An attempt to use a broadband acoustic signal for determining the dimensions of Baltic fish*

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Abstract

The resonant scattering of sound by fish swimbladders is described. Broadband acoustic signals scattered by fish schools in shallow water were analysed in order to find the resonant frequencies of fish swimbladders and to determine the fish length. Different spectral techniques were applied in order to discern the resonance peaks in the scattered signal spectrum.

1. Introduction

Species and size identification by the use of remote methods appears to be very promising for both fisheries and biological oceanography. Knowledge of the kind of organism and the depth of its occurrence in the water column enables fish trawls and biological samplers to be improved.

The recent rapid growth in computer techniques has improved objective methods of fish identification. These are based either on the neural network

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(artificial intelligence, directed to the analysis of echosounder images) or on the relationship between backscattering strength and the acoustic wave frequency. The latter group is represented by multifrequency sounding, especially useful in fish and plankton size determination (Holliday and Pieper, 1980; Holliday, 1992), explosions (Holliday, 1972) and deterministic broadband acoustic signals, such as chirp signals with linearly modulated frequency (Bjørnø and Kjaergaard, 1986; Zakharia, 1990). Spectroscopic measurements of sound attenuation in long-distance transmissions of the order of 10 km have also been conducted (Diachok, 1996), although these broadband techniques are rather expensive and need sophisticated equipment. Being harmful to living organisms, explosions cannot be applied in coastal and very shallow areas, although they are performed on a global scale by the U. S. Naval Research Laboratory in the Norwegian Sea, Pacific Ocean and Arabian Sea (Nero, 1996).

It is known that fish with a swimbladder resonate with the incident sound at a frequency > 20 times lower than the optimum frequency for the detection of a non-resonant body of the same size. The resonant frequency is closely linked to the swimbladder radius. Therefore, when using a broadband transmitter, it should be possible to find swimbladder resonances by spectral analysis.

The objective of this work was to test the hypothesis whether it is possible to estimate the length of a fish inhabiting shallow water on the basis of a scattered-signal spectrum.

A broadband source called a boomer, used as a routine tool in seismoacoustic investigations of the sea bottom, acted as transmitter. The spectrum of its signals contains frequencies of the resonant response of the swimbladders of a number of Baltic fish species (cod, herring and sprat). The echoes recorded, originating from fish congregating in dense schools as well as from diffuse organisms, were analysed in order to determine fish sizes.

2. Sound scattering by a fish swimbladder

Since it can resonate, the gas-filled swimbladder is the organ of a fish's body best suited to scattering. For rather low frequencies, of the order of several kHz, the scattering cross-section of the swimbladder is described as follows (Clay and Medwin, 1977):

$$\sigma(a_1, f) = \frac{4\pi a_1^2}{\left[\left(\frac{f_R}{f}\right)^2 - 1\right]^2 + \left(\frac{f_R}{Qf}\right)^2}, \tag{1}$$

where
a_1 – effective radius of the swimbladder,
f – incident sound frequency,
f_R – resonant frequency of the swimbladder,
Q – quality factor of the vibrating system equal to about 5–10 (Andreyeva, 1964).

The resonant frequency is inversely proportional to the swimbladder radius (Clay and Medwin, 1977):

$$f_R = \frac{1}{2\pi a_1}\sqrt{\frac{3\gamma P_0 + 4\mu\frac{3t}{a_1}}{\rho_A}}, \tag{2}$$

where
γ – polytropic exponent,
P_0 – hydrostatic pressure [atm], $P_0 = 1 + 0.1z$, z in metres,
t – thickness of the swimbladder wall, $t \cong 0.2a_1$,
μ – the real part of the shear modulus of the fish flesh; its experimental value lies within the interval $(1-2)\times 10^5$ N m^{-2} (Lebedeva, 1965),
ρ_A – water density.

It follows from eq. (2) that, owing to increasing hydrostatic pressure, the resonant frequency increases as the fish descends in the water column.

During vertical migration, fish are capable of keeping the mass of gas in the swimbladder constant or of retaining its constant volume and shape (Farquhar, 1977). The fish's descent is so slow that this can be assumed isothermal, $pV = \text{const}$. In the first case – constant mass – the resonant frequency is proportional to $P^{5/6}$, in the second case – constant volume – $f_R \approx P^{1/2}$ (Hersey *et al.*, 1961).

Assuming that the bladder volume of a marine fish makes up *ca* 5% of the total fish volume (Clay and Medwin, 1977), the following dependence between swimbladder volume V and fish length L has been derived by means of a regression curve (Klusek, 1990):

$$V = 3.4 \times 10^{-4} L^3, \tag{3}$$

where
L – is expressed in centimetres.

