THE ESTIMATION OF NORWEGIAN COD SIZE DISTRIBUTION FROM ACOUSTIC DATA

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The paper presents an algorithm for estimation the fish length distribution from acoustic target strength data. The theory of scattering from a tilted cylinder is used for modelling the fish directivity pattern of swimbladdered fish. The model allows for formulating the dependence of target strength on two main components; the maximum target strength and the fish directivity pattern. As both terms depend on fish length, the inverse technique used when processing is performed on introduced conditional distributions. The effect of fish tilt angle is in this way removed, or deconvolved from the target strength distribution.. The resulting fish maximum target strength distribution is further converted into fish length distribution using equivalent parameters for swimbladder morphology. The method is verified on actual data acquired during the Lofoten 2004 survey on spawning grounds of North East Arctic cod (Gadus morhua).

INTRODUCTION

Fish target strength estimation is a well-defined approach required for fish abundance estimation. However, if possible, a required quantity is also the actual fish size distribution of the insonified targets. This is why a routine acoustical surveys are dependent on regular trawl sampling made during acoustical surveying. The results are used later for empirical determination of target strength to length regression relationship. The fishing industry could also greatly benefit from direct estimation of size distribution on the fishing grounds.

The paper introduce algorithms for processing of single fish echoes, which could improve estimation of fish size, directly from target strength data. The conversion is not straightforward for directive targets like fish, as their size and orientation relative to the transducer is not known. A small target strength can then either be derived from a small fish, or from a large fish at unfavourable aspect angle. As modern split beam echo sounder systems used in acoustic surveys can accurately give fish position in the beam, but not its orientation, the most difficult quantity to estimate is actually fish tilt angle, which strongly influence the echo from a directive target [1].

The algorithmic approach proposed in the paper use the inverse processing approach performed in probability density function (PDF) domain. To define so-called kernel of inversion, some additional assumption are required, related to behavioural statistics of fish orientation and its morphological parameters. As the fish swimbladder has been identified in several species as the main reflector of acoustic energy [2], the theoretical analysis presented here are only useful for swimbladder-bearing fish. For these, its acoustic scattering is simplified to be similar as from a tilted cylinder, which in fact is enough to reconstruct the approximation of scattering field from entire fish, at least for further statistical processing.

1. THEORETICAL BACKGROUND

According to Medwin and Clay the scattering properties of swimbladdered fish can be modelled by using the theory of scattering from gas-filled cylinder. The amplitude of acoustic backscattering length of a gas-filled cylinder in water may be evaluated from Helmholtz-Kirchhoff integral and is given by [3]:

$$|l_{BS}(\chi)| = l_{BS0}\frac{\sin(kl_{ecb}\sin(\chi+\chi_0))}{kl_{ecb}\sin(\chi+\chi_0)}\sqrt{\cos(\chi+\chi_0)} \tag{1}$$

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 *sin (x)/x* dependence 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 the angular position of the fish χ:

$$TS = TS_0(l_{ecb}, a_{ecb}, f) + D_f(\chi, \chi_0, l_{ecb}, f) \tag{2}$$

where TS=20log|l_{BS}|, TS_0=20logl_{BS0} and D_f is the fish directivity pattern in dorsal aspect expressed in logarithmic domain:

$$D_f(\chi, \chi_0, l_{ecb}, f) = 20\log\left(\frac{\sin(kl_{ecb}\sin(\chi+\chi_0))}{kl_{ecb}\sin(\chi+\chi_0)}\sqrt{\cos(\chi+\chi_0)}\right) \tag{3}$$

When the set of data representing target strength values of many fish are considered, Eq. 2 can be treated as a sum of two random variables. Actually, this is not the sum of independent random variables, as the maximum fish target strength TS_0 and fish directivity pattern D_f both depends on fish equivalent cylinder length l_{ecb}.

The general equation describing relation for the sum of two random variables uses joint probability density function $p_{x,y}()$:

$$p_z(z) = \int p_{x,y}(x, z-x)dx \tag{4}$$

However using Bayes theory, Eq (4) can be transformed into convolution integral by means of conditional function $p_{y|x}()$:

$$p_z(z) = \int p_x(x)\, p_{y|x}(z-x, x)dx \tag{5}$$

Eq. 5 expressed using acoustic PDFs as presented in Eq. 2 results in the following equation:

$$p_{TS}(TS) = \int p_{TS_0}(TS_0)p_{D_f|TS_0}(TS - TS_0, TS_0)dTS_0 \tag{6}$$

and introduces conditional PDF of fish directivity pattern. This function represents the kernel of integral equation and it allows for a reconstruction of maximum targets strength PDF from actually measured target strength PDF. The function may be constructed by random generation using theoretical Eq. 3, in which the distribution of fish tilt angle χ that reflects the fish behavior in the beam is assumed to agree with normal process [4]. Furthermore it requires

