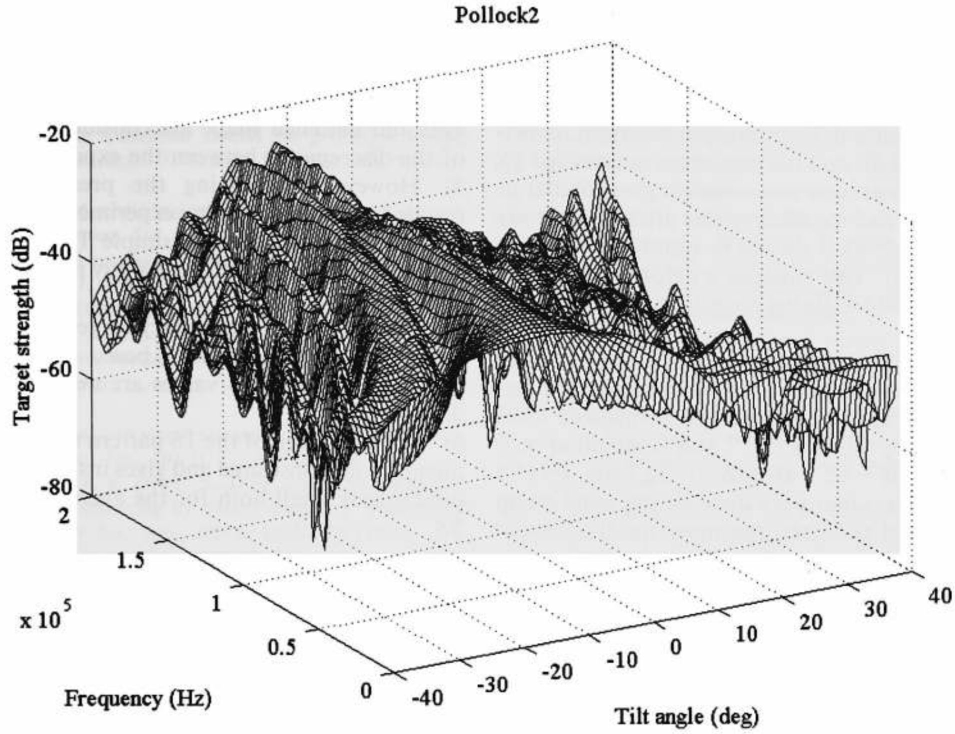

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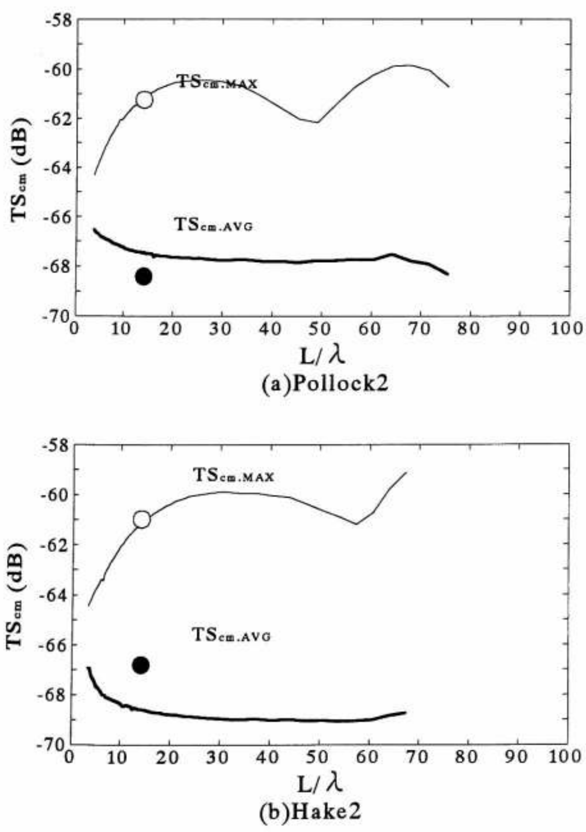

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