Swimbladders are easily detected by acoustic methods owing to the fact that they resonate. As can be seen from eq. (1), the scattering cross-section at resonance is almost 100 times greater than the geometrical cross-section of the swimbladder. The scattering cross-section of a swimbladder is several orders of magnitude larger than that of a rigid body, and much larger still than that of fish flesh. It is worth mentioning that the resonance frequency is about 25 times smaller than the optimum frequency for non-resonant object detection (Clay and Medwin, 1977).

3. Experimental

Measurements were carried out in October 1995 in the Gulf of Gdańsk from the r/v 'Oceanograf' (University of Gdańsk) by use of a UNIBOOM magnetoelectric transmitter (Institute of Geophysics, Polish Academy of Sciences, Warsaw). The transmitted energy was concentrated in the 600–8000 Hz band and the pulse energy was 300 J.

The signals reflected from the water inhomogeneities and sea bottom were recorded by the equidistant linear array towed behind the ship. Hydrophones were placed in a plastic hosepipe filled with kerosene. Compared to an omnidirectional single transducer, an array gives a better signal-to-noise ratio and good separation from ship noise. Echosignals were sampled by an analogue-digital converter (National Instruments) with a resolution of 12 bits (theoretically *ca* 72 dB dynamics) in the voltage interval +/− 5 V. By using the sampling frequency of 15 kHz, the frequency band of 6000 Hz was obtained. After summation and amplification the echo signals were recorded on disk in digital form and, at the same time, displayed on paper as in the case of a standard echosounder.

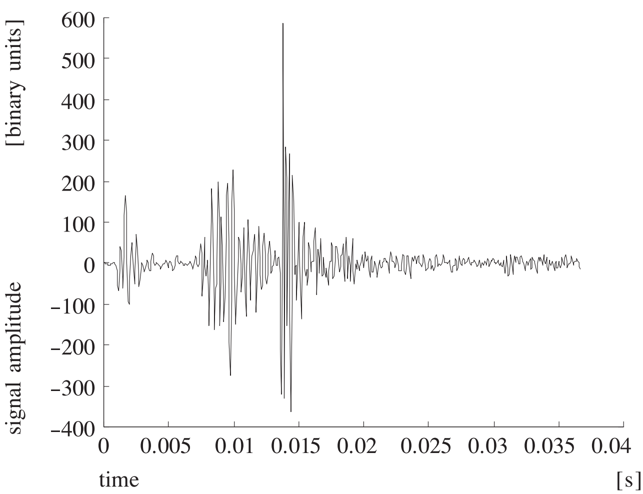


Fig. 1. An example of the echosignal from fish and sea bottom

An example of the received signal is presented in Fig. 1. The y-axis represents the signal amplitude in the binary units of the A/D converter. Three components can be distinguished here: the echo from the school of fish (0.008 s–0.012 s), bottom reflection (0.014 s–0.02 s), and noise. The next figure shows the transformed echogram – absolute values of the scattered signal intensity for 64 consecutive pulses (Fig. 2). The first bottom reflection is clearly seen between samples 105 and 140, the second

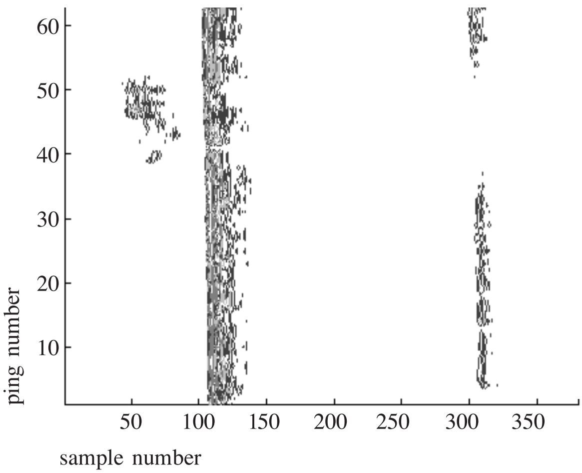
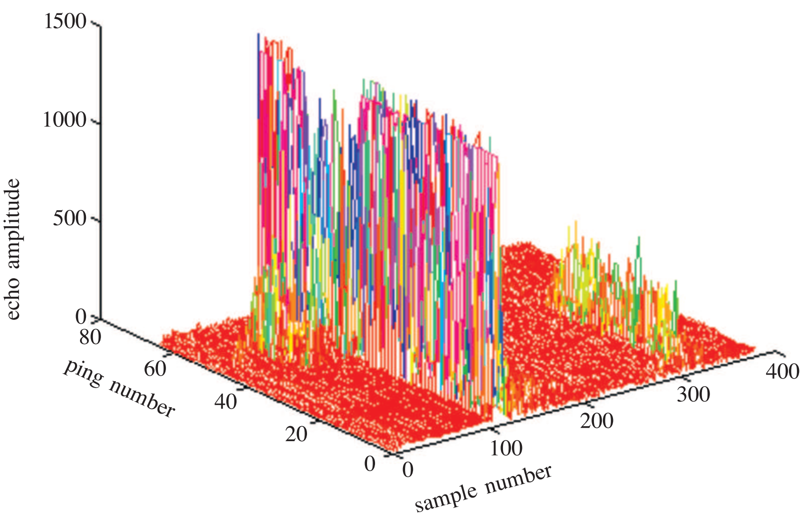


