MECHANISMS OF INTERFERENCE RESISTANCE OF THE SONAR SYSTEM OF DOLPHINS EXPOSED TO MAN-MADE INTERFERENCE

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ABSTRACT

The paper deals with the results of comparative experiments on the acoustic behaviour of the dolphin in the course of carrying out the task aimed at location of under-water targets in the natural acoustic environment and when exposed to man-made low-frequency interference. Thus, interference resistance of the dolphin sonar under in the complicated acoustic situation is provided by the following optimization mechanisms: pulse bursts (accumulation); varying frequency of pulse bursts (time selection); interval-time coding of bursts.

Key words: echolocation, interference resistance, acoustic interference, optimization mechanisms

1. INTRODUCTION

Acoustic behavior of the dolphin testifies to high development and ecological specialization of their distant sensory systems. The unique capacity of the dolphin sonar is based on the mechanisms responsible for optimization of the echolocation process.

In the laboratory experiments the dolphin was shown to increase sound pressure of echolocation pulses and decrease their frequency following the rise in the pressure of acoustic noise under the conditions of man-made interference of different spectrum coloring. In the experiments on interference resistance of the dolphin's sonar during discrimination of different targets, tuning away of the sonar from the interference was registered.

The present study focused on the echolocation behavior of toothed whales under the controlled conditions of the laboratory experiment on detection of underwater targets in the extreme acoustic conditions created by interference of anthropogenic nature.

2. METHODS

The experiment was carried out in open water following the methodology of alternative choice and acoustic control of the animal's behavior in response to sequential presentation of the stimulus. The dolphin was taught to occupy the starting position at a certain place of the cage (pile-and-net enclosure), assume correct orientation in the search sector (towards the target), and mark its decision by means of the motor reaction (pushing either left or right manipulator). The process of location was started by the experimenter and finished as soon as the animal came to the conclusion about absence or presence of the target in water.

The depth was 4 m. Acoustic interference of different spectrum coloring was generated by 8 radiators situated at a distance of 7 m from the starting position of the animal. The hydrophone was set at a distance of 50 m from the cage on the line connecting the dolphin and target. The frequency band of the register tract was 200 kHz, the non-uniformity of the amplitude-frequency characteristic not exceeding 2 dB. The target was sunk from the boat. The investigator and operator sitting in the boat communicated using radio channel. The characteristics of the targets used in the location task were T_1 = -1.6 dB, T_2 = -14 dB (target 1 is an angled reflector consisting of 5 mm thick triangular plates with a side length equal to 200 mm, made of 0.2 mm thick sheet; target 2 is a hollow cylinder 120 mm in diameter and 400 mm in height with walls 10 mm thick).

The measurements were performed using signals imitating dolphin pulses. A piezoacoustic transformer 100 mm in diameter, consisting of a set of transformers, was used as emitter. Acoustic impulse had a form of rapidly damping sinusoid (3 periods) with a bell-shaped spectrum pattern (maximum at 90 kHz). We used a ∅5 mm non-oriented receiver was used. The recordings were made at a distance of 2 m, 4 m, 5 m, 7 m, 9 m, 11 m. Calculations were carried out on the basis of 10 measurements for each target.

The targets were presented at a distance of 200 m from the animal. The details of the method applied are described in [1].

The obtained data on the acoustic activity of the dolphin during its work in the extreme acoustic conditions are compared with the signals used by the animals in the course of locating underwater objects in the natural conditions when the distance from the target is varied [2].

