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SOME ASPECTS OF KRILL ACOUSTIC SAMPLING

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ABSTRACT

In this paper the coherent structure of the first-order scattered signal is analysed and the influence of orientation distribution form on the signal energy is studied in the case of dense krill aggregation. In large krill concentration case the errors in krill abundance estimation due to neglecting of coherent addition of echoes are evaluated. The importance of consideration of the orientation distribution shape in krill abundance estimation is shown.

INTRODUCTION

One of the main directions of krill acoustics is krill abundance estimate in different parts of the ocean [1]. The evaluation algorithm (adequate description of the relationship between the sound reflectivity and krill abundance) and the perfect krill target strength models are necessary for a valid evaluation.

In particular, widespread linear relation between echo energy and target quantity (echo integration method) is not guaranteed for krill concentration evaluation [1]. Because of the krill tendency to form dense aggregations (densities > 10^2 - 10^3 individuals / m^3 [1, 2]), the evaluation algorithm must also take into account the multiple scattering among the targets, the coherent addition of echoes and „shadowing" effects. All these effects may be important in the case, and disturb the linear relation. Let us note that the influence of the phenomena on the concentration estimation is a research subject in fishery and zooplankton acoustics [3-7]. However, these results cannot be directly applied for krill because they do not consider the typical krill features as, for example, the differentiation of krill individuals in sizes and space orientations [2, 8-10], anisotropic scattering character of individual krill [8], typical krill space distribution [2].

Let us also note that, historically, the validity of krill concentration estimates grew together with an improvement of krill target strength models [8, 10, 11]. Particularly, great attention has been drawn to analyse krill target dependence on krill body orientation and to evaluate influence of this dependence on krill concentration estimation. The influence was studied only in the case when the multiple scattering, interference and „shadowing" effects were not essential. However, similar estimations should be made in cases when these effects are important.

In this paper we investigate the coherent structure of the signal scattered at dense krill aggregation and evaluate the errors of krill abundance estimation due to neglecting the interference phenomenon. We analyse the influence of orientation distribution form on the energy of scattered signal for dense krill aggregation. We also show that the information about krill orientation distribution has to be taken into consideration in krill concentration detection.

THEORETICAL APPROACH

Let us consider backscattering of the echosounder impulse with a length T and an angular frequency ω by the distribution of N immobile krill targets. Let us assume uncorrelation among the targets [6].

Let us also apply the model of randomly-oriented random-length finite cylinder [8] to describe an individual target. Let L_i be a length of i-th straight cylinder krill object (and arc length of uniformly bent cylinder object), $\vec{r}_i = \{x_i, y_i, z_i\}$ be a vector describing the position of this target in the space, and θ_i be the angle between the direction i-th object - echosounder and the plane whose normal is the axis of the cylinder object ($\theta_i = 0$ is broadside incidence). For the bent cylinder the plane is positioned at the midpoint of the axis.

Let the probability density function $W(\vec{r}_i, \theta_i, L_i)$ be presented as [8]:

$$W(\bar{r}_i, \theta_i, L_i) = W_r(\bar{r}_i)\, W_\theta(\theta_i)\, W_L(L_i)$$

and the functions $W_r(\bar{r}_i)$, $W_\theta(\theta_i)$, $W_L(L_i)$ be independent on scattering object number i.

Let us investigate the signal intensity I(t) averaged over an ensemble of the aggregation realisations differed by the position, orientation and length distributions of the krill targets:

$$I(t) = I_{nc} + I_c + I_m^{(1)} + I_m^{(2)}$$

$$I_{nc} = (\rho c)^{-1} \left\langle \sum_{i=1}^{N} p_1(t, \bar{r}_i, \theta_i, L_i)\, p_1^*(t, \bar{r}_i, \theta_i, L_i) \right\rangle$$

$$I_c = (\rho c)^{-1} \left\langle \sum_{i,j=1; i \neq j}^{N} p_1(t, \bar{r}_i, \theta_i, L_i)\, p_1^*(t, \bar{r}_j, \theta_j, L_j) \right\rangle$$

$$I_m^{(1)} = 2(\rho c)^{-1} \mathrm{Re} \left\langle \sum_{i,j=1}^{N} p_1(t, \bar{r}_i, \theta_i, L_i)\, p_m^*(t, \bar{r}_j, \theta_j, L_j) \right\rangle$$

$$I_m^{(2)} = (\rho c)^{-1} \left\langle \sum_{i,j=1}^{N} p_m(t, \bar{r}_i, \theta_i, L_i)\, p_m^*(t, \bar{r}_j, \theta_j, L_j) \right\rangle$$

where t is time, ρ, c - sea water density and sound speed, Re and * denote the real part and complex conjugation of the function. $p_1(t, \bar{r}_i, \theta_i, L_i)$ describes the pressure of the first-order echo signal scattered by i-th target and $p_m(t, \bar{r}_i, \theta_i, L_i)$ represents the pressure connected with scattering of the signal from the multiple scattering by all targets, by i-th target. Here I_{nc} and I_c describe respectively the incoherent and coherent parts of the first-order echo signal intensity. Let us note that attenuation of incident and scattered waves caused by the scattering shall be considered in this term. However, $I_m^{(1)}$ is responsible for interference among single and multiple scattered waves and $I_m^{(2)}$ represents the contribution due to the multiple scattering.