Fig. 2. Absolute values of the scattered signal intensity (after detection) for 64 consecutive pulses in the form of an echogram

bottom reflection occurs in the form of a slight trace above sample 300. In pulses 40 to 51 we see a small school of fish (samples 50–95), which has caused additional scattering and attenuation of the acoustic beam and in consequence, shadowing of the second bottom echo. Fig. 3 displays two different aggregations of fish in a three-dimensional form. In Fig. 3a there is a strong signal reflected by the sea bottom and against its background a dense school of fish persisting above the bottom in pulses 40–51. The fish aggregation introduces the shadowing effect – the first bottom reflection

a



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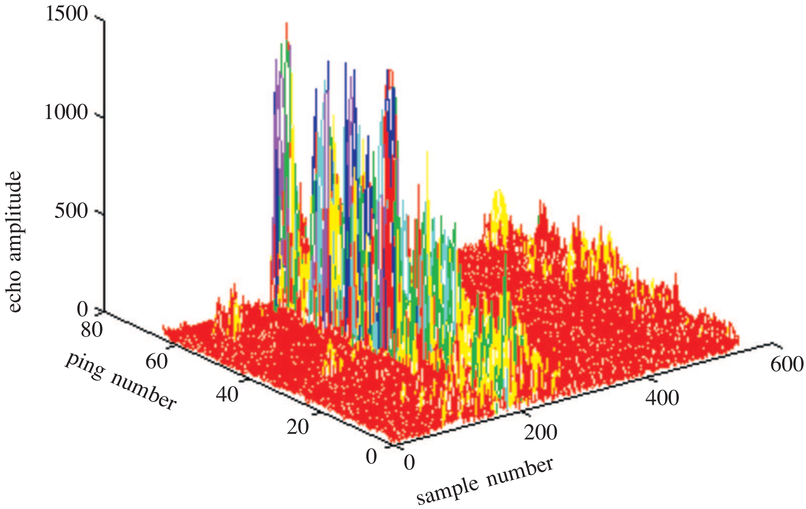


Fig. 3. Examples of various near-bottom fish aggregations and different grades of shadowing effect: large aggregation of fish over the bottom (a), diffuse fish over the bottom (b)

becomes weaker and the second one vanishes. Fig. 3b shows a similar situation for diffuse fish.

4. Signal analysis

The following methods of spectral analysis were applied to determine swimbladder resonances:

- FFT procedures with spectrum component filtration,
- Maximum Entropy Method (MEM),
- wavelet transform using a 'Mexican hat' window.

In the first step of searching for the resonant frequency of the fish swimbladders, the average spectrum was established for various parts of the scattered signal: for the school itself, for the bottom directly below the school, and for the bottom echoes before the school appeared (preceding pings) and after it disappeared (succeeding pings). An example of this procedure is shown in Figs. 4, 5 and 6. They all show the averaged spectrum density of different segments of the echo: from the fish school itself taken from the four strongest consecutive pings (Fig. 4), for the bottom echo directly under the fish aggregation for the same four pings (Fig. 5), and for the bottom echo for the preceding four pings, when the fish school was absent (Fig. 6). The x-axis represents the frequency in Hz, the y-axis the

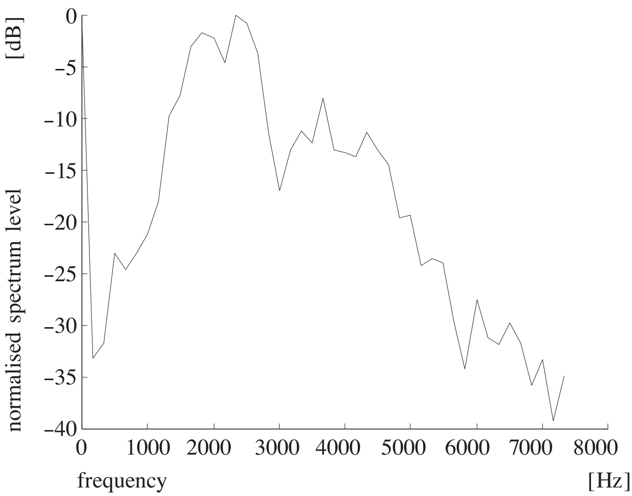


Fig. 4. Averaged spectral density of the echo from a fish aggregation for the four strongest consecutive pings

