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ACOUSTIC AND ELECTRICAL FIELDS OF FISH AND  
MARINE MAMMALS

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## INTRODUCTION

This compilation of abstracts contains material on dolphin communication and echo ranging, as well as on the electrical and acoustic properties of fish. The abstracts on fish reflect the total content of a recent collection of articles entitled Voprosy gidrobioniki (Problems in hydrobionics).

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Burdin, V. I., A. M. Reznik, V. M. Skornyakov, and A. G. Chupanov. Study of communicative signals in Black Sea dolphins. Akusticheskiy zhurnal, v. 20, no. 4, 1974, 518-525.

Experimental results of communicative sound signals in Black Sea dolphins (*Tursiops truncatus ponticus*) are reported. The existence of such signals is not in doubt, but the problem of the signal capacity and of the coding method of information transferred by dolphins has remained unresolved. Classification of signals reveals that they consist of a series of rather monotonous whistles. Hence, we may assume that either the system of communication in dolphins is primitive, or that our recording and analyzing equipment cannot differentiate between coded signal components. The purpose of the article is to isolate the most common group of signals and to determine their nature.

To isolate communicative signals of individual dolphins, the dolphins were placed in separate water tanks interconnected by two-way electroacoustic links. The tests were conducted on three adult females labelled as A, B, and C; C served as the control animal paired with A. A broadband, two-channel recorder was employed to record the signals emitted by dolphins. The acoustic link comprised a hydrophone, a pre-amplifier, an amplifier, and a transmitter. The frequency response characteristic of the line was flat to 15 db within the 0.5-100 kHz range. In the hydrophone - preamplifier - recorder system, the variations never exceeded 10 db within the same frequency range.

The tanks used in these tests were simply two halves of a large pool separated by a 0.5 m thick ferroconcrete partition which was only half a meter lower than the edges of the pool. One half of the pool was in turn subdivided into two smaller tanks.

The experiment began by switching on the electroacoustic line while water was being let out of the tanks until the level was lowered by 1 - 1.5 meters; signals were then continuously recorded for 1 - 1.5 hours. Seven communication tests were performed on pair A and B and six on pair A and C. The tests took place either in the morning hours (between 5 and 7 a. m.) or during the evening (between 10 and 12 p. m.); in the evening, the tanks were illuminated. Incidentally, no difference in dolphin sonic activity was observed between morning and evening.

The device used for the preliminary data processing consisted of the MEZ-41-A two-channel magnetic recorder with a four-fold playback speed reduction. This system also included frequency and amplitude detectors in each channel and a K-12-21 loop oscillograph. The recorded communicative signals were further processed to obtain oscillograms and sonograms of the sounds. The sonograms had a resolution of about 1.6 kHz for nonperiodic signals, and about 100 kHz for periodic signals (with respect to the working band of 0.5 - 100 kHz frequencies). The dynamic range at input was 30 db, and at the output, over 40 db.

During the first stage of investigation all recorded signals were classified according to the type of oscillogram at the output of the frequency detectors. Analysis of oscillograms and listening to recordings in slowed-down form made it possible to differentiate three groups of signals: whistles; individual clicks and series of clicks; and murmuring sounds. Table 1 shows the percentage of signals of the above three types for animals A and B during periods of time when signals were exchanged and when there was no exchange of signals. From the table it is evident that whistles are the most common form of signals.

We can see from the table that clicks amount to approximately 20 percent of all signals. Their classification is given in Table 2.

Table 1

Nature of signals (group number)	GROUP I whistles		GROUP II clicks		GROUP III murnurs	
	quantity	percent	quantity	percent	quantity	percent
Dolphin A						
during exchange	357	85.2	60	14.75	1	0.25
without exchange	1096	84	197	15.85	2	0.15
Dolphin B						
during exchange	205	63.5	110	35	5	1.15
without exchange	6	11	45	84	3	5
Total						
during exchange	560	76	170	23.2	6	0.8
without exchange	1102	82	244	17.7	5	0.3

Table 2

	low-frequency series	medium- frequency series	high-frequency series
duration, in sec	0.1-5	0.2-10	0.1
frequency, in pulse/sec	10	10-100	100-1000
dolphin A, in percent			
during exchange	20	70	10
without exchange	36	56	8
dolphin B, in percent			
during exchange	32	67	1
without exchange	18	82	0

In the low-frequency series, the pulses as a rule contain 4 periods, whereas signals in the medium-frequency series assume the form of an exponential pulse on the oscillogram. Clicks were frequently emitted by the dolphins together with whistles or in response to a whistle from another dolphin. The frequency of pulse sequences usually underwent changes within the series.

It is also clear that dolphins use the same "vocabulary" of sounds during a two-way communication as during a one-way communication.

High-frequency series are generally more specific. These are short and very dense packets of pulses which sound to the ear like low-frequency tonal pulses with a sharply varying frequency of the duty cycle. This permits the assumption that dolphins have some special mechanism for exciting high-frequency series which differs from the similar mechanism for generating low- and medium-frequency clicks.

Some researchers suggest (Lang and Smith, 1965) that the clicks have the purpose of determining the location of the partner in communication. The authors of the present article agree with this hypothesis: in their experiment they have observed long periods of communication between two dolphins through a series of clicks only. The problem however requires further study.

Table 3 introduces a more detailed breakdown of signals, dividing them into eight groups. It presents the results of analyzing in more detail the whistles emitted by dolphins A and B. It should be noted that clicks were the most typical sound emitted by dolphin B, unlike the case of dolphin A whose typical sound is a whistle. Signals in group III are the least typical, observed mostly at the very beginning of the communication experiment. In many cases, murmurs of up to 2-3 seconds in duration included short (0.1 - 0.3 sec) whistles.

Table 3

Type of signals (group)	I	II	III	IV	V	VI	VII	VIII
Shape of signal at output of frequency detector						-		
Duration, in sec	0.5-1.9	0.5-1.8	0.2-1	0.3-1	0.7-2.5	0.1	0.1-0.3	1-5
Frequency, in kHz	6-19	7-18	6-15	7-18	6-19	4-10	4-10	6-18
Dolphin A, in percent								
during communication	46	0.5	11	3.5	5.5	9.5	8	16
without communication	72	0.03	6.4	1.2	2.47	7.7	7.8	2.4
Dolphin B, in percent								
during communication	2.5	40	6.5	18.5	0	27	5.5	0
without communication	0	33	0	0	0	33	34	0

Based on data in Table 3, signals of groups III and IV can be considered as fragments of signals of the first and the second groups. Signals of group III are more typical of dolphin A, and group IV signals, of dolphin B. The duration of intervals amounts to about 10-20 percent of the signal duration. Cases were observed when during an interval between two signals emitted by one dolphin, the other dolphin emitted a short whistle or started a long whistle, as if continuing the whistle sound terminated by the first animal. While groups I - V represent signals of considerable duration, groups VI and VII represent whistles of short duration. These short whistles may either alternate with longer signals of the first five groups or they may be emitted separately within intervals of 0.5-1 second. Cases were observed when two dolphins in communication with each other exchanged only short whistles. Group VIII represents complex signals, for instance whistles consisting of two waves. The longest signal thus recorded by the authors consisted of 11 waves and lasted for 8 seconds.

As a rule, when in communication with each other, one dolphin starts its whistle immediately upon the termination of the whistle emitted by the other dolphin. This peculiar pattern of communication has been corroborated by other researchers, and was also confirmed by oscillograms, obtained by the authors.

Figure 1 shows a typical sector of the oscillogram on which a "conversation" between two dolphins, in this case A and B, was recorded. Roman numbers designate the type of signals emitted by the dolphins.

It is evident from this oscillogram that whistle terminations are superimposed on commencements, i. e., the termination of one dolphin's whistle coincides with the beginning of another dolphin's whistle.