A B

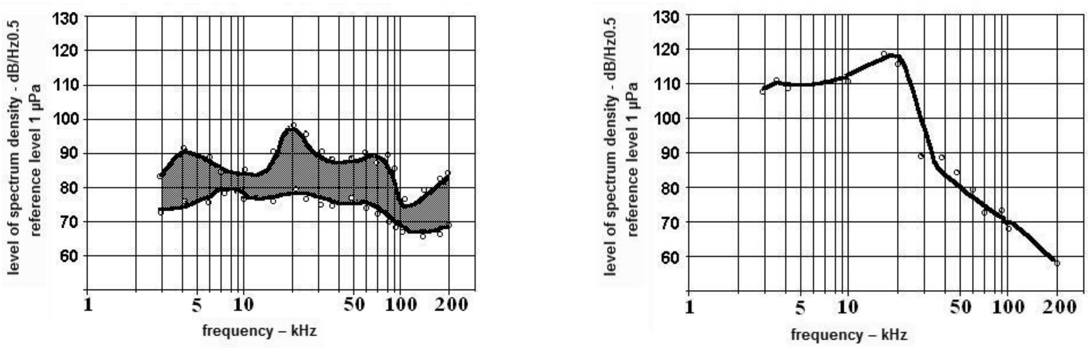

Fig. 1 Level of spectrum density of natural noise in the water area (June-October) – A; level of spectrum density of synthesized interference –B

The measured value of the level of spectrum density of natural noise in the water area is represented in fig. 1-A. There are 15 animals in the vicinity of the animal used in the experiment. The measured value of the level of spectrum density of synthesized interference is represented in fig. 1–B. The measurement was undertaken at the starting position in the experimental cage after the task has been accomplished.

3. RESULTS

The processing of the data on the acoustic behaviour of the dolphin shows that the echolocation process is modified depending on the acoustic environment. The echolocation system adapts to the interference situation optimizing the process of selecting the signal's echo on the interference background. Fig. 2 represents the oscillogram of the complete sequence of echolocation pulses radiated by the dolphin in the course of detecting a target at a distance of 200 m. As can be seen from the fig. 2, in the natural acoustic environment for echolocation the dolphin uses pulse mixing: pulse burst consisting of one pulse and pulse bursts consisting of two and three pulses. It is known that to detect a target at a distance less than 120 m the dolphin uses pulse bursts consisting of only one pulse, the time interval between pulses being longer than time taken by the pulse to reach the target and return back. Theoretically, these two values should be equal according to the formula $T_m=2L/C$ (L – distance to the target; C – sound velocity). The echolocation process of dolphins proceeds with a time lag up to 20 ms [3].

A

B

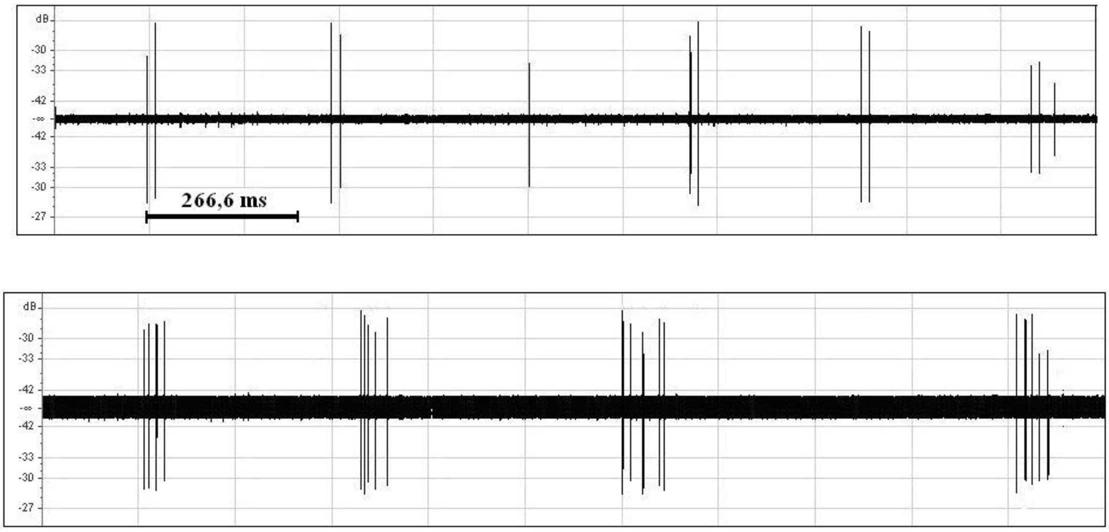

Fig.2. Oscillogram of the complete sequence of echolocation pulses irradiated by the dolphin in the course of target location (distance 200 m): in the natural acoustic environment –A; in the presence of a synthesized artificial interference – B. Ordinate - relative amplitude of the pulse; abscissa – time

