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IN SITU MEASUREMENT OF FISH TARGET STRENGTH

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ABSTRACT

A technique for performing *in situ* measurements of fish target strength using a single-beam transducer is described. The theoretical approach is based on earlier work by Ehrenberg (1972) and necessitates the solution of a deconvolution problem. The application of some recent numerical techniques to the problem is discussed.

A description is also given of a microprocessor based system which has been developed to extract single fish echoes from an echosounder output in real time. These echoes are processed to produce an echo amplitude probability function which represents the raw data for the target strength analysis technique.

INTRODUCTION

In order to quantify acoustic survey results it is essential to possess reliable estimates of fish target strength. At present these estimates are principally obtained from the results of experiments made on caged fish. These measurements were performed upon fish whose behaviour and physiology, and hence target strength, were influenced by necessarily small fish enclosures, located at operationally convenient depths.

An investigation by the Department of Agriculture and Fisheries for Scotland, Marine Laboratory, Aberdeen (Dunn, in press, Forbes, in press) has demonstrated the variability in target strength estimates which can be introduced by the combination of fish behaviour and the state of swimbladder adaptation. However, even if it is known that fish are adapted to a particular experimental depth, application of the resulting target strength estimate is complicated by the lack of predictability regarding the swimbladder dynamics of free swimming fish and by the unknown behavioural bias introduced by the experiment. Another source of bias in such experiments is the limited range of fish sizes available and hence the need for the assumption of a known target strength dependence upon fish size. For certain species which exhibit a marked seasonal variation in fat content, the timing of the experiment may also be important.

These biasses are substantially alleviated by measuring fish target strengths *in situ*.

IN SITU TECHNIQUES

The essential prerequisites for *in situ* measurement are that individual fish echoes can be resolved and that a representative sample of these fish can be caught for species and size determination. The technique is therefore facilitated by monospecific fish populations which do not exhibit wide size variations (for example, the blue whiting population, *Micromesistius poutassou* (Risso), which occurs to the west of the British Isles). In principle, fish target strength can be calculated from the echoes produced when single fish pass through a calibrated acoustic field. However, it is not possible to determine the position of a particular fish within the acoustic beam of a conventional echosounder and hence the effects of transducer directivity must first be removed from the received echo distribution.

Ehrenberg (1974) has described a direct way of removing transducer directivity using a dual beam system. In this technique a narrow beam transducer detects single fish which occur on the axis (calibrated region) of a wide beam transducer. This represents an elegant solution to the problem which requires no complex mathematical analysis and only modest signal handling capabilities in the echo signal processor. (In common with all *in situ* techniques, a computer is required to perform the necessary real-time signal processing.) The assumption is also made that the maximum target strength occurs when the fish are on axis.

Alternatively, it has been proposed that the effects of transducer directivity can be removed statistically from the received echo distribution. The advantage of this approach is that no modification is required to existing survey equipment and hence it is currently under investigation at the Ministry of Agriculture, Fisheries and Food, Fisheries Laboratory, Lowestoft. The technique has been previously attempted by Craig and Forbes (1969) and Midttun and Nakken (1973); however, their solutions have been shown to produce appreciable uncertainty in the resultant target strength distribution and hence can only serve as an approximation to the true solution.

Whilst the location of particular fish within an acoustic beam cannot be calculated, their position can be described statistically given the directivity function of the transducer and an assumption regarding the fish distribution. The resulting beam pattern density distribution may be convolved with the fish target strength distribution to produce a received echo intensity distribution. The problem in *in situ* target strength measurement is, therefore, to recover the target strength distribution given the other two distributions.

MATHEMATICAL FORMULATION

The problem has been mathematically formulated by Ehrenberg (1972) and is briefly reproduced below:

The integrated squared echo from the i^{th} fish is

$$I_i = CT_i g^4(\theta_i, \phi_i) \qquad I_i \geq \text{Threshold}, \sigma$$

$$= 0 \qquad I_i < \sigma$$

where C is a constant

T_i is the target strength of the i^{th} fish

$g^4(\theta, \phi)$ is the directivity function of the transducer and

θ_i, ϕ_i specifies the angular location of the i^{th} fish in the beam pattern.

Define $A = CT$) with densities p_A (a), p_B (b), where p_B(b) represents
$B = g^4 (\theta, \phi)$) a joint pdf of fish density and transducer directivity (Ehrenberg, 1972; Peterson *et al*, 1976).