There is a relative monotony in the pattern of sounds which, as seen from Fig. 1, take the form of spikes.

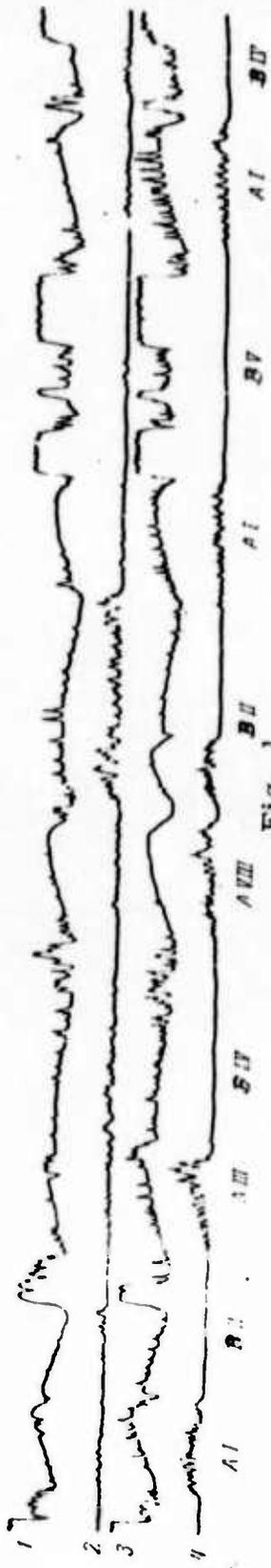


Fig. 1.  
 1 - frequency of the basic tone of dolphin B;  
 2 - signal amplitude of dolphin B;  
 3 - frequency of the basic tone of dolphin A;  
 4 - signal amplitude of dolphin A.



Fig. 2.

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Figure 2 shows those sectors of the oscillograms which were selected from the middle portion of a type I whistle and which contained high-frequency inclusions on the frequency of the second (a, b) and third (c) harmonic.

Figure 3 shows a sonogram of communicative whistles of dolphins A and B, both containing high-frequency inclusions. The harmonic nature of these inclusions is obvious and their frequency is always in the region in the second, third, etc., harmonic of the basic tone of the whistle.

The above pattern allows one to make the following hypothesis, viz., that the mechanism of generating communicative whistles contains a resonator, continuously excited in the resonance frequency, as well as a quick-acting mechanism which damps the basic-frequency oscillations and excites oscillations on overtones.

High-frequency inclusions can have a duration of less than 0.5 millisecond to over 300 milliseconds. Some type I whistles recorded by the authors contained, especially in the initial stages, a strong component at the second harmonic frequency of 5-100 milliseconds. The authors also recorded several signals of 0.5 millisecond duration whose frequency was 25-35 kHz thus corresponding to the second harmonic of the basic tone. These signals had inclusions of up to 200 millisecond duration at the frequency of their second harmonic.

High-frequency inclusions differ considerably from ranging clicks emitted in conjunction with the whistle. Figure 4 shows a sonogram of a type VIII signal, which was accompanied by a low-frequency series of clicks.

The role of high-frequency inclusions has already been studied by other researchers; signals of a two-way communication were detected which contained the characteristic "tail" in the region of the 4-5 Hz frequency.



f, kHz

1 sec

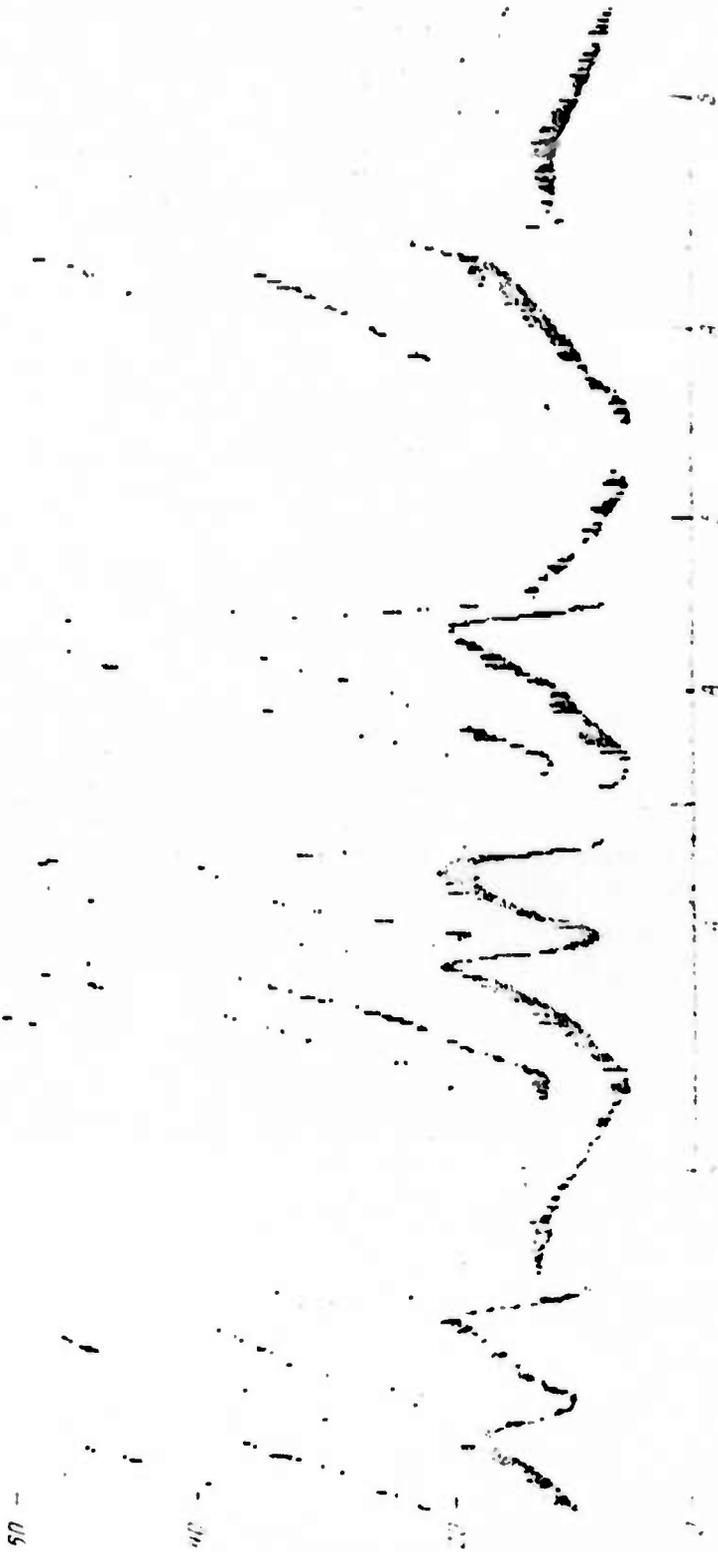


Fig. 3.