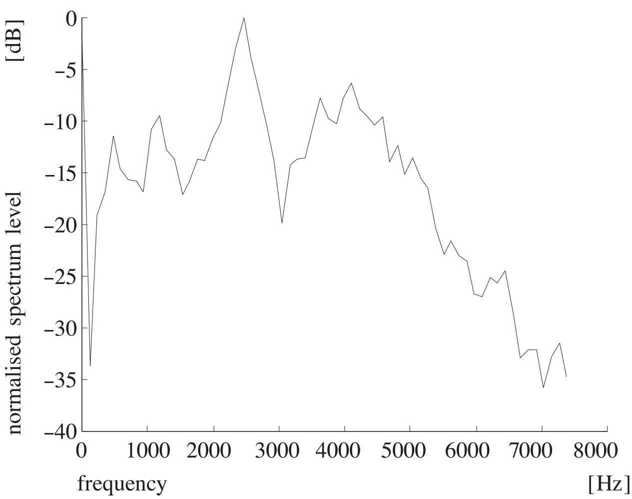


Fig. 5. Averaged spectral density of the bottom echo in the presence of a fish aggregation for the same four pings as in Fig. 4

echo spectrum level normalised to the maximum value in dB. Comparison of these three diagrams shows the bottom echo level at the frequency band 1500–2000 Hz to be decreasing; this is caused by the fish school (Fig. 5), whereas the maximum echo level for the school lies in approximately the same band (Fig. 4). In all probability, this frequency interval is responsible for the resonant scattering by fish swimbladders. Fig. 7 could provide confirmation of this hypothesis. It depicts the time series of one selected

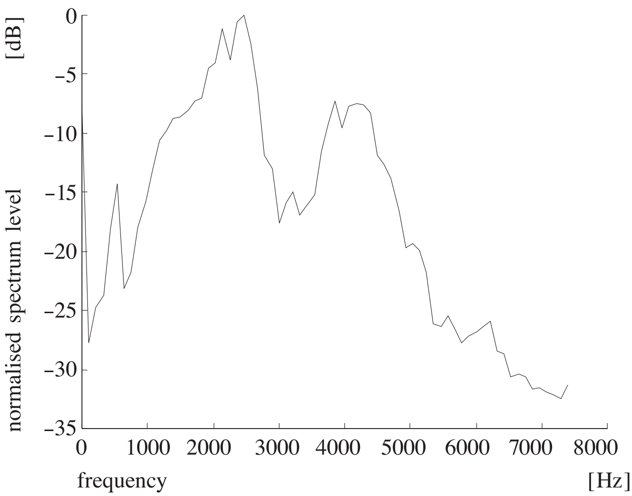
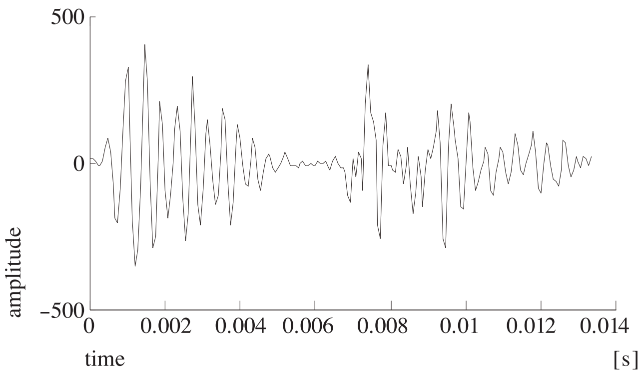


Fig. 6. Averaged spectral density of the bottom echo for the preceding four pings, when the fish aggregation was absent

a



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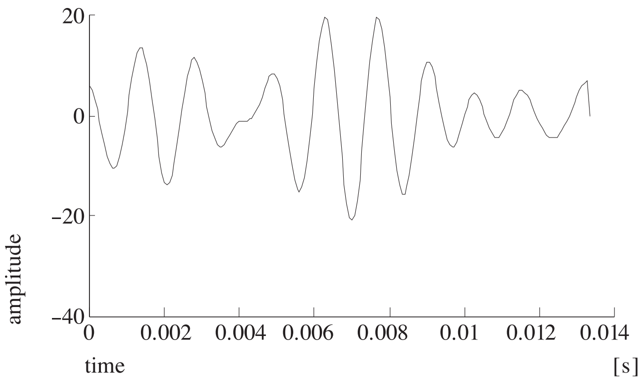