The presented results demonstrate that the delay is not a constant value. Being determined by the echolocation mode used by the dolphin it depends on the search distance, duration of pulse bursts, processing time and time taken by decision making. To present the obtained data in a more convenient form we have introduced the coefficient of overlapping: $K=T_{e.}/T_m$ ($T_{e.}$ – results of the experiment). For the perfect observer this coefficient assumes the value equal to 1.

Fig. 2- B represents the oscillogram of the complete sequence of echolocation pulses radiated by the dolphin in the course of detecting a target at a distance of 200 m in the presence synthesized artificial interference. As can be seen from the oscillogram for echolocation the dolphin uses pulse bursts consisting of a sequence of pulses. The time interval between such bursts in the sequence exceeds considerably the value of delay equal to 20 ms. Analysis of the obtained data showed that for the *a priori* known distance the overlapping coefficient is equal to 1.5. If the target is absent, the value of the coefficient K varies in the range 1.8÷2.2. For the unknown distance the overlapping coefficient can reach a value higher than 4.

Data obtained in the experiment on changes of the coefficient of overlapping depending on the distance from the target are represented by dots and thin regression line in Fig. 3-A. As seen from the plot, for the perfect observer (K=1) the period of dots T_m in the sequence is equal to 800 ms for a distance of 600 m, whereas the maximum experimental value (K=1.8) is T_e = 1440 ms.

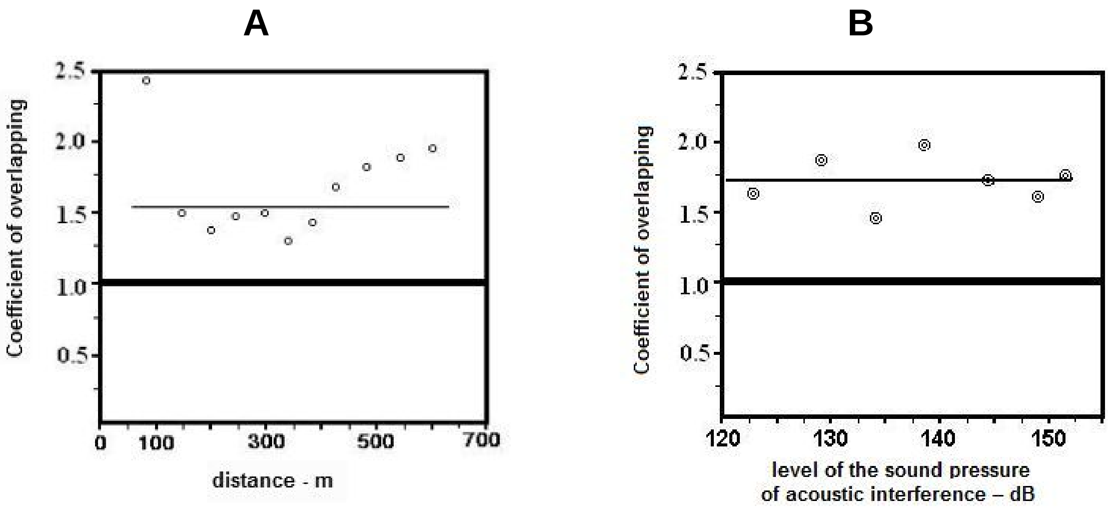

Fig. 3. Coefficient of overlapping depending on: distance from the target – A; level of the sound pressure of acoustic interference – B

Data obtained in the experiment on changes of the coefficient of overlapping depending on the sound pressure of acoustic interference are represented by dots and thin regression line) in Fig. 3-B. In the plots, all the experimental data (dots) correspond to the average of 5÷10 trials. In the plot, the bold line corresponds to the operation of the perfect observer (K=1) T_m = 266.6 ms. As seen from the plot for T_e , the experimental data undergo 1.5÷2.0 fold variations. Thus, the optimization mechanism basically consists in time selection of the target.