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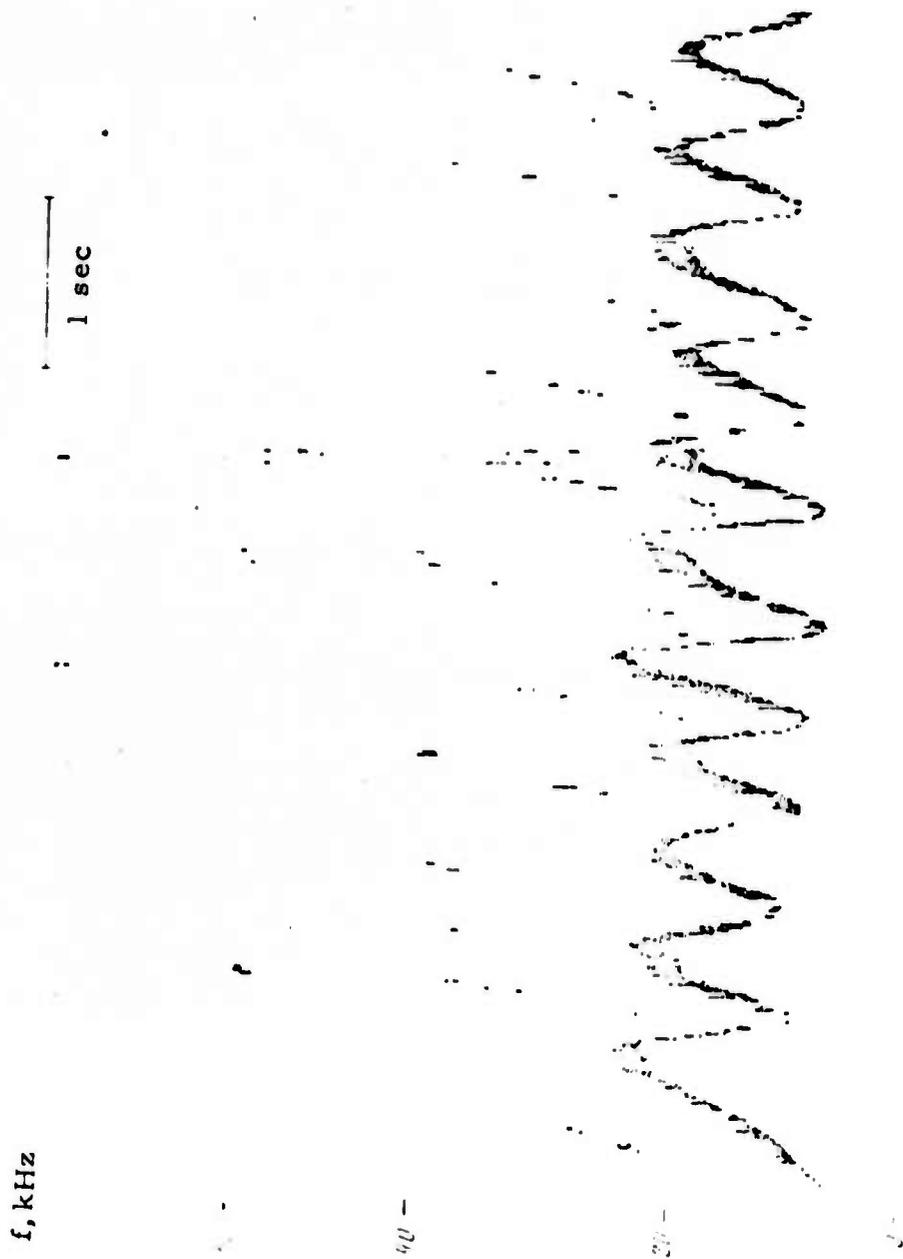


Fig. 4.

Using all the data accumulated on the problem of high-frequency inclusions and their sequences, it is possible to evaluate the transmitting capability of the dolphin-to-dolphin communication channel. We shall assume that the maximum repetition frequency of these inclusions does not exceed 50 Hz. Assuming further that the frequency of every inclusion can correspond to one of the four harmonics, i. e., the transmitted volume of information to a dolphin would be 2 bits, we can deduce the upper limit of the transmitting capacity of the communication channel:

$$C = 50 \times 2 = 100 \text{ bit/sec.}$$

In other words the figure is close to the speed of human perception. Since it is necessary to have a certain amount of excess information to ensure reliable transmission, we may assume that the actual speed of information exchange in dolphins does not exceed 10 to 20 bits per second.

Should a physical model of communication between dolphins be attempted, such a model would be based on the assumption that whistles perform the function of transmitting information between the dolphins. The role of the high-frequency component differs from the low-frequency one. The strong, weakly-damped (in water) and poorly-directional low-frequency component emitted by the dolphin aims at establishing and sustaining contact with another dolphin. The high-frequency component plays the role of transmitting information in a two-way or multiple information exchange. When establishing contact, the reporting dolphin emits a chain of partially overlapping whistles, similar to one shown in Fig. 1. This whistle chain builds a communication bridge to be used by short high-frequency pulses of fine structure to carry its basic information load. Even though the maximum sensitivity of the dolphin's hearing system lies within the range of 40-100 kHz, it is clear that the specific nature (low power and definite direction) of the emitted high-frequency components would make the reception and decoding of information very difficult outside the bridge. The existence of such a bridge permits the dolphins to improve on the conditions of communication through suboptimal space-frequency filtration. The suboptimal space-frequency

filter should have a directivity pattern whose maximum should be oriented toward the source of the signal; the filter should also have a frequency response containing transmission windows for those frequencies which would correspond to the fine structure components of the signal. The dolphin obtains all the necessary data for synthesizing such a filter by extrapolating the characteristics of the acoustic field at the receiving point at the frequency of the basic whistle tone. Several factors are conducive to this extrapolation: the relatively slow changes in basic tone frequency; the almost continuous nature of the emission; the presence of a simple harmonic interdependence among the components of the fine structure.

Giro, L. R., and N. A. Dubrovskiy. The possible role of supracranial air sacs in the formation of echo ranging signals in dolphins. Akusticheskiy zhurnal, v. 20, no. 5, 1974, 706-710.

A model of dolphin supracranial air sacs and their function are examined. An individual sac is presented in the form of a spherical cavity of rubber-like material. Frequency response and transient response of such a cavity are calculated. It is established that in a model of the above type, only low frequency oscillations can be generated, due to resonance of spherical-symmetric waves. These oscillations almost always appear on oscillograms of dolphin signals.

Supracranial air sacs are three pairs of air cavities, each with one inlet and one outlet, encapsulated in muscles. In the model of these cavities, rubber-like material is employed whose elastic constants approximate those of muscle tissue. In rubber-like materials, the velocity of shear-wave

propagation is greater than the propagation of compressional waves, due to the fact that Lamé moduli  $\lambda$  and  $\mu$  obey the ratio  $\mu/\lambda \ll 1$ . It is known that the velocities of shear and compressional waves equal  $c_t = \mu/\rho$  and  $c_l = (\lambda + 2\mu)/\rho$ , respectively, where  $\rho$  is the density of the medium. The compatibility between the muscle tissue and water provides almost unlimited penetration of compressional waves into water. In the case of shear waves, since with respect to water  $\mu = 0$ , the tissue/water interface is soft. The shear wave when reflected from this border, generates compressional waves which propagate either back into the tissue or into the water. The energy of these secondary waves is by two orders lower than the energy of the primary compressional waves; hence, in subsequent calculations these secondary waves are simply disregarded.

Geometrically speaking, the air sacs of the dolphin do not have a regular shape. Experiments have shown, however, that dissipation of sound in an elastic medium (in a low-frequency approximation) does not depend on the shape of the cavity but merely on its volume. Thus, in the model, the cavities have a regular spherical form and retain only the same volume.

First of all it is necessary to determine the frequency response of the given model. We assume that a monochromatic compressional wave strikes the spherical cavity of the air sac model made of rubber-like material. The wave potential  $\phi^0 = M \exp [i(\omega t - kr)]$ , where  $M$  is the amplitude. Wave scattering is considered without taking its absorption in the medium into account.

Wave equations in an elastic medium with the two moduli  $\lambda$  and  $\mu$  and which are harmonically time-dependent take the forms  $\Delta\phi + k_l^2\phi = 0$  and  $\Delta\psi + k_t^2\psi = 0$ , where  $\phi$  and  $\psi$  are the scalar and vector potentials, respectively, while  $k_l^2 = \omega^2/c_l^2$  and  $k_t^2 = \omega^2/c_t^2$ . At the boundary of the cavity, the tangential and normal stresses become zero.

