Modeling of fish target strength angular dependence for indirect target strength estimation methods

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Introduction

In fishery acoustics it is common to model echo peak values acquired from the school of fish using Rayleigh distribution. Peterson [1] was the first who noted that when the size of the fish is large compared with acoustic wavelength, the total scattered acoustic pressure will be the sum of smaller pressure levels scattered from various parts of the fish. Thus using an analogy coming from the signal theory, which states that when many sine waves of random phase and random amplitude are superimposed, the PDF of the resultant envelope is the Rayleigh PDF.

A simple scattering model of a fish has been developed by Clay and Heist [3]. During high-resolution laboratory measurements it appeared that the peak value in fish echo profile corresponds to the swimbladder and head, and low level returns are from the skeleton. Additionally, when the fish was moving and flexing the echo was fluctuating from ping to ping. So, as the echo from medium-resolution sonar ping is composed of the echoes from individual parts of the fish the interferences from moving fish can be modeled as a composed of a concentrated component and distributed component. They use two-parameter Rice probability density function (PDF) to describe such fluctuations as an analogy between scattering process and Rice's signal theory. Clay and Heist PDF model were partly proved by experimental data, and presented by other authors, i.e. [4]. The second parameter γ can be interpreted as ratio of concentrated component σ_c to distributed component σ_d ($\gamma=\sigma_c/\sigma_d$) and it depends on fish behavior and morphology and also on fish length to wave length (L/λ) ratio. When γ is small, the Rayleigh distribution is obtained, when γ is large, it results in the Gaussian distribution. These two limiting cases apply respectively to large and small fish.

Beside Clay and Heist's stochastic model, more accurate model was formulated by Foote [5] using Kirchhoff approximation and morphology of the swimbladder. Stanton [6] described scattering from finite bent cylinder, which approximates the shapes of the zooplankton and fish. Clay and Horne [7] applied the ray-mode model using actual cod morphology (KRM model). These recent models are improvements in the modeling of fish backscatter because they allow more realistic approximation of the fish body and swimbladder morphology.

Theory

According to [2] the scattering properties of swimbladdered fish can be modeled using theory of scattering from gas-filled cylinder. The amplitude of acoustic scattering length of a gas-filled cylinder in water may be evaluated from Helmholtz-Kirchhoff integral and is given by [2]:

$$\left|l_{BS}(\chi)\right| = l_{BS0}\frac{\sin\left(kl_{ecb}\sin(\chi+\chi_0)\right)}{kl_{ecb}\sin(\chi+\chi_0)}\sqrt{\cos(\chi+\chi_0)} \qquad \text{eq. 1}$$

where $l_{BS0} = l_{ecb}\ (a_{ecb}/2\lambda)^{1/2}$ is maximum backscattering length, a_{ecb} and l_{ecb} are the radius and length of the equivalent swimbladder as a cylinder, $k=2\pi/\lambda$ is wave number, χ is fish angular coordinate and χ_0 is a tilt angle of the swimbladder. The maximum backscattering length l_{BS0} increases with increasing

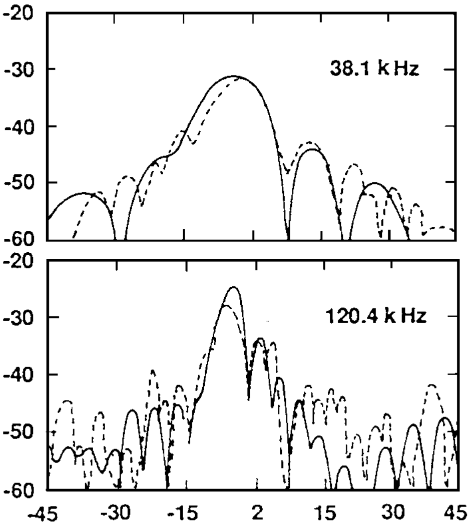

Fig.1. Target strengths as a function of tilt angle for a 31.5cm pollack at dorsal aspect at two frequencies 38kHz and 120kHz as measured by Foote [5].