Let us investigate the terms I_{nc} and I_c of signal intensity I(t). To obtain the analytical formula connecting the terms with the main parameters, we will take an approach similar to that used in [5-7]. The application of the approach yields:

$$I_{nc} = (\rho c)^{-1} N \Phi_1 \langle \sigma_{bs} \rangle_{\theta, L}$$

$$I_c = (\rho c)^{-1} N (N-1) \Phi_2 \left| \langle f \rangle_{\theta, L} \right|^2$$

where $\sigma_{bs} = |f(\theta_i, L_i)|^2$ and $f(\theta_i, L_i)$ are respectively the backscattering cross-section and scattering amplitude of target. Here the functions Φ_1 and Φ_2 are dependent on the sounding signal geometry, take into account the „shadowing" effects [6] and have the form:

$$\Phi_1 = \int_V |P_0(t - 2r/c)|^2 \exp(-4\int_0^r \beta(r) dr) D^2(\bar{r}) W_r(\bar{r}) r^{-4} d\bar{r}$$

$$\Phi_2 = \left| \int_V |P_0(t - 2r/c)| D(\bar{r}) W_r(\bar{r}) \exp(2ikr - 2\int_0^r \beta(r) dr) r^{-2} d\bar{r} \right|^2$$

where the function $P_0(t)$ describes the exciting impulse form, k denotes the wave number, k = ω/c, the function D defines the beam pattern form. Here the integration volume V depends on the spatial dimensions of the plankton aggregation and the sounding impulse. The functions $\langle \sigma_{bs} \rangle_{\theta, L}$, $\langle f \rangle_{\theta, L}$ and the attenuation coefficient β(r) (corresponding with „shadowing" effects) are given by:

$$\langle \sigma_{bs} \rangle_{\theta, L} = \iint d\theta\, dL\, W_\theta(\theta) W_L(L) |f(\theta, L)|^2$$

$$\langle f \rangle_{\theta, L} = \iint d\theta\, dL\, W_\theta(\theta) W_L(L) f(\theta, L)$$

$$\beta(r) = 1/2N \langle \sigma_{bs} \rangle_{\theta, L} W_r(r)$$

INFLUENCE OF THE INTERFERENCE OF THE INDIVIDUAL ECHOES

To evaluate the interference effect in the energy investigation of echoes scattered by krill, we can define the function:

$$K_{\mathrm{int}} = \int_{T_r} I_c(t) dt \Big/ \left(\int_{T_r} I_{nc}(t) dt \right)$$

which is the ratio of the energy carried by the coherent impulse part to that of the incoherent part. Here T_r is the length of the scattered pulse received by the echosounder.

To evaluate the K_{int} we assuume the following function representing the krill space distribution:

$$W_r(\bar{r}) = W_0 (1 + \sin(\kappa z))$$

To describe the length and orientation distributions of krill we use the Gaussian function according to the papers [2, 8]. The straight cylinder model is considered for the individual krill target [8]. The functions describing exciting echosounder pulse and echosounder beam pattern form are modelled by:

$$P_0(t) = \begin{cases} P_0 & t \in [t_1, t_1 + T] \\ 0 & t \notin [t_1, t_1 + T] \end{cases}$$

$$D(\theta, \varphi) = \begin{cases} 1 & \varphi \in [0, 2\pi], \theta \in [0, \theta_*] \\ 0 & \varphi \in [0, 2\pi], \theta \notin [0, \theta_*] \end{cases}$$

where in the moment t_1 the exciting pulse begins, θ and φ denote usual angular co-ordinates. We also assume that the value of standard deviation of length S_L is very small compared to the mean length $\bar{L}$: $S_L << \bar{L}$, and that the relation between average angle of cylinder orientation $\overline{\theta}$ and standard deviation of angle orientation S_θ is: $S_\theta \geq \overline{\theta} + w$. The conditions $cT/2 \ll z_{min}$; $kz_{min} \gg 1$; $2k \gg \kappa$; $\kappa L_{agg} \gg 1$; $\kappa \theta_*^2 z_{max} \ll \pi$ (L_{agg} is the characteristic vertical scale of changes of aggregation cross-section form; z_{min} , z_{max} are the distances between the echosounder and the upper and lower zooplankton layer borders respectively) are also supported. Under all presented assumptions one can find the expression for K_{int}:

$$K_{int} = \pi^{1/2} \theta_*^2 \tilde{n} z_{min} z_{max} k^{-2} \tau^{-1} s^{-1} \cdot$$

$$\cdot \frac{\left[\int_0^\infty du \exp[-(u-1)^2 / s^2] u [1 + 2\varphi(u)]^{-1/2} \exp[-\phi(u) / (1 + 2\varphi(u))] \right]^2}{\int_0^\infty du \exp[-(u-1)^2 / s^2] u^2 [1 + 4\varphi(u)]^{-1/2} \exp[-2\phi(u) / (1 + 4\varphi(u))]}$$

where $\tilde{n} = N / V_{agg}$ (V_{agg} - space volume of aggregation); $\tau = cT/2$; $s = 2^{1/2} S_L / \overline{L}$; $\alpha_s = 0.2$ [8]. The functions $\phi(u)$ and $\varphi(u)$ are described by the following expressions:

$$\phi(u) = \alpha_s \overline{\theta}^2 \overline{L}^2 k^2 u^2 ; \quad \varphi(u) = \alpha_s S_\theta^2 \overline{L}^2 k^2 u^2 .$$

Here the condition $k\tau = \pi n$ (n is an integer number), typical of echosounder, is taken into account.

The variation of the coefficient K_{int} with respect to the frequency F ($F = \omega / 2\pi$) is illustrated in Figures 1 (a) - (c). The calculations are performed for the z_{min} = 20 m, z_{max} = 40 m, $\tilde{n}$ = 2000 m^{-3}, $\theta_* = 8^0$, T = 0.0015 s, and for the parameters $\overline{L}$ = 0.04 m, $S_L = 0.1 \overline{L}$. Fig. 1(a) gives the numerical results for $\overline{\theta} = 0^0$, Fig. 1(b) - for the $\overline{\theta} = 22{,}5^0$ and Fig. 1(c) - for the $\overline{\theta} = 45^0$. The curves marked by the circles correspond to the case $S_\theta = 30^0$, by the squares - $S_\theta = 50^0$, by the rhombs - $S_\theta = 70^0$ and by the triangles - $S_\theta = 90^0$.

SIGNAL ENERGY DEPENDENCE ON THE TYPE OF KRILL ORIENTATION DISTRIBUTION

To investigate the influence of the krill orientation distribution form on the signal energy, we can introduce the function:

$$K_e(S_\theta, \overline{\theta}) = \int_{T_r} I^{(1)}(t) dt / \left(\int_{T_r} I_0^{(1)}(t) dt \right)$$

where the functions $I^{(1)}(t) = I_{nc}(t) + I_c(t)$ and $I_0^{(1)}(t)$ are calculated for the arbitrary values of S_θ, $\overline{\theta}$ and standard values $S_\theta^{(0)}$, $\overline{\theta}^{(0)}$ respectively. The coefficient characterises the signal energy difference for different parameters of krill orientation distribution.

Under the conditions presented in the previous section one can yield:

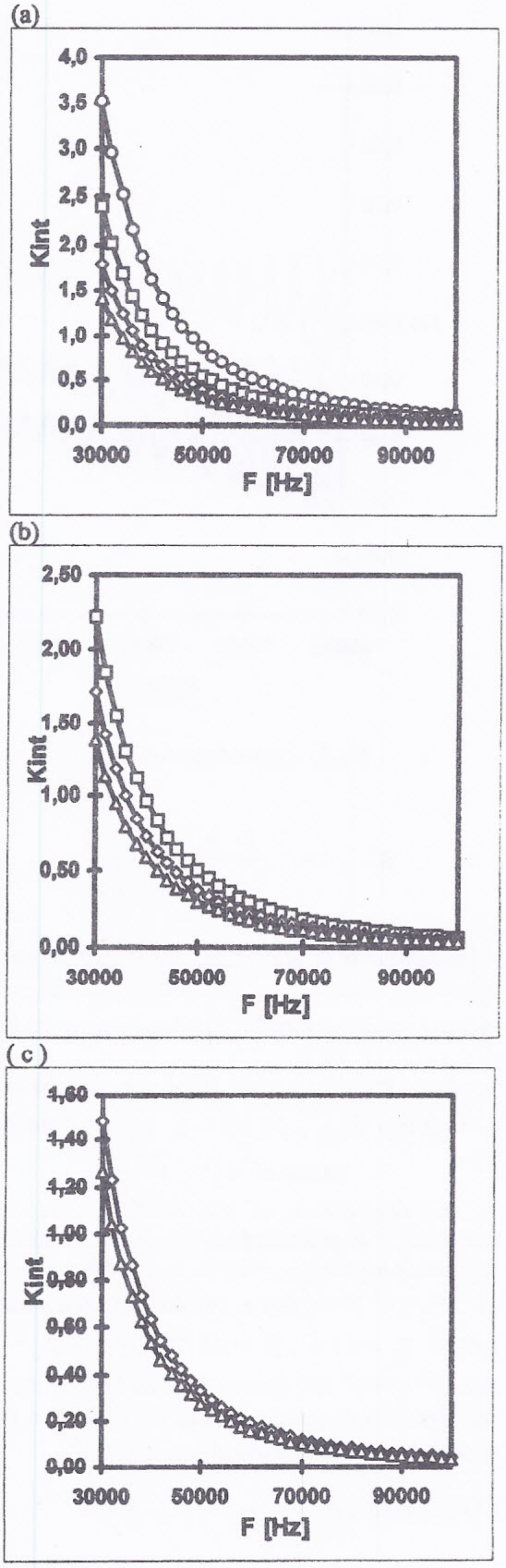

Fig.1. Dependence of K_{int} on F for $\overline{\theta} = 0^0$ (a); $\overline{\theta} = 22{,}5^0$ (b); $\overline{\theta} = 45^0$ (c).

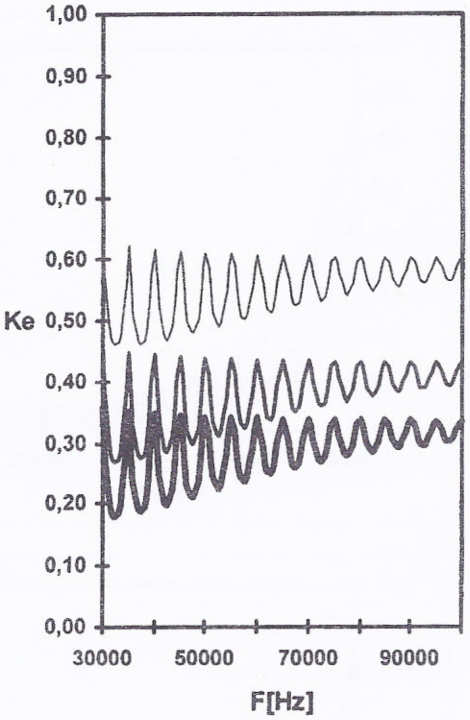

Fig.2. Dependence of K_e on F.

$$K_e = \frac{1 + K_{int}}{1 + K_{int}^{(0)}} \cdot \frac{\left[\int_0^\infty du \exp[-(u-1)^2/s^2] u^2 [1+4\varphi(u)]^{-1/2} \exp[-2\phi(u)/(1+4\varphi(u))]\right]}{\int_0^\infty du \exp[-(u-1)^2/s^2] u^2 [1+4\varphi_0(u)]^{-1/2} \exp[-2\phi_0(u)/(1+4\varphi_0(u))]}$$

where $K_{int}^{(0)}, \phi_0(u), \varphi_0(u)$, are values of functions K_{int}, $\phi(u)$, $\varphi(u)$ for standard values of $S_\theta^{(0)}$, $\overline{\theta}^{(0)}$.

The dependence of the coefficient K_e on the frequency F is presented in Fig. 2. The evaluation is conducted for the $z_{min} = 20$ m, $z_{max} = 40$ m, $\tilde{n} = 2000$ m^{-3}, $\theta_* = 8^0$, T = 0.001 s, and for the parameters $\overline{L} = 0.04$ m, $S_L = 0.1 \overline{L}$, $\overline{\theta} = 0^0$. The values $S_\theta^{(0)} = 30^0$ and $\overline{\theta}^{(0)} = 0^0$ are chosen as standard. In the figure the upper curve corresponds to the case $S_\theta = 50^0$, the middle - $S_\theta = 70^0$ and the lower - $S_\theta = 90^0$.

CONCLUSIONS

This investigation indicates the importance of the coherent addition of the echoes for the broad range of the parameters of the krill aggregations (the acoustic properties of krill targets materials, target geometry form and the type of the space, orientation and length of krill distributions) and of the echosounder signal characteristics (frequency, pulse length, pulse form, beam pattern form). The errors of the krill abundance estimations corresponding to the neglecting of the interference, are evaluated on the base of derived analytical formulae. They reach 70% for lower frequencies (about 30 kHz).

The study also demonstrates that the dependence of the signal energy on the type of krill orientation distribution is significant. So the information about krill orientation distribution has to be taken into consideration in krill concentration detection.

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