Solutions that satisfy the above equations and the boundary conditions take the form  $\phi = \phi(r, \theta) = \phi^0 + \Phi(r, \theta)$ ;  $\psi = \psi(r, \theta)$ , where  $\theta$  is the angle between the vectors  $k$  and  $r$ .

Since a shear wave does not penetrate through the rubber and into water, its role in the dolphin's signal in water may be disregarded.

The dolphin's signal is usually recorded in the wave zone; thus we shall concern ourselves with the distances  $r$ , where  $k_1 r \gg 1$ .

In the wave zone the expression for  $\Phi(r, \theta)$  takes the form

$$\Phi(r, \theta) = A \frac{ie^{ik_1 r}}{k_1 r} \sum_{m=0}^{\infty} (2m+1) b_m P_m(\cos \theta) e^{im\theta}, \quad (1)$$

where  $P_m(\cos \theta)$  is the Legendre polynomial and  $b_m$  are coefficients determined from boundary conditions. For a spherical wave ( $m = 0$ ) we have

$$b_0 = \frac{j_0(k_1 R) + 2\beta^2 \left[ \gamma_0(k_1 R) - 2 \frac{j_1(k_1 R)}{k_1 R} \right]}{h_0^{(2)}(k_1 R) + 2\beta^2 \left[ h_0^{(2)}(k_1 R) - 2 \frac{h_1^{(2)}(k_1 R)}{k_1 R} \right]}$$

where  $\beta^2 = \mu/\lambda$  and  $j_m$  and  $k_m^{(2)}$  are the Bessel and Hankel spherical functions. For  $k_1 R = 2$  the value of  $b_0$  reaches its maximum, i. e., in this case, we obtain a clearly expressed resonance for spherical waves.

Having the frequency characteristics of the system, we can find its response to the initial echo-ranging pulse. Let us assume that it constitutes a  $\delta$ -pulse (instantaneous impact or discharge) and let us examine this pulse as it is transformed upon interacting with the spherical cavity in the dolphin's muscles.

Duhamel's integral is used to determine the results of this transformation:

$$y(t) = \int_0^t \delta(t-\tau) h(\tau) d\tau.$$

Spectra of the functions  $y(t)$ ,  $\delta(t)$  and  $h(t)$  are linked by means of the convolution theorem  $S_y(\omega) = S_\delta(\omega)S_h(\omega)$ . Because  $S_\delta(\omega) = 1$ , then  $S_y(\omega) = S_h(\omega)$ . Response of the spherical cavity in an infinite medium to the harmonic frequency wave  $\omega$  can be determined from expression (1). Thus the output spectrum may be presented in the following form:

$$S_y(\omega) = S(\omega) = M_1 \frac{ie^{-i\omega r}}{k_1 r} \sum_{m=0}^{\infty} (2m+1) b_m P_m(\cos \theta), \quad (2)$$

where  $M_1$  is amplitude. Response of the cavity to the  $\delta$ -pulse takes the form

$$\Phi(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S(\omega) e^{i\omega t} d\omega. \quad (3)$$

The output signal of the system may either be directly deduced from expression (3) or it may be obtained from analyzing the vibration of the oscillator whose spectral characteristic (response) is determined by formula (2).

Let us now examine the analytical expression for the spectrum of a dissipated signal in a distant zone ( $kr \gg 1$ ) at low frequencies ( $kR \ll 1$ ). From formula (2) we take only one term ( $m = 0$ ) and replace  $k_1$  with  $k$ . Then, taking into account the approximate relations

$$j_0(kR) \approx 1, \quad h_0^{(2)}(kR) \approx 1 + \frac{i}{kR},$$

$$j_1(kR) \approx \frac{kR}{3}, \quad h_1^{(2)}(kR) \approx \frac{kR}{3} + \frac{i}{(kR)^2},$$

we obtain the expression

$$S(\omega) = \frac{M_1 i}{kr} \frac{1}{1 - \frac{i}{kR} \left( 1 + \frac{i}{kR} \right)}$$

The value  $|S^0|^2$  can also be written as

$$|S^0|^2 = \frac{R}{r} M_1^2 \frac{x^2}{x^2 - (1-x)^2 x}, \quad (4)$$

where  $x = kR$ ;  $x_0 = k_0 R = 2\beta$ ; and  $\omega_0 \approx 2c_t/R$  - resonance frequency.

A graph representing the value  $|S|^2 = |S^0(x)|^2 r^2/R^2 M_1^2$  and the function  $x$  is given in Fig. 1. Vibrations of the oscillator with the above

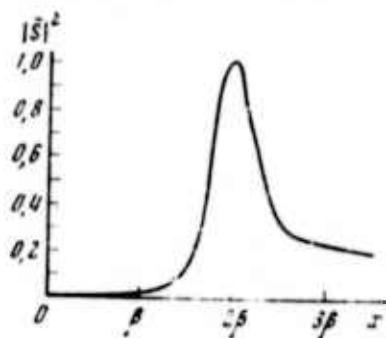


Fig. 1. Value  $S^2$  versus function  $x$ .

frequency response under an instantaneous impact is described by the following function:

$$\Phi(t) = \frac{A}{r} e^{-\epsilon t} \cos \left[ \omega \left( t - \frac{r}{c} \right) \right]. \quad (5)$$

Expression (5) is obtained from formula (3) taking into account the condition  $kR \ll 1$ . The halfwidth of the oscillator resonant curve is determined from formula (4) and equals

$$\frac{4\beta^2}{2-6\beta} \frac{c}{R}$$

A graph representing the function  $\Phi(t) = r/A e^{\epsilon r/c} \Phi(t)$ , where  $\tau = (t - r/c)$ , is shown in Figure 2. The Q-factor of the oscillator is derived from

$$Q = \frac{\omega_0}{2\epsilon} = \frac{2-6\beta}{4\beta} \quad (6)$$

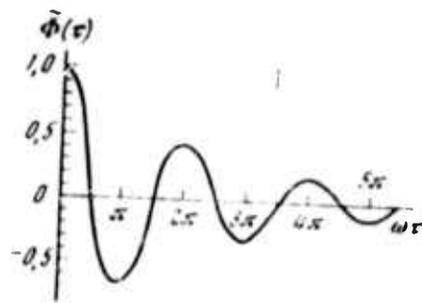


Fig. 2. Response of a spherical cavity to the  $\delta$ -pulse. Values  $\omega\tau$  are on the x-axis, function  $\Phi(\tau)$  on the y-axis.

At  $\beta \ll 1$  the above formula differs only slightly from the formula  $Q = 1/2 \beta$  obtained by M. A. Isakovich in his Obshchaya akustika, Moscow, Nauka, 1973, when dealing with free oscillations of a spherical cavity in an elastic body. With provision for absorption in an elastic medium, the value  $Q$  decreases and equals  $1/(ka + n)$ , where  $n$  is the angle of losses caused by shear deformations (according to Isakovich).

Similar results can be obtained if the spherical cavity is excited from within. In dolphins, such excitation is possible whenever air abruptly flows into or out of the sac.

All the data obtained on the model are applied to dolphin air sacs, as exemplified by two white-sided dolphins. The radii of spheres corresponding to the vestibular, tubular, and premaxillary sacs were 1.5, 0.25 and 1.5 cm, respectively. Resonant frequencies  $f_0$  of the cavities were 0.85-3.2 kHz for the vestibular and premaxillary sacs and 5.1-19.1 kHz for the tubular sac. Based on studies made by G. L. Zaslavskiy (Investigation of echo-ranging signals in dolphins with the aid of a two-channel recording systems, Biofizika, v. 17, no. 4, 1972, 717-720), there is a strong possibility that dolphin air sacs may be responsible for generating low-frequency echo-ranging pulses.