The relationship between the density functions of A and B and the density function of I is given by

$$p_I (i) = C' \int_0^{\infty} \frac{1}{a} \; p_A (a) \, p_B \, (i/a) da \qquad i > \sigma$$

where C' is a threshold dependent constant which ensures that p_I (i) integrates to 1. The target strength distribution can be assumed to be contained within a finite interval (0, A_{max}).

Equation (1) can therefore be rewritten

$$p_I (i) = C' \int_i^{A_{max}} \frac{1}{a} \; p_A (a) \, p_B \, (i/a) da \qquad i \geqslant \sigma$$

The kernal p_B (i, a) = 0 for i > a and therefore this is a Volterra integral equation for the unknown function p_A (a).

Equation (2) may be rewritten in a generalized form

$$y\ (i) = \int_{i_o}^{i} h\ (i,a)\ f\ (a)\ da.$$

If h (i, a) and y (i) are known exactly, various direct techniques exist for the solution of the equation. Alternatively, it could be converted to an equation of the second kind which could more readily be solved (Baker, 1974; Linz, 1969). However, when y (i) corresponds to noise contaminated observations at discrete intervals, few reliable solution techniques exist. Others are notorious for producing unstable solutions which are often subject to large errors. Ehrenberg (1972) attempted a solution by approximating the unknown function by a n^{th} degree polynomial:

$$f\ (a) = \sum_{j=1}^{n} \alpha_j a^{j-1}$$

If the original problem is restated as the minimization of

$$R = \sum_{k=1}^{N} W_k \left[\int_{i_o}^{i} h\ (i,a)\ f\ (a)\ da - y\ (i_K) \right]^2 ,$$

where the given data points are $(i_k,\ y\ (i_k))$ $k = 1, N$ and w_k are the weights, substitution for f (a) yields

$$R = \sum_{k=1}^{N} W_k \left[\sum_{j=1}^{n} \alpha_j \int_{i_o}^{i} h\ (i,a)\ a^{j-1}\ da - y\ (i_K) \right]^2 .$$

This is then minimized by setting $\partial R/\partial \alpha_m = 0$ for m = 1, n and the resulting simultaneous equations solved for the coefficients

α_j, j = 1, n.

Ehrenberg achieved some reasonable results using this technique: however, the accuracy of the solution is limited by the degree of the approximating polynomial. With practical data, a solution using greater than a third degree polynomial is extremely difficult to obtain due to the degree of ill-conditioning in the final system of linear equations. It can be demonstrated that a cubic polynomial is insufficient to represent practical target strength distributions.

Radziuk (1977) has described an alternative solution to this type of problem. The unknown density is subdivided into a number of intervals and then low order polynomials are fitted to each section subject to the constraints that the function value and first derivative are continuous at each data boundary. The least squares method described previously is then used to determine all the polynomial coefficients simultaneously, thereby avoiding bias towards any subset of data. This is analogous to the technique used by Payne (1970) for data smoothing.

This algorithm has been tested on several known deconvolution problems and generally the extracted probability density functions (pdf's) have been a good fit to the theoretical curves. The major failing with integral equation solutions, namely their extreme sensitivity to changes in the input data, would not appear to be a problem. The addition of random errors to the input data did not cause wild oscillations in the solution and localized output changes did not propagate throughout the curve.

In practice the final set of simultaneous equations to be solved are frequently ill-conditioned, some with determinants of 10^{-50} or worse. The method is also sensitive to the number and location of the knots: non-optimal knot placement can cause large errors in the output function. Despite these problems, the algorithm has been demonstrated to work satisfactorily and effort is now concentrated on applying the technique to the target strength problem. A Monte Carlo simulation of echo intensity pdf's has been created and using these data it is hoped to fully assess the algorithm and its sensitivity to such things as errors in the beam pattern function.

DATA COLLECTION

The equipment used in preliminary experiments on blue whiting has been described by Robinson (1976). A transducer is towed sufficiently close to the fish aggregations to resolve single fish targets and in order to compensate for any changes in transducer sensitivity the echosounder is calibrated at this operational depth (350 m in the case of blue whiting). The received echoes are amplified in a short range Time Varied Gain amplifier which has an accurate 40 log R characteristic before being rectified and recorded on an instrumentation recorder. To minimize bias against small targets this equipment was designed to have the widest possible dynamic range.