frequency. The *sin (x)/x* determines angular properties of fish pattern as the *cosine* dependence is very week. Eq. 1 can be rewritten in the logarithmic form, which more clearly shows dependence on angular position of the fish χ:

$$TS = TS_{MAX} + B_f(\chi) \qquad \text{eq. 2}$$

where TS=20log|l_{BS}|, TS_{MAX}=20logl_{BS0} and $B_f(\chi)$ is the fish beam pattern expressed in logarithmic domain:

$$B_f = 20\log\left(\frac{\sin\left(kl_{ecb}\sin(\chi+\chi_0)\right)}{kl_{ecb}\sin(\chi+\chi_0)}\sqrt{\cos(\chi+\chi_0)}\right) \qquad \text{eq. 3}$$

For modeling purposes the equivalent parameters of fish swimbladder were derived from a simple model, which approximates fish swimbladder to a finite cylinder as proposed by Haslett [8]. The swimbladder is first approximated by a combination of a hemisphere, a short cylinder, and a cone of fixed dimensions relative to the fish fork length. Then this shape is modified to a cylinder maintaining their geometrical cross section. The model is shown in Fig.2. Although the model lacks versatility [9] its simplicity allows for statistical modeling of probability distribution function of single fish.

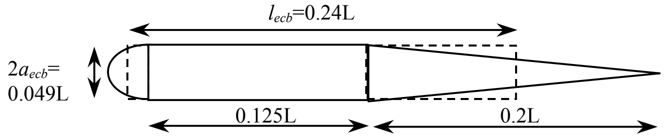

Fig 2. A simple approximation of the swimbladder to a cylinder as proposed by Haslett [8]; L – fish fork length.

Using this model we can estimate maximum value of TS as:

$$TS_{MAX} \approx 20\log\frac{L}{4} + 10\log\frac{a_{ecb}}{2\lambda} \qquad \text{eq. 4}$$

and compare it to the mean value of TS according to the National Marine Fisheries Service regression model fit:

$$<TS> = 20\log L - 26 = 20\log L/20 \qquad \text{eq. 5}$$

Modeling

Treating tilt angle as random variable representing fish orientation in the transducer beam, eq. 1 was used in modeling probability density function (PDF) of backscattering length of the single fish. Fig. 3 presents the modeled angular patterns for 20cm and 40cm fish along with its PDF function. It is noteworthy to observe the possibility of obtaining two-modal distribution for larger fish or for higher frequencies (what is evident from eq. 1). It may explain obtaining multimodal PDFs for homogeneous school of fish as some of the fish may stay in different orientation.

Further modeling was performed for school of fish having uniform length distribution in the range between 5cm to 40cm, as shown in Fig. 4a and 5a. Every fish was swimming "in the transducer beam" and changing the angle it was observed from. The trace of the fish was assumed to be on straight line, but depending on fish depth it resulted in random number of echoes. It was also assumed that fish tilt angle has normal distribution as presented in Fig 4b and 5b. The results in the form of PDFs are presented for two swimbladder tilt angles 1° (Fig.4) and 7° (Fig.5) and for two frequencies 38kHz (subfigure c) and 120kHz (subfigure d).

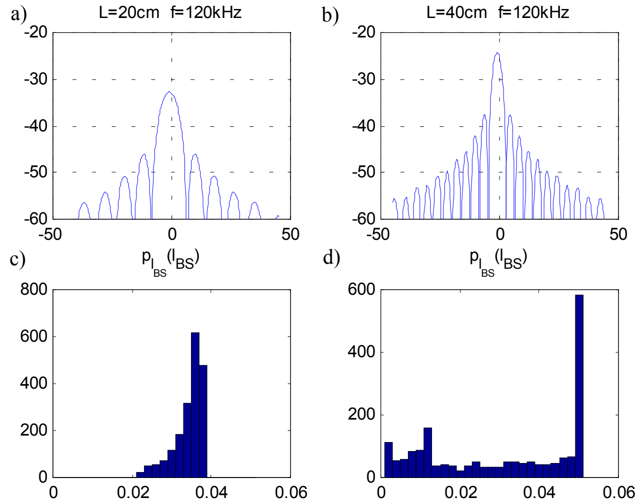

Fig.3. Target strength angular dependence for a 20cm and 40cm fork length fish at f=120kHz modeled by eq.2 and its PDF in absolute domain when normal distribution of fish tilt angle assumed; swimbladder tilt 1°.