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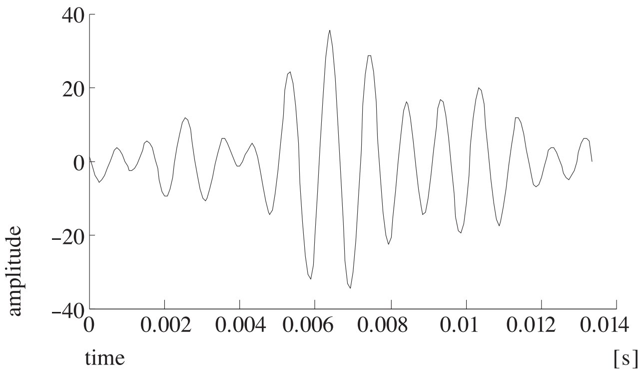
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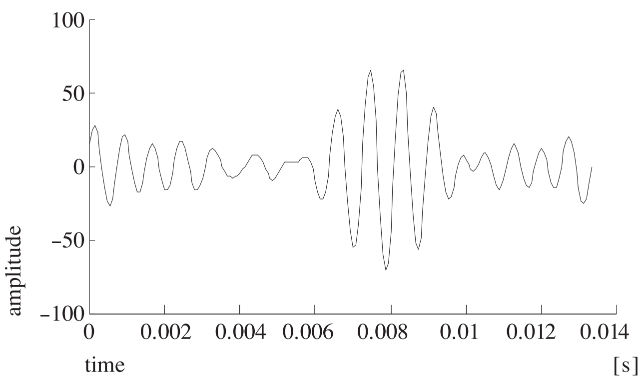
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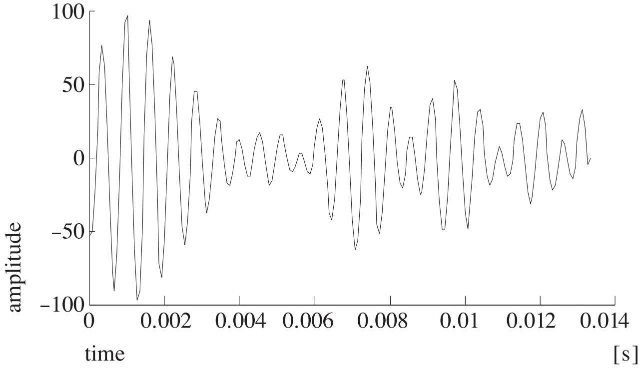
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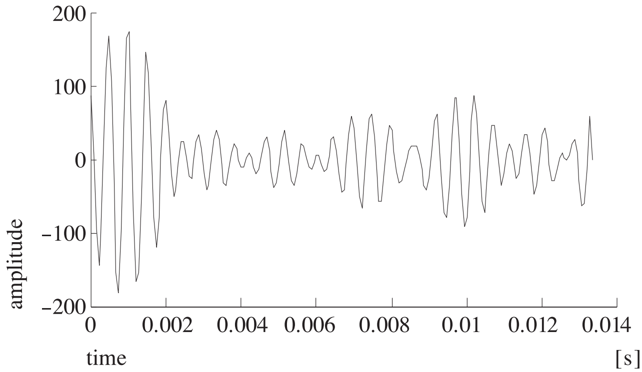
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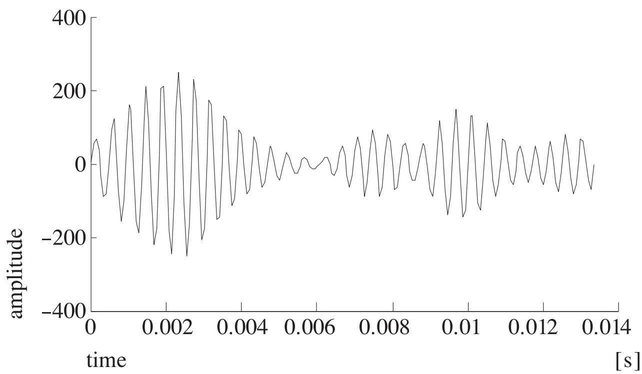
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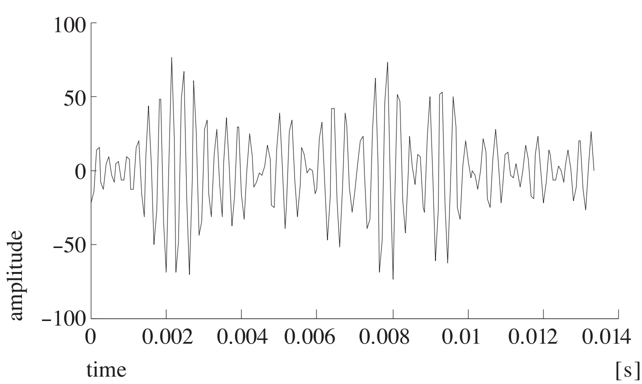
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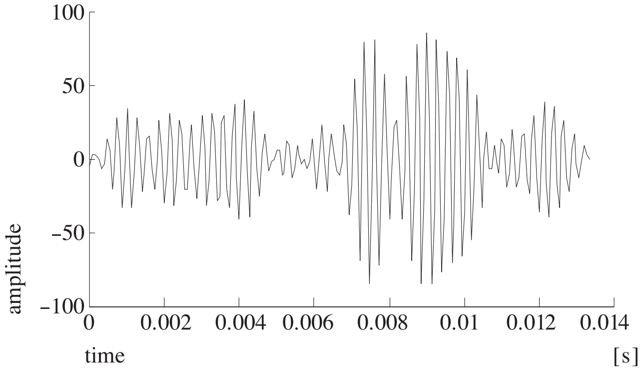