another assumption for an approximate value of fish swimbladder inclination angle χ_0, typically known for different fish species i.e. [3], [5].
Introducing relative dimensions of equivalent cylinder $l_r = l_{ecb}/L$ and $a_r = a_{ecb}/L$ it is possible to express maximum target strength as a function of fish length. Moreover, when using $l_r \approx 1/4$ and $a_r \approx 1/40$ approximations as in Haslett model [6], we can define approximate dependence of maximum value of fish target strength TS_0 on fish length L as:

$$TS_0 = 20\log(L^{3/2} l_r \sqrt{a_r / 2\lambda}) = 30\log L + 10\log f[kHz] - 33 \quad (7)$$

in which approximated value of sound speed $c \approx 1500$[m/s] was used when converting from sound wave length λ to operating frequency f. The $30logL$ relation is evident here due to dependence of equivalent cylinder length and equivalent cylinder radius. Eq. 7 allows to recover L distribution from TS_0 distribution estimated previously by inversion procedure using following formulae:

$$L = 10^{\left(TS - 10\log(f) - 20\log l_r \sqrt{a_r / 2c}\right)/30} \quad (8)$$

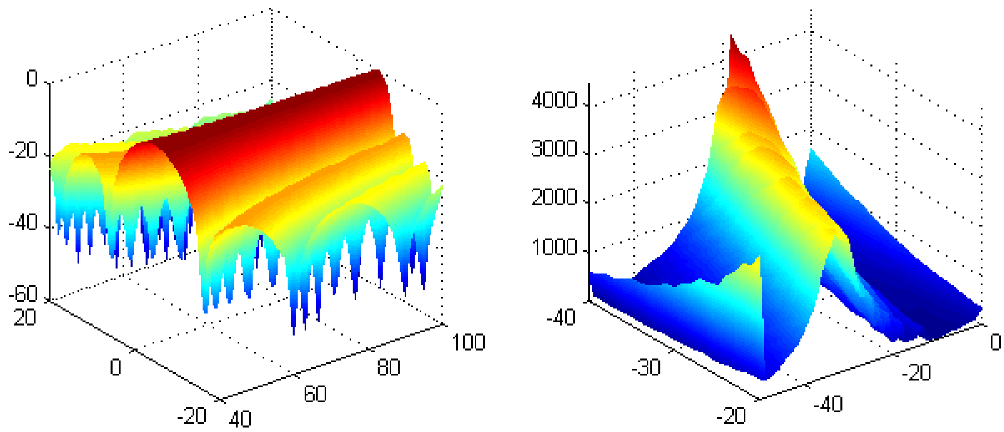

Fig.1 A sample fish directivity pattern assuming tilted cylinder model for its swimbladder calculated for 38kHz (left) and randomly generated conditional PDF of fish directivity pattern assuming normally distributed tilt angle with mean 5° and variance 3° (right)

2. EXPERIMENT

Echo sounder recordings using five Simrad EK60 split beam echo sounders were made from R/V "G. O. Sars" during the Lofoten 2004 survey on the spawning grounds of the North East Arctic Cod. The survey covered the shelf between 500 m to about 50 meters depth on the outside and inside of the Lofoten islands, from 67°N to 70°N, lasting from March 17 to April 5, 2004. The sea temperature in the vicinity of the sites for TS measurements was nearly constant, 6.8 – 7.1°C from about 40 – 300 meters depth. The echo sounders were calibrated by standard sphere calibration methods, both with respect to center sensitivity, pulse duration and split beam target compensation as described in detail in the Simrad EK60 manual. The calibration spheres used were CU64 (18 kHz), CU60 (38 kHz) and the WC38.1 (70, 120 and 200 kHz). All transducers were mounted in one of the instrument keels of the vessel in a maximum packing arrangement, and have all a nominal full half-power beam widths of 7°, except for the 18 kHz, which is wider, 11°. The echo sounders were operated in parallel at maximum pulse repetition frequency (PRF), transmitting soon after the bottom echo was safely received. For the sake of comparability, the transmitted pulse duration was identical on all frequencies, 1.024 ms, only occasionally changed on one sounder for improved vertical resolution. In order to avoid unwanted acoustic non-linear effects, the transmit power on each frequency was set according to recommendations by the Institute of Marine Research and Simrad. All raw data from the echo sounders were stored in addition to the data transmitted to the post processing system used for analysing the survey data, the Bergen Echo Integrator, BEI. Vessel movement, as heave, roll, pitch and yaw was logged from the Seatex MRU 5 to the bottom topography system Simrad EM 1002 at 10 Hz, and to the ping data file in the ER60 echo sounder. Environmental and oceanographic information was obtained from CTD observations (Sea-Bird SBE9).

