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HYDROACOUSTIC SIGNALS EMITTED BY BELUGA (DELPHINNAPTERUS LEUCAS) FOR DETECTING AND ECHOLOCATING THE SUBMERGED OBJECTS

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Abstract - The results of measuring the beluga's signals used by it for detecting and echolocation of the target presented to it at a distance of up to 600 m are given. The analyses of temporal sequences of the acoustic signals generated by the beluga has shown that for detecting the submerged object the animal uses series of impulses generated at the interval of $\Delta t < 5$ ms, emitted in a wide sector (up to 36^0), then it executes scanning by narrow-oriented solitary impulses with Δt up to 200 ms and for finding the target it illuminates it by a series of such signals. If the target is complicated (small depth, long distance), then for detecting and echolocation the beluga uses series of impulses of up to 0.6 c duration with the time-impulse modulation.

Probably, the first studies of hydroacoustic signals emitted by the beluga were conducted yet in 1949 [1]. Discussion on probability of detecting the distance up to the submerged object being echolocated by the dolphin , while using the measurements of time intervals between the acoustic impulses emitted by the animal, has been held for more than 30 years already. Really, if C - sound velocity in water, t_i - time between signal emission and the reception of the echo, then the distance up to the echolocation object is $r = Ct_i / 2$. Firstly, the supposition on the fact that the echolocation system of bottlenose dolphin works as hydro-sounder with the impulse modulation, was made in paper [2]. Basing on the notion that the dolphin has to learn each next impulse upon accepting the echo of the previous one, the time interval between the impulses Δt should satisfy the condition $\Delta t > t_i = 2r / C$. Experiments have shown that the bottlenose dolphin indeed keeps Δt in such a way that the echo-signal comes during the interval between the impulses emitted by it [3]. Bio-acoustic sonar of the beluga generated as a result of its adaptation to the life in the Arctic areas, characterized by the increased reverberation effects, differs of the other dolphins' sonar. In paper [4] it was noted that for echolocation of the target at distances from 40 up to 80 m the beluga started the hydro-sounding signal from $\Delta t = 30$ ms increasing up to 60 ms, and at the distances of 80-120 m the intervals between the impulses varied from 200 to 220 ms. At all distances the bottlenose dolphin had Δt more than t_i . It is likely that for the first time in paper [4] it is stated that for detecting the target the beluga uses a series of impulses produced, similar to solitary impulses of the bottlenose dolphin, with the time intervals of $\Delta t > t_i$.

Below it is analyzed temporal sequences of the acoustic impulses corresponding to the echolocation signals generated by the beluga from the cage at detecting and echolocating the targets presented to the animal at different distances, as well it is concerned the adaptation of bio-acoustic sonar of specially prepared beluga for solving the tasks of search and echo-sounding the submerged objects at large distances. Measurements were carried out in summer hydrological conditions in the shelf zone of the Sea of Japan. The echolocation signals of the trained 13-years old dolphin (male) were studied. The animal situated in the cage performed the echolocation of a metal cylinder presented at fixed distances and depths. The sea depth in the place of cage location was 8 m and with the distance along the route it was increasing up to 24 m. The beluga head's position during the echolocation was fixed at the depth of 1.5 m with the help of a special device. At the distance of 1.8 m off the animal's head it was horizontally erected a 4-element hydro-acoustic array with the aperture of 1.2 m and the distance between the hydrophones making 0.4 m. Lines, connecting the dolphin's head and the corresponding hydrophone made the following angles (a perpendicular is directed to the array): Ã.1 = -18^0, Ã.2 = -6^0, Ã.3 = $+6^0$, Ã.4 = $+18^0$. The array provides reformation of the acoustic pressure into the electric signals with the help of four uni-type hydrophones. Electric signals coming from the hydrophones, after filtering at the entrance and the preliminary amplification under the water, were transferred along the cable line to the cage into the processing block providing the additional band filtration (band of transference 30-130 Hz), amplification, amplitude detection and low-frequency filtration in the range of up to 500 Hz. Upon this, four analogue signals corresponding to the LF-reformed signals measured by hydrophones Ã.1,…,Ã.4, were coming to the system of temporal densening which provided their transference along the double-core cable line to the on-land station. At the on-land station the signals were desifered and input to the PC. For some experiments in parallel with the array, the dolphin's acoustic signals were measured without detecting.