The technique used to extract single fish echoes from the recorded data is crucial to the validity of the reconstructed echo amplitude pdf. In practical conditions of varying fish density it is insufficient to merely accept the echoes whose pulse width does not exceed a predetermined figure at a given threshold. In an attempt to improve on this approach a microprocessor based system has been developed. This equipment performs the following functions:-

1 Digitizes the received echoes, at a 20 kHz sampling rate within a programmable range gate.

2 Measures the rate of change of echo amplitude and stores the points of zero gradient.

3 Selects single echoes based upon:

  a Their pulse width between the echo minima (the maximum allowable pulse width being amplitude dependent);

  b their separation from neighbouring echoes;

  c the ratio of an echo maximum to its adjacent minima.

4 Compiles an amplitude/frequency histogram of the selected single fish echoes.

5 Displays the digitized echo trace on an oscilloscope and clearly marks the position of those targets which satisfy the single target criteria.

All of the above operations are completed in real time for each ping. The programs have been implemented on a Z80 microprocessor and require 2 K of ROM program store and 4 K of RAM, most of which is used as a refresh buffer for the oscilloscope.

Real time display of the selected single targets has proved a particularly useful feature which has enabled the system performance to be rapidly evaluated. The use of modular software has also allowed modifications to the echo selection criteria to be accomplished with relative ease. An example of processed blue whiting echoes is shown in Figure 1.

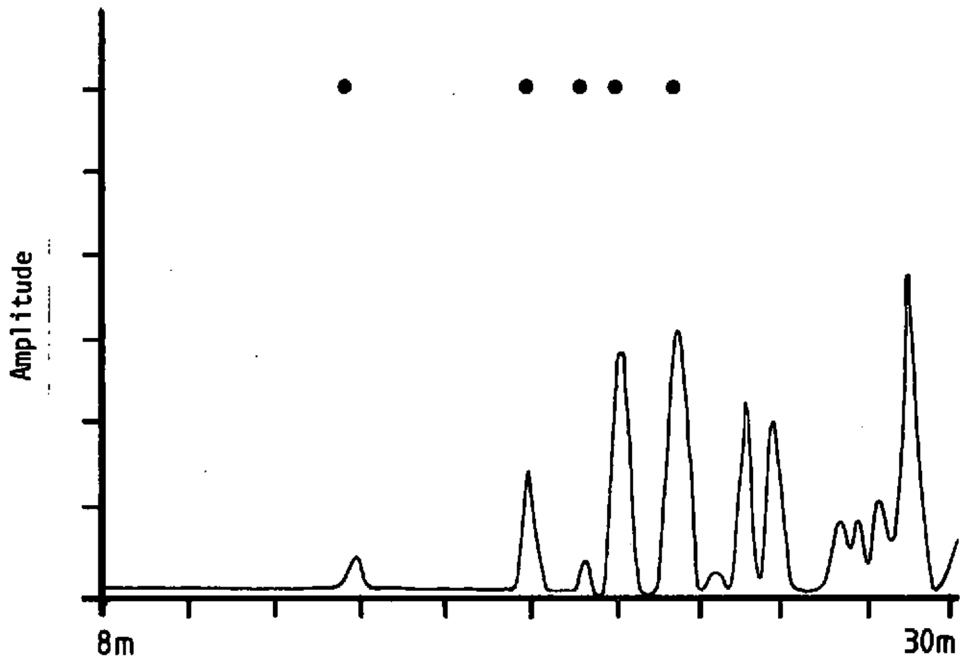

Figure 1 Digitised Blue Whiting Echoes

This trace displays amplitude corrected echoes within the range 8 m to 30 m from the transducer; the dots above the trace indicating the position of selected single targets.

After the required number of transmissions have been analyzed, the microprocessor can be instructed to dump the histogram of received echo intensities to tape. This histogram then forms the raw data for the previously described deconvolution process. The amount of data to be collected in an experiment is determined by the need to accurately reconstruct the received echo pdf and is a function of the transducer directivity and fish density. With the equipment used by MAFF a minimum of 10,000 pings on single blue whiting are required. Typically, this takes two to three hours to collect.

CONCLUSION

In situ techniques represent the only reliable means of estimating the target strength of free swimming fish. Whilst it is recognized that their development is at an early stage and that they may only be useful for certain species of fish, it is thought that their importance merits further detailed study.

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