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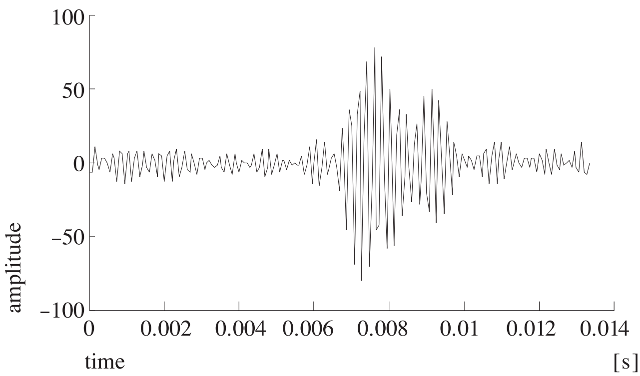

Fig. 7. An example of the echo signal from a fish aggregation and sea bottom (a) and 9 spectral components, filtered in the frequency bandwidth of 1/3 octave for the central frequencies 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000 and 5000 Hz (b–j)

ping spanning both the fish school echo and the bottom echo. Filtration was carried out in a frequency bandwidth of 1/3 octave for the central frequencies: 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000 and 5000 Hz. For comparison, the upper diagram shows the entire echo (complete spectrum). It was found that the maximum ratio of the fish signal to the bottom signal occurs at 1600 and 2000 Hz, which can be interpreted as resonant scattering by the swimbladders. Fig. 8 illustrates the spectrogram of the fish echo and bottom echo for one pulse. For the sake of clarity, the filtered signals have been normalised to the maximum value in each band.

The signal time series for fish and bottom echoes are rather short and do not usually exceed 100 samples (6.67 ms), which limits the resolution

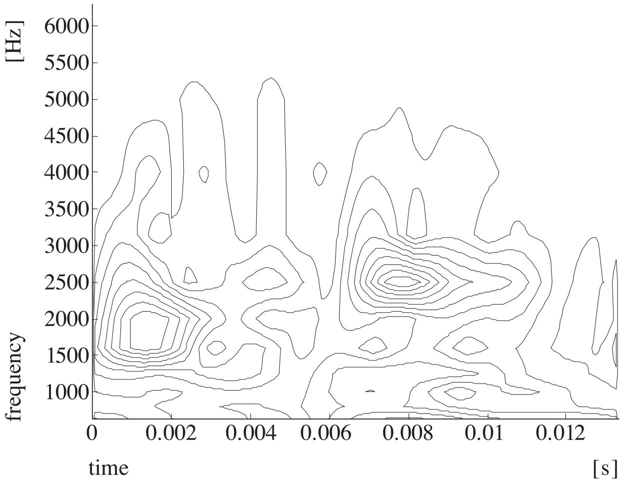

Fig. 8. Spectrogram of the echosignal. Filtered signal normalised to the maximum value in each band