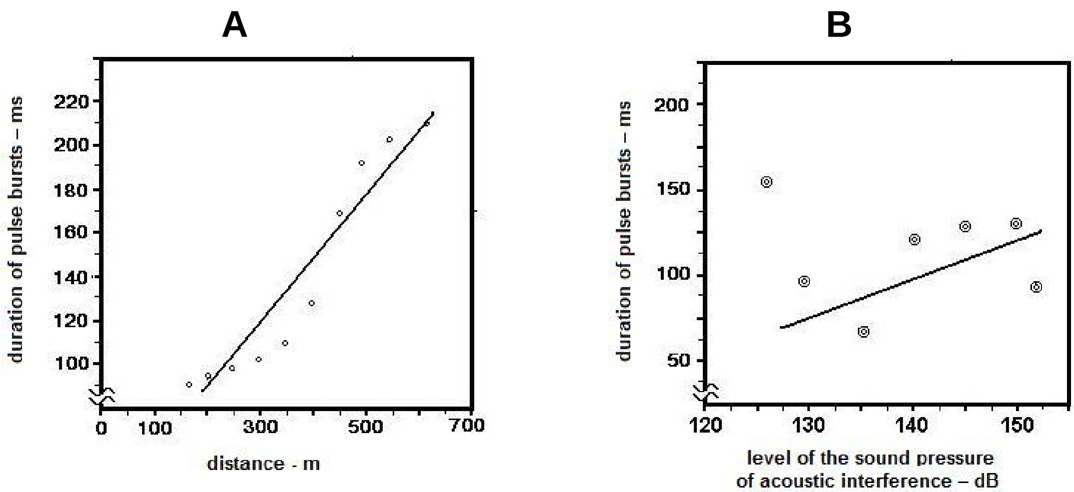

Fig. 4. Duration of pulse bursts depending on: distance from the target (A); level of the sound pressure of acoustic interference –B

Data on duration of pulse bursts depending on distance from the target and level of the sound pressure of acoustic interference up to 155 dB are represented in Fig. 4 A and B, respectively. The duration of the signal was shown to change in both cases. The initial rise in the level of the acoustic interference results in sharp changes in the signal duration. Subsequent gradual rise in the level of the interference is smoothed due to the adaptation process, which can be observed in the plot (Fig. 4-B). Hence, the optimization mechanism is expressed in increasing the signal duration.