Figure 1 gives the acoustic impulses (acoustic signals after the LF-transformation) corresponding to the dolphin's search and echolocation of the target, presented at the depth 2 m in 30 m off the cage (Fig.1a) and near the surface (Fig.1b) in 100 m off the cage. Analysis of temporal sequence of impulses presented in Fig. 1, shows that at first the white porpoise performs the search with the help of series of impulses with $\Delta t = 1-3$ ms and duration $t = 30-40$ ms, with the increasing time interval ΔT between the series (see plot of Δt in Fig.1a), note some scanning in the horizontal plane. In the first case, the beluga found the target in 2 seconds and started to illuminate it by the solitary impulses with $\Delta t \approx t_i = 40$ ms, in 4 seconds more the animal once again illuminated the target by the solitary impulses with $\Delta t \geq t_i$ and left the device fixing its head. In the second case (Fig.1b) the beluga was echolocating the target with the help of series consisting of 3-4 solitary impulses propagating in a narrow angle sector. Further, let's call such impulses as narrow-oriented ones. Note, that ΔT was sequentially increasing from 425 up to 500 ms, and the series duration, on the contrary, was decreasing from 216 up to 92 ms ($t_i = 133$ ms). Thus, to detect the complicated target the dolphin uses series of solitary impulses, note, that for analyses and taking the decision it is necessary that $t < t_i < \Delta T$. When the target was sunk to the depth of 2 m (100 m off the cage), the beluga easily found it, and for echolocation it used solitary narrow-oriented impulses with $\Delta t \geq t_i$.

Figure 2 shows the echolocation impulses emitted by the beluga for search and echo-sounding the target presented at the depth of 2 m at 350 m ($t_i = 467$ ms) off the cage. The first 8 seconds (see Fig.2a) the beluga was performing the search with the help of series of impulses spatially concentrated in direction of -6^0. At the 10-th second it emits a series (see Fig.2b), with $t = 1062$ ms. Figure 2b shows Δt values characterizing the variations of time intervals between the impulses in a series. According to Figure 2b the energy of the acoustic signals forming series 1, is practically evenly distributed in a sector from -18^0 to $+18^0$.

In 656 ms the beluga emits a series of impulses in direction -6^0 (see Fig.2a), and then a group of solitary narrow-oriented impulses in a sector from -18 to -6, and in 4 seconds more, probably, upon having found the target, the dolphin illuminates it by a series of solitary impulses, which energy is concentrated in a sector from -18^0 to -6^0. Let's consider them in more detail : $(t + \Delta T)_{1.1} = 490$ ms, $(t + \Delta T)_{1,2} = 672$ ms, $(t + \Delta T)_{1.3} = 648$ ms and $t_i = 467$ ms, consequently, t of series is almost twice as less as t_i , $\Delta T_{1.2}$ is somewhat more than t_i , $\Delta T_{2.3}$ is 61 ms less than t_i , and $\Delta T_{3.4}$ is practically equal t_i . On this basis, we can suppose that in this case, as well as in detecting the nearest targets by solitary impulses, the dolphin alternates the duration of time intervals between the series ΔT, concentrating the impulse energy in a narrow angular sector, and also varies the number of impulses in a series and the interval Δt. The experiments have shown that the angular distribution of energy of the acoustic signals generated by the beluga (see Fig.2b) can be considerably wider than 6.5^0 [5]. The beluga can vary the distribution of the energy of the impulses emitted by it in the space. Evidently, the power of the signals emitted by the animal is not related to Δt, but depends on the echolocation task being solved by the animal. We should also note that the beluga manages the diagram of direction of the acoustic signals emitted by the animal, by way of changing the conditions of the acoustic field distribution in a forehead bulge with the help of deformations of fat pad/cushion (visual observations).

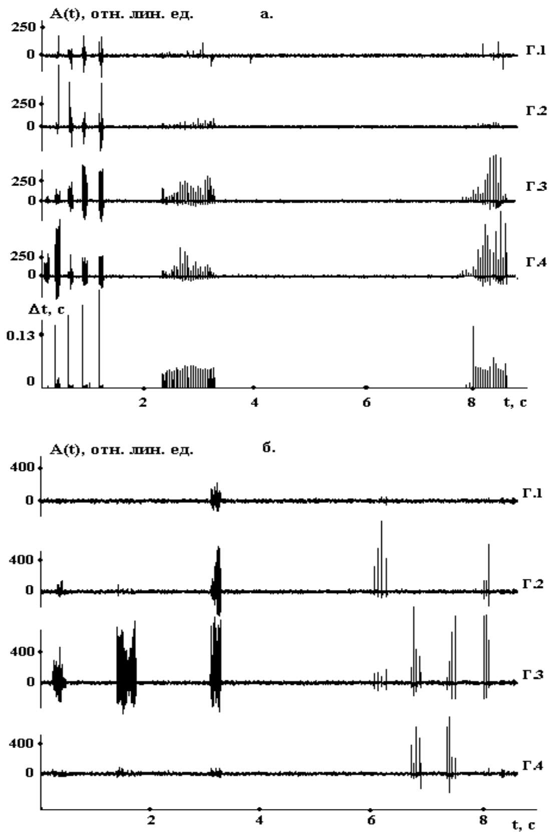

Fig. 1.