An oscillogram of an echo-ranging signal recorded by a hydrophone mounted on one of the dolphin's sides is shown in Fig. 3. The similarity between the theoretical curve shown in Fig. 2 and the experimental curve in Fig. 3 is evident. The spectrum of the low-frequency component of the dolphin echo-ranging pulse is shown in Fig. 4.

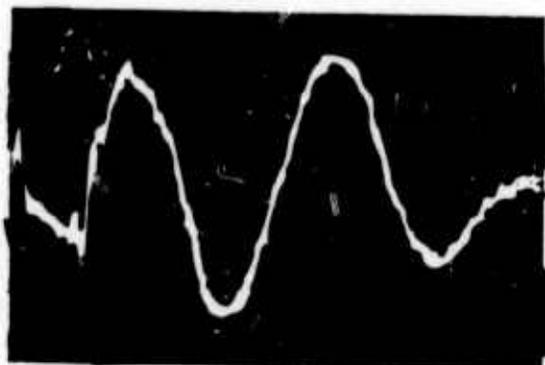


Fig. 3. Oscillogram of the low-frequency component of the dolphin's echo-ranging system.

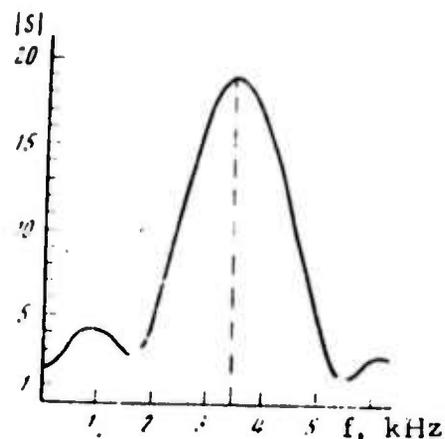


Fig. 4. Spectrum of the low-frequency component of the dolphin's echo-ranging signal. Frequency in kHz is on the x-axis; the modulus of spectral density in relative units is on the y-axis.

The similarity of the low-frequency component spectrum and the spectrum of free oscillations of the model is close. It must however be noted that the width of the real spectrum is slightly greater than that of the model spectrum ( $2\Delta kR = \beta$ ), due probably to the failure to account for absorption. Absorption takes place in both the rubber model and the real muscles and leads to additional energy losses and to the broadening of the low-frequency component spectrum.

Almost all authors using various models of sound emission agree on the fact that air driven from the air sacs into the lungs and back is the main source of energy in generating echo-ranging pulses.

Spectra of the low-frequency component of echo-ranging pulses were also derived on a BESM-6 computer; these were taken at the beginning and at the end of the series of pulses and are shown in Fig. 5.

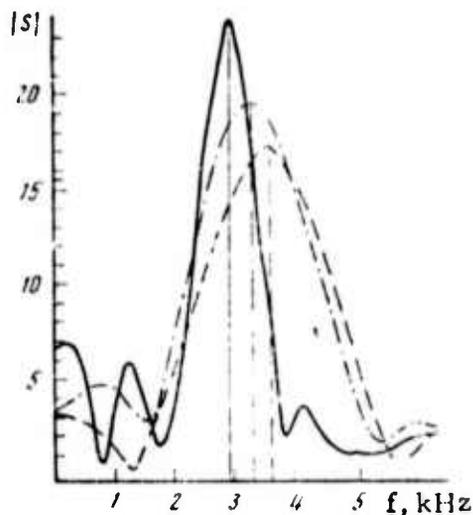


Fig. 5. Spectrum of the low-frequency component at the beginning of the series of echo-ranging pulses is represented by the solid curve. The dashed curve shows the spectrum after 50 pulses, the dash-and-dot line - the spectrum after 58 pulses. Frequency in kHz is along the x-axis; the modulus of spectral density in relative units is along the y-axis.

Protasov, V. R., V. M. Krumin' and V. A. Kuznetsov. Relation of electrical and acoustic signals in fish. IN: *Voprosy gidrobioniki*, Moscow, Nauka, 1974, 5-9.

A certain relationship was established between the electric discharges of weakly electric and non-electric fishes and their acoustic signals, as shown in Figure 1 below.

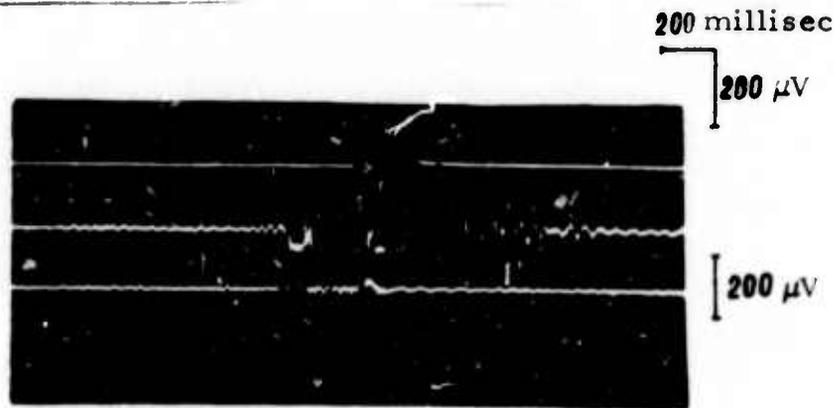


Fig. 1. The upper curve is the acoustic and the lower curve is the electric signal emitted by the loach (*Misgurnus fossilis*) under stimulation.

Investigations were conducted in both laboratory and natural conditions, with both fresh-water and salt-water fish. Apparatus used for recording the signals has been described in several previous articles. Results have shown that electrical discharges are accompanied by acoustic signals (picked up by the submerged barium-titanate hydrophone). The authors suggest that electrical discharges of the fish could actually be secondary phenomena produced as a consequence of electrode polarization, whereas acoustic signals are the result of hydrodynamic effects originating from the movements of the fish. The authors describe some of their experiments with fishes, as well as with diesel engines; experiments with the engines were made in Rybinsk Reservoir and the method is shown in Figure 2 below.

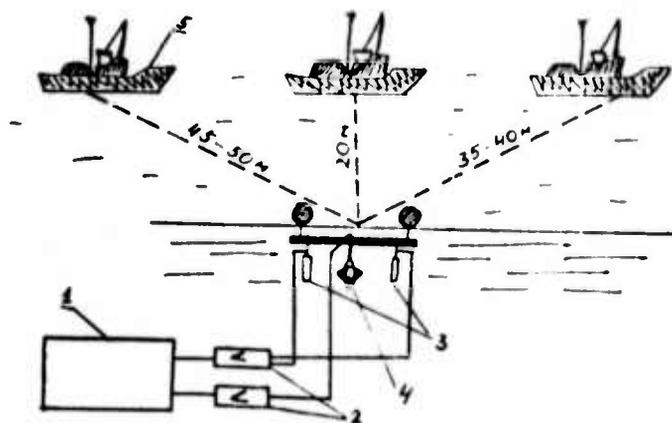


Fig. 2. Diagram of recordings of diesel-powered vessels in the Rybinsk Reservoir.

1- UHER-4200 Report Stereo magnetic tape recorder;  
 2- preamplifiers; 3- laminated electrodes (dipole antenna); 4- barium titanate hydrophone; 5- the vessel whose signals were recorded.

The following conclusions are drawn from these experiments: The emission by fishes of electrical and acoustic signals is synchronous; electrical signals of both biological and nonbiological origin can be recorded by hydrophones not shielded against electrical signals; for bioacoustic signals, shielded hydrophones should be used in conjunction with equipment for electrical discharge recording.

Protasov, V. R., G. D. Kozlov, and A. A. Georgiyev. Magnetic field of the electric discharge of catfish (*Malapterurus electricus*). IN: Voprosy gidrobioniki, Moscow, Nauka, 1974, 10-12.