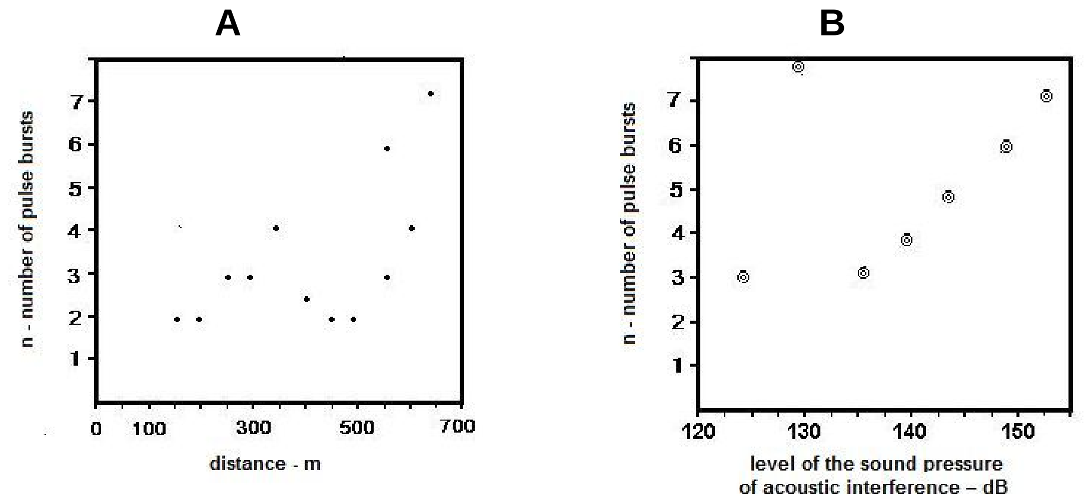

Fig. 5. Number of pulse bursts depending on: distance from the target (A); level of the sound pressure of acoustic interference –B

Aggravation of the acoustic situation leads to changes in the duration of the target search by the dolphin, which is clearly manifested in changing the number of pulse bursts used by the animal in the course of echolocation. Such changes in the number of pulse bursts used by the dolphin depending on the distance from the target and on the level of the sound pressure of acoustic interference are shown in Fig. 5-A and 5-B, respectively. In the two plots there is a distinct trend towards increase in the number of pulse bursts, which is obviously related to worsening of the ration signal/interference.

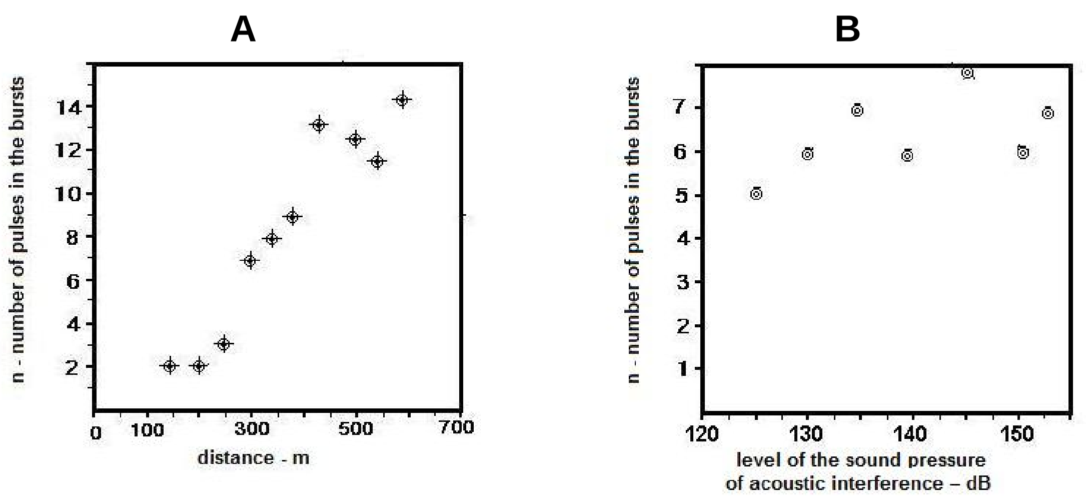

Fig. 6. Number of pulses in the bursts depending on: distance from the target (A); level of the sound pressure of acoustic interference –B

Depending on the acoustic conditions of the environment dolphins use for echo sounding signals in the form of pulse burst with a number of pulses in a burst from 1 to 30 pulses, the number of bursts varying from 3 to 15.