Conclusion

In the paper the model of scattering from the fish based on theory of scattering from tilted cylinder is used for statistical modeling of PDF of single fish. The influence of the frequency and tilt angle of swimbladder is discussed. The same model is applied to modeling the echoes from the school of fish, which generally confirms the tendency to obtain Rayleigh distribution.

It was shown, that the measured distribution of acoustic fish length differs from actual fish length frequency. The transformation of these both distributions is a result of multiplicative influence of random fish length and random fish pattern. Hypothetical process of removing fish pattern effect requires application of inverse technique to eq. 2 as the information about fish length is mainly in TS_{MAX}. This also requires the knowledge about distribution of fish tilt angle, which may be obtained by detailed analysis of fish movement in the beam (fish tracking) and the knowledge of mean fish swimbladder tilt angle.

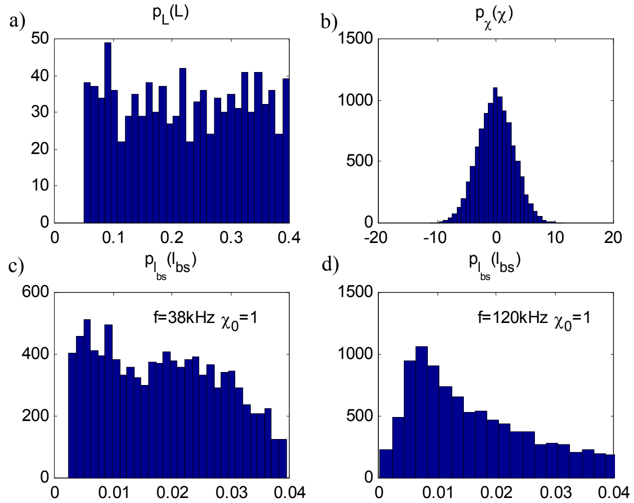

Fig.4. Assumed fish school length distribution (a) distribution of tilt angle (b) and obtained distribution of backscattering length for two frequencies f=38kHz (c) and 120kHz (d); swimbladder tilt 1°.

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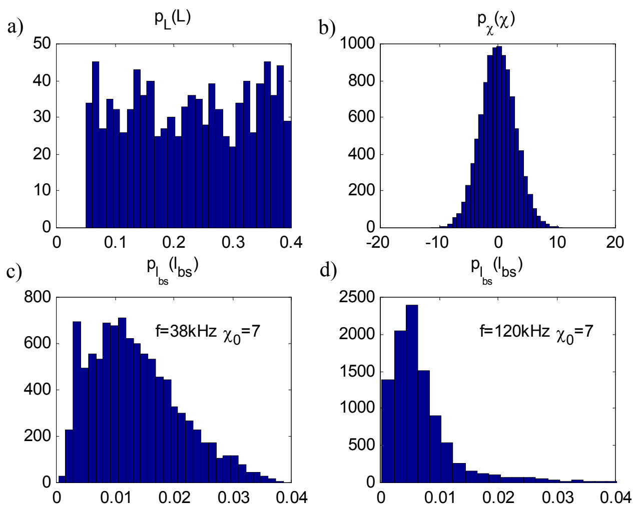

Fig.5. Assumed fish school length distribution (a) distribution of tilt angle (b) and obtained distribution of backscattering length for two frequencies f=38kHz (c) and 120kHz (d); swimbladder tilt 7°.