The authors report on their experiments with recording the magnetic component of the electrical discharge of catfish recorded simultaneously with the electrical signal (by the usual electrode method). To record the magnetic component of the electric signal, the authors employed an induction coil with several thousand turns on a ferrite core, capable of recording an induced alternating magnetic field on the order of  $10^{-7}$  oersted in the audio frequency range.

It is known that catfish electrical discharges are a series of unipolar pulses with amplitude up to 60-65 [ $\mu\text{v}$ ?] and a duration of 1.5 millisecond.

Under the effect of the magnetic field accompanying the catfish discharge, the emf produced in the induction coil is transmitted through an amplifier of biopotentials onto the screen of a CRT. The signal is recorded on film. The induction coil with its static screen was placed outside the aquarium tank holding the catfish. The electrical signal from the electrodes was simultaneously recorded on the second channel of the oscillograph. Figure 1 below shows the block diagram of the simultaneous recording of the electrical and magnetic components of catfish electrical discharge.

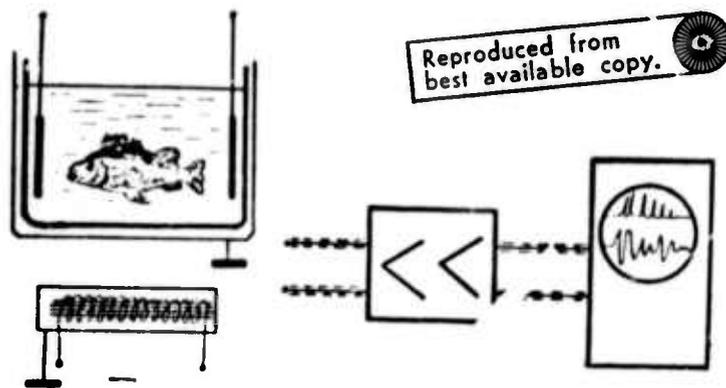


Fig. 1. Simultaneous recording set-up.

It was clearly determined from the above experiments that during the generation of electrical signals by the catfish (exposed to various environmental situations) a pulsed magnetic field is formed in the surrounding space. Figure 2 below shows recordings of the electrical (top) and magnetic (bottom) components of the electrical discharge of catfish.

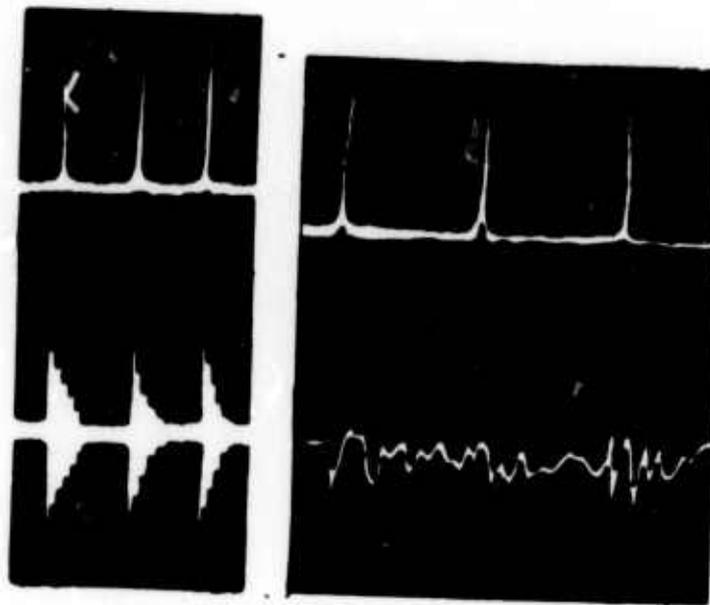


Fig. 2. Recording of the electrical discharge of catfish in two channels: by the electrodes (upper portion) and by either the induction coil or a toroid (lower portions). Duration of a single electrical pulse is 1 -1.5 millisec.

Baron, V. D., A. A. Dankova, and A. A. Orlov. Structure of the electrical organ of the Black-Sea ray (Raja clavata) and an estimation of its energy potential. Voprosy gidrobioniki, Moscow, Nauka, 1974, 13-15.

Rays possess a high degree of sensitivity to electrical fields (~3 microvolt/cm), in addition to having their own electrical organ. The electrosensitive ampullae of Lorenzini are fairly well known as to their structure and functions; however, the structure of the skate electrical organ and the mechanism of generating electric discharges require additional studies. In this article, the authors endeavour to histologically determine the structure of the ray electrical organ and, by using a model, evaluate the magnitude of the summary electrical discharge and the internal resistance of the organ.

The electric organ of *Raja clavata* is located along the vertebral column in the last two thirds of the tail, spaced symmetrically in pairs along the column in the form of long electrical cones separated from each other by a layer of connective tissue. Every cone contains a large number of electrical discs that are perpendicular to the longitudinal axis of the cone. The organ begins with one cone some 5-8 cm away from the end of the tail; the farther away from the tail, the closer are the cones to each other. In the very middle of its total length the organ has a spot not surrounded by muscle tissue, i. e., here, the organ comes in direct contact with the subcutaneous connective tissues. Within the last 2-3 cm of its length, the electrical organ is in direct contact with both the vertebral column and the skin. Unlike the number of cones (whose number can be determined), the number of discs varies according to their density in the cone and the length of the cone itself. Analysis of longitudinal and lateral histological sections performed on the organ permit the conclusion that in the middle section of the organ, there are about 250 discs per 1 cm and that the electrical organ of *Raja clavata* contains a total of approximately 5000 discs.

The summary magnitude of the electrical discharge of the organ was computed as follows: the organ contains 16 columns with discs; the emf of each column is the sum of the emf's of individual discs. Hence, the total emf of the organ can be obtained from the formula:

$$E_{\text{sum}} = \frac{\sum_{i=1}^N \frac{E_i}{r_i}}{\sum_{i=1}^N \frac{1}{r_i}}$$

where  $E_i$  is the emf of the whole column,  $r_i$  is its internal resistance,  $i = 1, 2, \dots$ , and  $N = 16$ .

The value of the internal resistance of a single disc (and hence the value of  $r_i$ ) can be estimated if one assumes that the membrane current density is one milliamperere per square centimeter and the active surface of the disc is  $\sim 3 \text{ mm}^2$ .

Computations conducted by the authors reveal that the total emf of the organ, i. e.,  $E_{\text{sum}} = 1.9 \text{ v}$ , whereby the total internal resistance is about 2 kilohm.

Protasov, V. R., B. M. Basov, and I. I. Pyatnitskiy. On the mechanism of electrical detection in fish. IN: Voprosy gidrobioniki, Moscow, Nauka, 1974, 16-18.

It is known that many weakly electric fish have an electro-generating system and high-sensitivity (up to 0.01 microvolt/cm) receptors. These fish, for the purposes of orientation in the surrounding environment, employ a very specific mechanism of electrical detection which may be summed

up as follows. Periodically, such fish form a dipole electric field around their bodies which undergoes definite change as soon as the field is penetrated by an foreign object whose conductivity differs from that of water. Changes brought about in the electric field lead to the redistribution of potential difference along the body of the fish. In turn, this redistribution is recorded by the electroreceptors of the fish, thus providing information on the ambient space. This mechanism of electrical detection helps the fish to detect various objects within the effective radius of the current field.

The above mechanism of electrical detection naturally is applicable only to those fishes equipped with high-sensitivity electroreceptors on the surface of their bodies. Investigations have determined that certain species of fish have well-developed electroreceptors. Nevertheless, they too are capable of electrical orientation in the ambient space. In the present article, the authors propound a hypothesis on the possible mechanism of electrical detection without the use of electroreceptors.