Trawling on this particular survey was conducted as usual for these surveys, partly on fixed locations, but mostly on registrations for identification of the targets and for biological sampling. The trawls used were the Campelen 1800 bottom survey trawl and the Åkratrawl, a medium sized midwater trawl. Standard biological parameters were measured on all catch samples, individual total length, weight, gonad and liver index, age and stomach content.

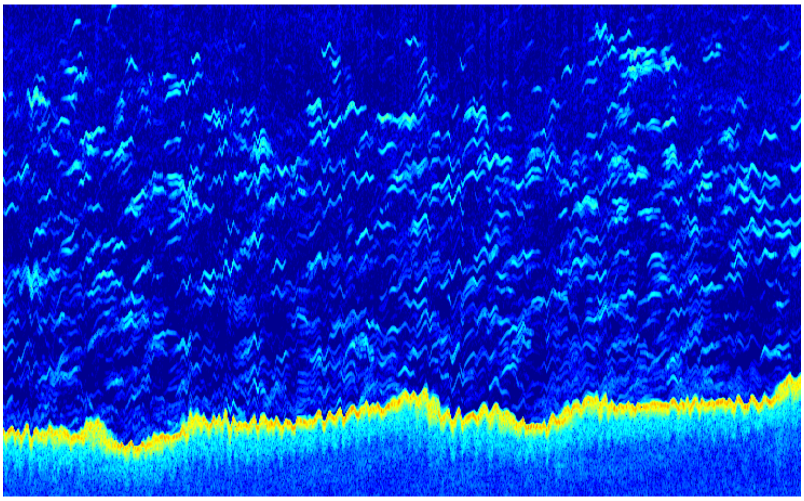

Fig.2 Sample image with registration of clean cod echoes at depth range 100-160m acquired with 38kHz system

3. STATISTICAL PROCESSING

For the purpose of statistical inversion near four thousands echoes of cod (*Gadus morhua*) were extracted from around 4000 thousands of pings acquired with five frequency system (18, 38, 70, 120, 200kHz). The data from 18kHz subsystem were excluded from processing, as the transducer pattern was different than from other subsystems. The data were then processed and compared to cod catches made during the survey. The processing chain is presented in Fig. 2. The tilt angle effect is statistically removed from acoustically measured target strength (show in Fig.2a) by the usage of randomly generated conditional PDF of fish directivity pattern shown in Fig.2b in the form of two-dimensional matrix. The resulting maximum target strength estimate (Fig.2c) is transformed into estimate of fish length by antilogarithmic transformation of the PDF function using Eq.8 and is presented in Fig2d. The results for different frequencies and different assumed swim bladder tilt angles are presented in Figure 3. In all cases it was initially assumed that the swimbladder length for a cod is 0.23 of its fork length [4], and the radius of equivalent cylinder is 1/40 of fish length. For typically observed value of swimbladder tilt angle equal to 5°, the results for all frequencies are in agree with catches histograms.

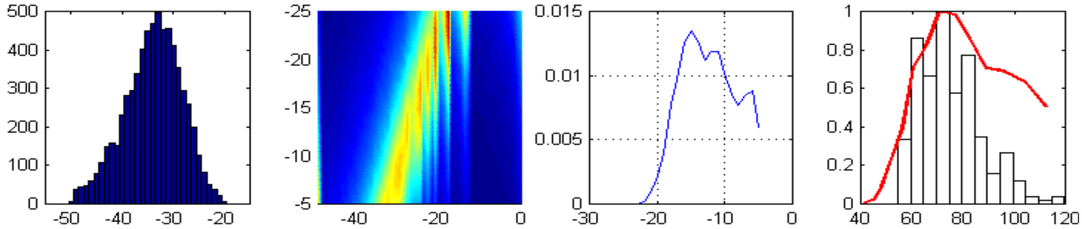

Fig.3 Inversion processing chain: a) acoustically measured target strength TS at 200kHz b) conditional PDF of the fish directivity pattern assuming swim bladder tilt angle equal to 5° - kernel of inversion c) estimated maximum target strength PDF d) reconstructed fish length distribution along with the catch histogram (in cm)