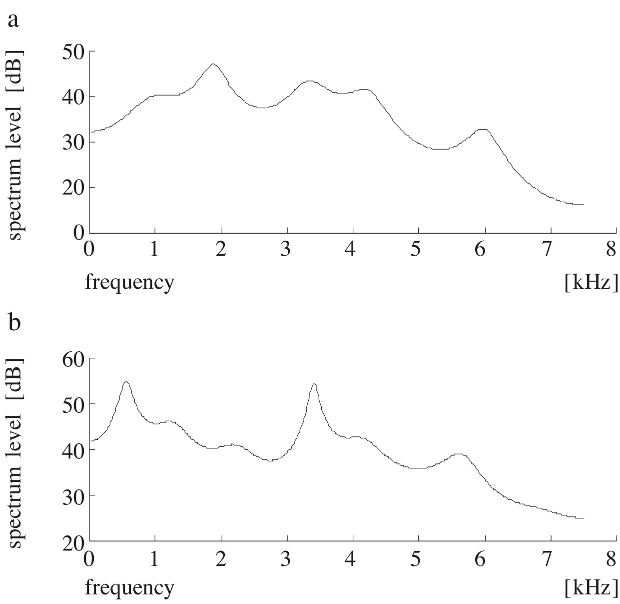

Fig. 9. The results of spectral analysis by the MEM method for the fish echo (a), bottom echo (b)

capability. Other sources of error include the statistical error of the FFT method, the random location of individual fishes in a school, and the instability of the measuring system. In the FFT methods the required series length has to be at least 10 cycles. Applying the Maximum Entropy Method allows this length to be shortened to 3 cycles. The advantage of this method is better resolution and the smoothing of random spectral peaks. The results of spectral analysis by the use of MEM (Fig. 9) are similar to the results of the FFT method presented above, but determining the central of the swimbladder resonance frequency is more accurate. From Fig. 9 $f_R = 1800$ Hz can be determined – it is a maximum in the fish echo spectrum and a local minimum in the bottom echo spectrum.

The third method of the spectral analysis is based on the wavelet transform using the 'Mexican hat' window. The wavelet transform is a set of signal convolutions $f(t_i)$ or $f(x_i)$ with the window function (wavelet) $g(x/a)$, where t_i – times related to the consecutive samples and x_i – depths related to the consecutive samples, a – scale. In a discrete case it is defined as

$$W(a, x_i) = \frac{1}{a} \sum_{j=1}^{n} f_j(x_j) g\left(\frac{x_j - x_i}{a}\right). \tag{4}$$

The wavelet analysed can be represented as a window of dimension a moving along the signal. When the wavelet has the properties of the shape and periodicity of the signal, the absolute values of W reach a maximum.

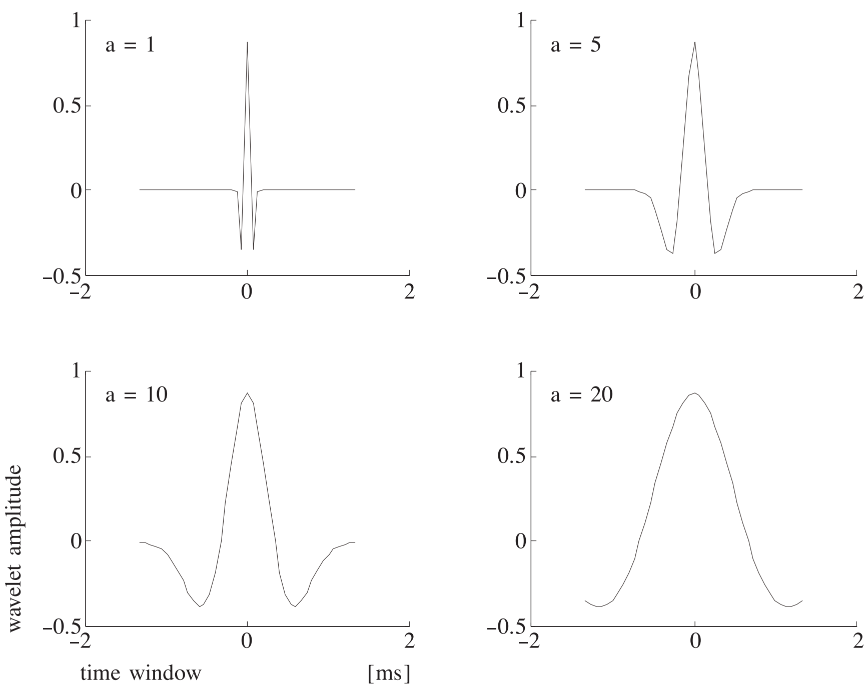

Fig. 10. The shape of the window for different values of the window width a

The form of $g(x/a)$ can be selected depending on the requirements and the data structure. In our case the Mexican hat was chosen:

$$g(x) = \frac{2}{\sqrt{3}}\pi^{-\frac{1}{2}}(1-4x^2)\exp(-2x^2). \tag{5}$$

The shape of the window for different values of a is shown in Fig. 10. The spectrogram for fish and bottom echoes obtained by wavelet analysis with step $\Delta a = 0.25$ is shown in Fig. 11a. For comparison, Fig. 11b displays