The electrogenerating system of fish periodically discharges through a certain load R (water). The value R varies depending on the penetration of various objects with different conductivity into the current field of the fish. Changes occurring in the load entail changes in the state of the electrogenerating organ of the fish (as a consequence of changes in the current parameters). All such changes, however small, are recorded by the nerve endings of the fish organs and hence enable the fish to detect objects, which in other species would be detected through electroreceptors.

Basov, B. M. On the use of weak electric fields by the common eel (*Anguilla anguilla*) during migrations. IX: Voprosy gidrobioniki, Moscow, Nauka, 1974, 19-22.

It has been proven that certain fish species are capable of forming weak and strong pulsed electric fields of short duration; the voltage of such fields is about 8 - 10 microvolt/cm at a distance of 6 - 10 cm away from the fish.

This article discusses electric fields generated by the common eel. Investigations have confirmed that the voltage of the field generated by the discharge of a common eel is much higher than the voltages of fields formed by other fishes (perch, gudgeon, pike, mackerel, drum, salmon, etc), being about 40 - 60 microvolt/cm. When at rest, the eel generates no discharges, but aggressive, defensive or alimentary responses are accompanied by characteristic discharges of 2-3 millivolt.

During the spawning period, the eel migrates to the sea and its cerebellum increases, as corroborated by morphophysiological studies. Since the cerebellum and the medulla oblongata of the fish are responsible for the control of electrical organs as well as for the analysis of information obtained from the electroreceptors, the author assumes that, due to the increase in cerebellum during the migration period, the electrical activity in the marine environment also increases. The author refers to an article by S. A. Rommel and J. D. McCleave in Journal of Sciences, 176, 1972, who arrived at similar conclusions with respect to the American eel (*Anguilla rostrata*).

Druzhkin, L. A., and V. R. Protasov. Longitudinal electric oscillations generated by fish. IN: *Voprosy gidrobioniki*, Moscow, Nauka, 1974, 23-24.

The authors propound the following hypothesis: Whenever electromagnetic waves are emitted there always exists a non-emitted electromagnetic field which is referred to as field of induction whose energy is usually greater than the energy of emission. The electrical and magnetic components of the electromagnetic field of emission decrease in inverse proportion to the distance from the emitter. We know that the field of emission rapidly attenuates in sea water. Mathematical analyses have proven that especially in sea water the field of induction must also be inversely proportional to the distance. This field is not an emissive one: it generates oscillatory motion in sea water for a distance that is greater than generated in air.

Fonarev, G. A., V. S. Shneyer, and V. R. Protasov. Electrical fields in the hydrosphere and their possible effect on the behavior of fish.

IN: Voprosy gidrobioniki, Moscow, Nauka, 1974, 25-27.

In recent years it has been established that many salt-water fish respond to extremely weak electrical fields and currents (expressed in hundredth fractions of a microvolt/cm versus a current density of  $2 \cdot 10^{-15}$  amp/cm<sup>2</sup>). The present article deals with the problem of the effect of such fields on the behavior of fish.

The authors propound a hypothesis that solar activity effects fish through telluric currents. It is necessary to note that thus far it has not been determined what is the constant component of telluric currents in seas and oceans measured within the error range of about 1 microvolt/km. Hence, the well-known hypothesis by A. T. Mironov on the dominant role of the constant component in fish migration must be reconstructed. Telluric currents (and fields) are induced alternating currents with different periods and amplitudes and a complex pattern of distribution in time and space. Telluric currents have the same time dependence as magnetic variations; they have an eleven-year cyclicity, the same periods, the same pattern of disturbances, etc. Telluric currents are more intensive in the zone of auroras, in shallow waters, and near shore. In coastal waters, their direction is determined by the shape of the shoreline, but in the open sea their direction is usually latitudinal. The largest telluric fields have been observed during magnetic storms when they reached a magnitude of several tens and even hundreds of millivolts per kilometer (corresponding to a current density  $j \approx 10^{-2}$  amp/cm<sup>2</sup>). Ohm's law determines the relations between fields, currents and water velocity; hence, we may have cases when there is an electric field and no current and vice versa, e.g., surface currents in the ocean have no electric fields. For such currents, in middle latitudes, when  $v = 50$  cm/sec,  $j = 5 \cdot 10^{-5}$  amp/m<sup>2</sup>.

Electrical fields attain their maximum when the current moves from the surface down to the bottom. Then, in middle latitudes, if  $v = 50$  cm/sec, the value of  $E = 20$  millivolt/km. In a large-scale steady current of the Gulf Stream type, there is a permanent system of electrical fields and currents which may play a certain role in fish migration.

Sea waves generate electrical effects of considerable magnitude, with the currents usually flowing along the crests. In middle latitudes, in sea state 6,  $j = 2 \cdot 10^{-4}$  amp/m<sup>2</sup>. Electrical fields are formed in the vertical direction and in the direction of wave propagation. In sea state 6,  $E = 7 \cdot 10^{-2}$  millivolt/m.

Frantov, G. S., V. I. Gordiyenko, and N. I. Kalashnikov. Bioelectromagnetic field sensor and its possible biological application. IN: Voprosy gidrobioniki, Moscow, Nauka, 1974, 28-30.

The article discusses the possibility of designing a sensor for simultaneous reception of the electrical and magnetic components of biosignals. Such a bioelectromagnetic field sensor to be used in studying impedances of living organisms should consist of an induction coil with two sections: section I with  $W_1$  number of turns wound in parallel along the perimeter of the coil; and section II, with  $W_2$  number of turns wound like a solenoid over the basic layer (section I). The winding of section I forms a magnetic antenna, whereas section II acts as an electrical antenna. Since impedance is the ratio of the vector component of electric field strength  $E_i$  to the vector component of magnetic field strength  $H_i$ , the resultant impedance is the value which in the Cartesian coordinate system  $(x, y, z)$  is proportional to

$$\sqrt{\left| \frac{E_x}{H_x} \right|^2 + \left| \frac{E_y}{H_y} \right|^2 + \left| \frac{E_z}{H_z} \right|^2}$$

In practice, this implies that the field components of any given point in space  $(x_0, y_0, z_0)$  must be studied, which would permit gaining new insight into manifestations of the electromagnetic bioactivity of a number of organs of animals. The authors suggest several methods for measuring the relationship between two electrical signals that reflect the electrical and magnetic components of an electromagnetic field. For instance, a device containing two high-speed recorders of the cardiograph type, or selective circuits, or any device that can measure the energy of each of the signals for a definite time separately and then determine their relationship. Bio-electromagnetic field sensors are well suited to study electromagnetic fields of the brain, heart, nerves, or electromagnetic emission of organisms.

Protasov, V. R., and M. N. Ungerman. Electro-physical measurements in the ocean. IN: Voprosy gidrobioniki, Moscow, Nauka, 1974, 31-34.

It is well known that all physical processes in the ocean are closely related to each other and to physical processes in the Earth's crust and atmosphere. In turn, physical processes in the ocean affect biological activity therein, in addition to providing information on ocean resources in general.

Most biological objects show a high sensitivity to electromagnetic fields and also generate such fields themselves. We presume that there is enough evidence to substantiate the hypothesis of the presence of a system of electric currents in the ocean and of its relation to telluric currents and to the Earth's magnetic field and its variations.

High electric conductivity determines the propagation of electromagnetic fields in sea water. Despite a high degree of attenuation, it has been proven that electromagnetic fields can propagate over great distances. Thus it is of importance to consider the fact that the electrical and magnetic

components of the electromagnetic field do not attenuate in the same way. The parameters of the medium determine the differences in attenuation. If a dipole is placed in a conductive medium, the following two formulae describe the intensity of the electrical (E) and magnetic (H) components of the electromagnetic field at a certain distance (b) from the dipole:

$$E = \frac{Mi\omega\mu}{4\pi b^2} e^{ikab} (1 - ikab) \quad (1)$$

$$H = \frac{M}{4\pi b^3} e^{ikab} (1 - ikab - k^2 ab^2) \quad (2)$$

where ka is the wave number of the medium.