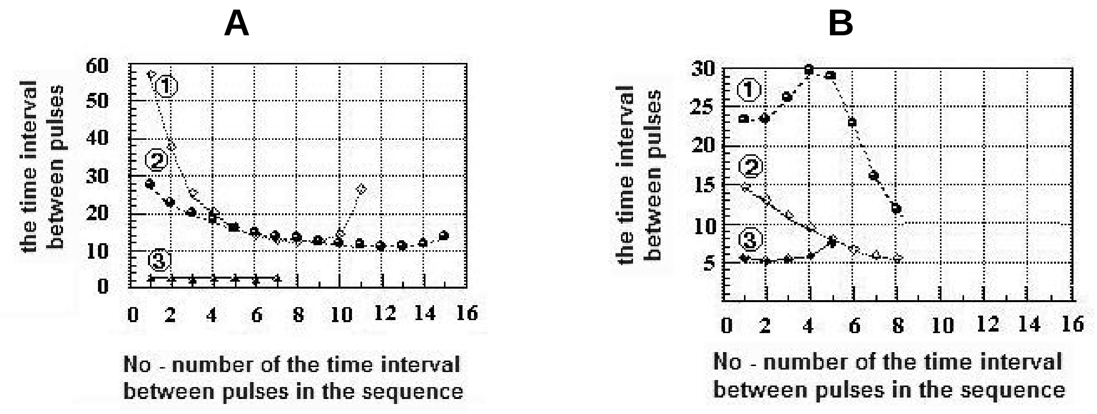

Fig. 7. Changes in the time interval between pulses in the bursts (three bursts) depending on the number of the time interval in the sequence: A – echolocation in natural acoustic environment (600 m); B - echolocation in the presence of an interference of 150 dB

Changes in the number of pulses in the bursts of pulses depending on the distance from the target (Fig. 6-A) as well as on the level of the sound pressure of acoustic interference (Fig. 6–B) testify to unambiguous relationship between the increase of pulses in the bursts of pulses radiated by the dolphin in the course of echolocation and aggravation of the acoustic conditions. Comparative analysis of the two plots (Fig. 6 –A, B) suggests that the potential of increasing the number of pulses in the bursts is not limited by the interference level equal to 150dB. Stabilization achieved at the level of 5 to 8 pulses in the burst is a mere manifestation of the adaptation process. Sharp changes of the interference level (either rise or drop) result in increase of the number of pulses in the bursts up to 10 – 15.

Changes in the duration of bursts of pulses may take place due to: 1) changes in the interval between pulses in the burst; 2) changes in the number of pulses in the burst or 3) both reasons (mixed type). Changes in the time sequence of pulses in the burst and in the number of pulses in the burst for three bursts are shown in Fig. 7. As seen from the plots (Fig.7 – A,B), the time sequence of pulses as a rule is not uniform, though some exceptions are possible (Fig. 7-A). The third burst of pulses (Fig. 7-A), consisting of 9 pulses, exhibits a uniform sequence of pulses with the time interval between pulses equal to 1.8 ms. A similar third burst of pulses in Fig.7-B exhibits a non-uniform sequence of pulses with the time interval varying from 5.0 up to 8 ms. Variations of the time sequence in one burst of pulses can be 6-fold (Fig. 7-A, burst 1). So far no clear principle describing changes in the time interval has been found.

3. CONCLUSIONS

All the reported changes in the time sequence of pulses in bursts prove that dolphins encode the radiated sequence. In technical systems, such changes in signals are called interval-time coding. Pulses in the burst differ one from another by their position on the time axis. Theoretically, the total number of bursts composed by similar pulses is equal to $\mathbf{C^{B}_{N}}$, where **B** is the base of a signal, equal to the band's width of a pulse multiplied by duration of the burst (both factors are integers) and **N** is the number of pulses in the burst [4]. In such a case the total number of bursts will be very big for great values of bases. The value of A takes into account all plausible combinations of interval-time coding. The range of its values obtained in the experiment performed on the dolphin decreases the number of feasible combinations. The final judgment regarding the value of possible combinations will be achieved only on the basis of the study of the resolution capacity of the hearing system in the course of decoding of radiated signals.

Thus, it was demonstrated in the course of target location at a long distance and under the conditions of the man-made acoustic interference dolphins use the same mechanisms of adaptation to hard acoustic conditions.

On the basis of the obtained data we can conclude that mechanisms optimizing the echolocation process should involve:

- irradiation of bursts of pulses and their time selection;
- changing duration of bursts of pulses;
- changing the number of pulses in the bursts;
- interval-time coding of the sequence of pulses in the bursts.

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