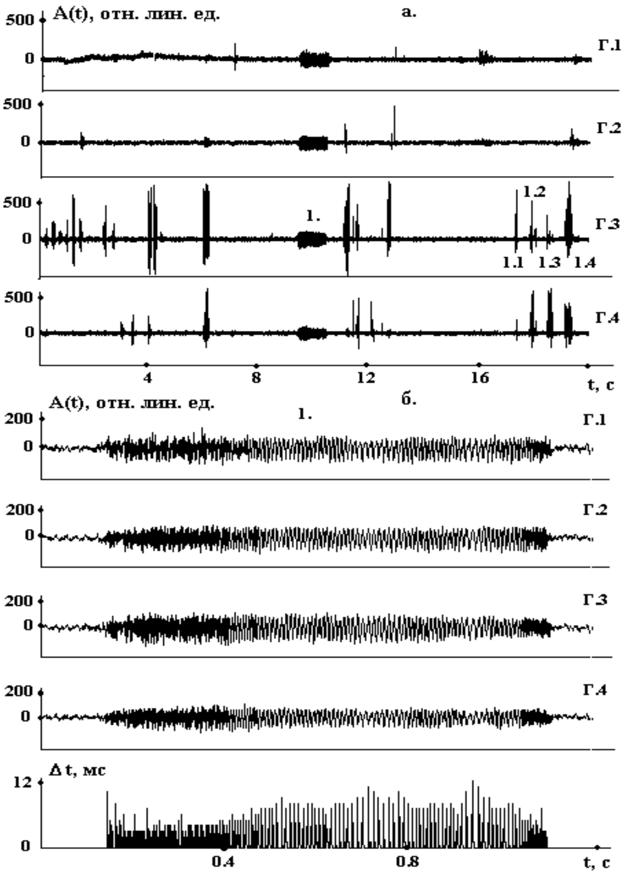

Fig. 2.

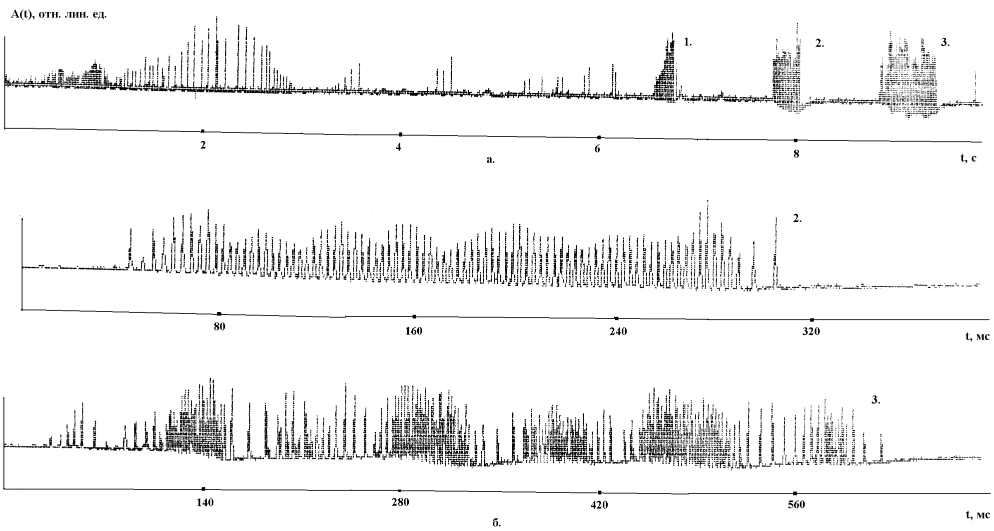

Fig.3.

Fig.3 presents the probing impulses emitted by the white porpoise at detecting the target presented at the depth of 5 m in 600 m off the cage $(t_i = 800$ ms). In Fig.3a we distinguish the series of impulses 1, 2 and 3. Series 2 and 3 are shown in more details in Fig.3b. Their time characteristics are the following: $t_1 = 220$ ms, $\Delta T_{1.2} = 980$ ms; $t_2 = 260$ ms, $\Delta T_{2.3} = 820$ ms; $t_3 = 580$ ms; consequently

ΔT between series 2 and 3 exceeds t_i just for 20 ms. For the second finding and echolocating the target (figure is not given), the beluga emitted a series of impulses with the following time characteristics: $t_1 = 170$ ms, $\Delta T_{1.2} = 1120$ ms, $t_2 = 170$ ms, $t_3 = 320$ ms, $\Delta T_{3.4} = 800$ ms; $t_4 = 150$ ms. Figure 3 shows that at echolocation at large distances, out of the narrow-oriented solitary impulses the beluga forms the quasi-periodic (series 2 at Fig.3b) and time-impulse modulated impulses (series 3 at Fig.3b) with t of up to 580 ms. In some experiments it was visually observed that at echolocating the target at the distance of 600 m the beluga was changing its head's position in the fixing device and it even was turning on its back, which was probably related to the animal's desire to illuminate the target better, while changing the spatial interference structure of the acoustic field generated by the animal.

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