Protasov, V. R., M. N. Ungerman, and G. S. Frantov. Application of bionic principles to geological electrical prospecting. IN: Voprosy gidrobioniki, Moscow, Nauka, 1974, 35-37.

The authors emphasize that the electrical organs of fish have many things in common with instruments used in electrical prospecting. Hence, the study of ways how the fish receive signals and detect objects should be of importance for designers of prospecting instrumentation. Of particular interest should be the ability of the fish to emit, either simultaneously or successively, electromagnetic and acoustic vibrations. Another problem is information processing by the fish: comparison of signals received from different receptors is imperative for the complex electroacoustical evaluation of the ambient environment.

No concrete data are given.

Neproshin, A. Yu. Methods of detecting biological sounds against a background of ocean noise. IN: Voprosy gidrobioniki, Moscow, Nauka, 1974, 38-41.

The operation of passive fish-finding sonar depends on the ambient noise whose parameters may fluctuate over a wide range according to prevailing meteorological conditions. In the spectrum of acoustic frequencies, the ocean noise distribution is rather uneven: low-frequency noise in the range up to 10 Hz reaches the highest level; with increased frequency (attenuation - 6 decibels per octave) the sound pressure level drops.

When recording ocean background noise on magnetic tape recorders, there is always a problem in simultaneously recording all signals within the entire frequency range, since the drop in the ocean noise level at the 50 Hz and 10 kHz frequencies exceeds 40 decibels.

In bioacoustic investigations it is important to record spectral noise levels and signals in their natural relationships; hence the receiving and recording systems must be of very high complexity to cope with this problem. However, the recording methods in fish-finding sonars can be simplified.

To detect a signal against the background of ocean noise with a non-uniform spectrum, the converter should have a cascade-type filter which will "whiten" the spectrum. The filter will attenuate frequencies with high noise levels, but will not affect them whenever the noise level is low. Its conversion factor would take the form of

$$K = \frac{1}{N(\omega)}$$

The authors used a Uher Report-400 Stereo taperecorder (input resistance  $R_{bx} = 3 \cdot 10^3$  kilohm, capacitance of the converter - 5000 picofarad).

The spectral characteristics of a hydrophone are shown in the figure below, when the characteristics are matched with the amplifier ( $R_{bx} = 100 \text{ Megohm}$ ) and when the hydrophone is loaded at a low ohmic resistance ( $R_{bx} = 3.9 \text{ kilohm}$ ).

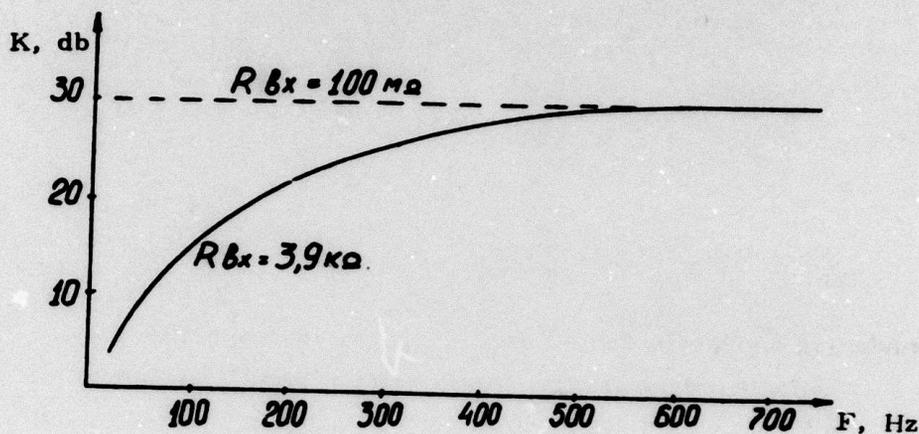


Fig. 1.

From the figure one can see that beginning at about 500 Hz and proceeding into the region of lower frequencies, the attenuation is uniform, i. e., 6 decibels per octave; at frequencies above 500 Hz both curves merge.

Neproshin, A. Yu. Detection of acoustic signals of salmon from selected spectral characteristics. IN: *Voprosy gidrobioniki*, Moscow, Nauka, 1974, 42-45.

Designs for passive fish-finding sonar should always consider the type of fish involved. It is necessary to account for certain definite peculiarities so that only such acoustic signals can be selected that are stable in space and time, i. e. at any time and in any environment. In case of the salmon, clicks and irregular drum-type beats are the most typical steady signals. This is confirmed by observations of Pacific salmon (genus *Onchorhynchus*) from the third to the fifth stage of development, and in *Salmo*

gardniery and *Salmo irrideus* in the earlier cycles; it is conceivable that Pacific salmon may also generate these signals in their earlier stages. Other sounds emitted by the salmon, such as drum beats in series, creaking (squeaking), rasping, etc, have been traced to the fresh-water environment only, i. e., they are related to the spawning or the pre-spawning period.

Spectral analysis of sounds emitted by *Oncorhynchus nerka* shows that when designing a fish-finding sonar specifically for the detection of red salmon, the pertinent spectral sector is from 800 to 1500 Hz which is stable over the whole range of classification characteristics; another stable criterion can be served by the spectral sector of 80-100 Hz. All these spectral sectors would have to be shifted either into the lower frequency or higher frequency region whenever the sonar is designed for other types of salmon.

Neproshin, A. Yu. Effect of own ship's noise on the operation of a passive fish-finding sonar.

IN: Voprosy gidrobioniki, Moscow, Nauka, 1974, 46-49.

Recording of acoustic signals emitted by fish against the background of noise made by engines, compressors, refrigerators, etc, has already been discussed by a great number of researchers. Among other things, it has also been emphasized that acoustic signals of certain fishes can be satisfactorily recorded despite the noise.

The present article reports on the results of recording and analyzing own ship's noise. The ship in whose vicinity the noise problem was studied was of the SRTM-800 type (a freezer-trawler). The present article concerns tests with the medium-size trawler-freezer Vera Belik of Sakhrybprom (Sakhalin Fishing Industries). The author shows the distribution of the spectral level of hull structure noise in the area of certain frame lines. Measurements of noise under way were not included in this experiment.

Measurements were taken in deep water under good weather conditions (sea state 2) while the ship was allowed to drift. The sea noise level during silent routine was measured by a calibrated hydrophone and was then recorded on magnetic tape. Hydrophone depth varied from several meters to several dozen meters. As a supplementary test, the auxiliary engine (6 NDV-24 - 6 cylinders, 750 rpm) was started. Noise levels were measured along the entire starboard and port sides every 2-3 meters, beginning with frame No. 3 (on the starboard side at the bow). During the measurements the hydrophone was 1 meter away from the ship and 2 meters deep. Data recorded on magnetic tape were analyzed by an ultrasonic frequency spectrum analyzer (through 1/3 octave filters). Finally averaged spectral characteristics were compared with the sea noise spectra (Knudsen spectra).

As a result of these tests, the following conclusions are drawn:

1. For high-speed ship machinery, it is typical that levels are elevated in the spectrum from 500 Hz up.
2. The low-frequency sector of the hull noises has low levels in the area of the 29-30 frame line (where the sonar antenna is usually placed) and may be disregarded. Interfering noises in the region up to the 29-30 frame line for the frequency range of 50-800 Hz are determined by the sea noise. To eliminate the effect of the high-frequency portion of the spectrum with high noise levels, it is advisable to use an upper frequency cutoff filter at the boundary frequency of 1 kHz.
3. In those cases when the bioacoustic signal is in the range of 800-5000 Hz, the antenna of the fish-finding sonar should be in the area of the 10-11 frame line where the engine noises at sea state 3 exceed the sea noise by 2-5 decibel.