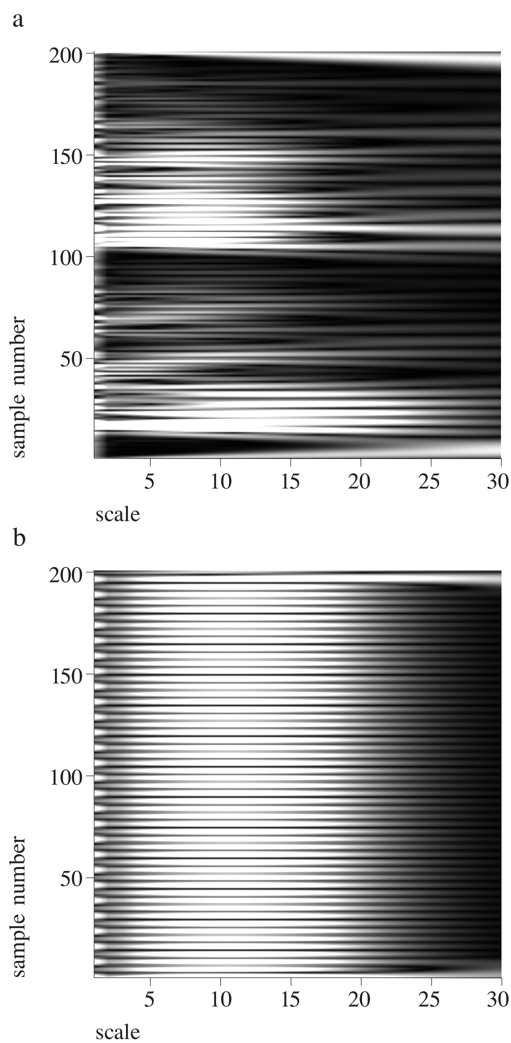

Fig. 11. The result of wavelet analysis with Mexican hat window with a step of $\Delta a = 0.25$ for the echosignal from a fish aggregation and the sea bottom (a) and for a harmonic signal of frequency 2000 Hz (b)

the analogous result obtained for a harmonic signal of frequency 2000 Hz. Analysis of Fig. 11 yields the resonant frequency of the swimbladders $f_R = 1800$ Hz, which is analogous to the result obtained by MEM.

5. Results

Eq. (2) enables the effective radius of the swimbladder to be estimated on the basis of its resonant frequency. Taking the following parameters

$$\begin{aligned}
\gamma &= 1.4,\\
P_0 &= 1 + 0.1z = 1.3 \times 10^5 \text{ N m}^{-2},\\
\mu &= 2 \times 10^5 \text{ N m}^{-2},\\
\rho_A &= 1000 \text{ kg m}^{-3},
\end{aligned}$$

we can calculate from (2) and (3):

$$\begin{aligned}
a_1 &= \frac{1}{2\pi f_R}\sqrt{\frac{3\gamma P_0 + 2.4\mu}{\rho_A}} \approx 0.28 \text{ cm} \quad \text{(swimbladder radius)},\\
V &= \frac{4}{3}\pi a_1^3 \approx 0.095 \text{ cm}^3 \quad \text{(swimbladder volume)},\\
L &= \sqrt[3]{2941\,V} \approx 6.5 \text{ cm}.
\end{aligned}$$

It was highly likely that the detected school of fish consisted mainly of sprats. The estimated value of L is obviously an approximate one because of the limitation of the spectral analysis methods applied and the assumption that a fish swimbladder is spherical in shape. In reality, this shape is more nearly cylindrical or ellipsoidal, and the resonant frequency is somewhat different. Another source of error may lie in our insufficient knowledge of the shear modulus μ of a particular fish species.

6. Conclusions

- A 'boomer', a broadband acoustic wave source, was applied to the detection of resonant scattering by fish.
- In most cases, it is possible to distinguish the fish scattering frequencies in the complete echo spectrum.
- When fish aggregations are not very dense, this method enables the maximum (resonant) frequency of sound scattering by fish school to be estimated and the prevailing fish size to be determined.
- For dense schools of fish the size evaluation is scarcely feasible for a variety of reasons:

  - there is a strong reflection at the water-fish school boundary because of the large contrast in the acoustic impedance – the reflected signal spectrum resembles the transmitted signal spectrum.
  - signals scattered by various swimbladders interact with each other (multiple scattering), so that the resonance peaks broaden and become indiscernible.

- Spectral analysis by the Fourier method yields somewhat limited results because of the short time series (less than 10 ms) and, in consequence, a poor frequency resolution.
- Application of other methods of spectral analysis – the Maximum Entropy Method or the Wavelet Transform – appears to give better frequency resolution and better discrimination of the resonance peaks.

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