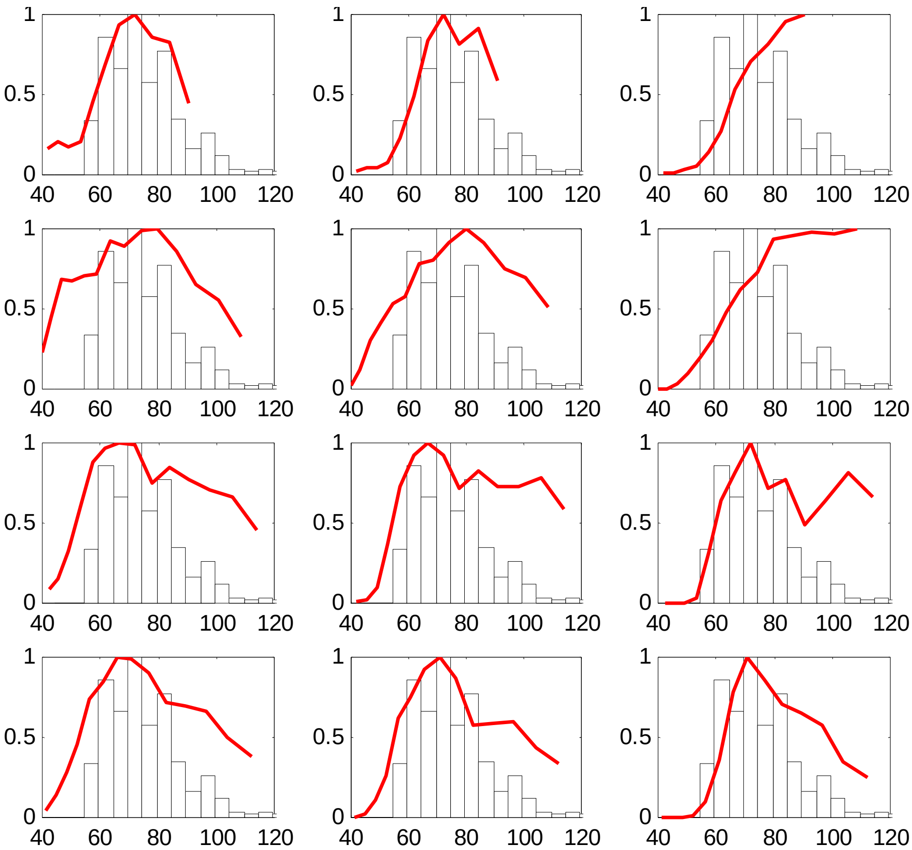

Fig.4 Normalized inverse reconstruction of fish length distribution for the different frequencies recorded (rows represents 38kHz, 70kHz, 120kHz and 200kHz) and for different assumed swim bladder tilt angles (columns represents 2°, 5°, 8°) along with the catch histogram

4. CONCLUSIONS

A system for estimation of fish length distribution from split beam target strength data may consists of two stages: application of fish identification algorithms and statistical processing performed on identified fish species separately. The identification algorithms may use the concept of relative frequency response, which has been proved to be an important acoustic feature characterising acoustic targets [7]. The relative frequency response may be determined from calibrated and digitised data acquired by split-beam system transmitting simultaneously at several frequencies. It allows for splitting of data into categories equivalent to different, but known fish species. The second stage presented in the paper may statistically remove the fish tilt angle effect from each dataset. It results in an estimate of the maximum fish target strength distribution from target strength distribution that is influenced by fish the directivity pattern. The final process converts the maximum target strength distribution into an estimated fish size or length distribution. However, some detailed morphological features of each species are required in both processes.

The species identification algorithm was not used in data processing, as the main aim of the paper was verification of the inversion scheme for data acquired during the survey. A similar analysis is already published for the walleye pollock (*Theragra chalcogramma*) data [8]. The results presented here for cod as shown in Fig. 5 confirms that the higher frequencies are more robust for unknown fish tilt angle distribution as the different cases presented indicate a better similarity to the observed catches. . The data coming from lower frequencies systems as for example from 38kHz system typically used in fishery acoustics may is more inaccurate results when statistics of fish orientation and its directivity pattern is unknown.. This observed effect may indicate that the use of frequencies where the organism size is several times larger than the acoustic wavelength is favourable, and more sensitive for fish orientation. However, when using a multifrequency approach the process of estimating the fish length distributions may be significantly improved by simple error analysis performed between estimates obtained for different frequencies, or by a combined approach.

The results of inverse processing are not perfect. The main reason for this lies in ill-conditioning of inversion scheme and in the problem with determination of the kernel of inversion, largely influenced by unknown fish orientation. If stopping the vessel, or measuring from a stationary system, target tracking may be used to derive direct measures of the tilt angle distribution. Further analysis using this method will later be tried on such data.

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