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DEVISING AN ACOUSTIC METHOD FOR INVESTIGATION OF A COMPLEX FORM OBJECT PARAMETERS

Introduction. *The general principles of the technique of synthesis of reflective characteristics of complex surfaces for small wavelengths are considered in the article. The problem is set in the conditions of using sound waves and sonar. The calculated scattering characteristics are obtained using a facet model.*

Purpose. *The purpose of the paper is to create a method of acoustic research and determination of spatial characteristics of objects of complex shape, which contains the developed facet model of the object and the model of the reflected signal. This method consists artificial models of objects and models of the reflected signal, with the further purpose of research and determination of spatial characteristics of objects, recognition of objects, etc. It is expected that based on the simulation of signals reflected from these models, it will be possible to classify objects. An important difference from most studies is a number of assumptions about what to do with the model and how to calculate the result, because, as a rule, the main element of such studies is the reflection surface only.*

Results. *For the purpose of this research simplified model of signal reflection from a surface area in space is considered. We established a correspondence between wave propagation in the space and change of the value of the function representing reflecting wave. At any given moment of time the total reflected signal is the sum of all reflected signals from all surfaces. The integral form was proposed for this purpose. The analytical formula intended for the integral was designed for one of the specific cases of reflection. There were numerical experiments performed to test such formula with regard of facet model of the ship. Resulting waveform looks in accordance to expectations.*

Conclusion. *In accordance with the task the paper demonstrates the method of constructing a model of objects and sound signals reflected from them, paper also considers the general principles of the method of synthesis of reflective characteristics of complex surfaces for small wavelengths. It is shown why and how exactly such a model is built and the presence of a significant difference in the signal characteristics for different angles is clearly demonstrated. The main advantage of this model is the ability to conduct experiments exclusively in digital form, without the need for expensive field experiments. Further research should continue in the direction of selecting or creating an optimal recognition system based on neural networks.*

Keywords: *facet model, remote sensing, underlying surface, sonar image.*

INTRODUCTION

Nowadays, researches in the acoustic field and solving the task of determining the direction and distance to the sound source bear high relevance, especially in the context of developing information technology to improve the defense and security of the state [1, 2]. The transition from the development of methods and means of passive location of sound sources to active location is actively performed, which particularly affects hydroacoustics field. First of all, it has been widely adopted for practical marine problems solving, because no types of electromagnetic waves propagate in water over any significant distances due to its electrical conductivity. Therefore, the only effective type of waves to be created and propagated underwater is the acoustic wave.

Compared to the similar task of active location with the help of radio waves, ultrasonic location has a number of features that complicate the development and possible use of such tools. This is most pronounced in the problem of determining the parameters of the mobile maneuvering objects, foremost their shape. In the case of radiodetection, a high-speed maneuvering object is an aircraft, observation of which for a certain period of time, e.g., for half a minute, gives in addition to distance, speed, maneuverability such parameter values as radar cross-section (RCS) and its variance [3]. The value of the variance is an important parameter for identification. At the same time, for sound waves and marine transport due to much lower speeds and much less maneuverability of objects, the power of the reflected signal, which is a function of the radar cross-section, has much less informative variance because objects are irradiated by waves mainly from the singular direction. In addition, there are other features that require that the task of studying the sonar reflected signal is set and solved independently.

PROBLEM STATEMENT

Currently, the most interesting and promising tasks relate to the problem of probing objects with short wavelength sound, which potentially allows to obtain maximum information about the relief of the underlying surface or the shape of the object under study.

Audio frequencies from 300 to 20 kHz and ultrasounds from 20 kHz and above are used for communication and probing. In addition to communication and probing in hydroacoustics, the following tasks are set:

- detection of noise signals and determination of the direction unto them;
- classification of the received signals.

Today, a significant amount of research is focused on the collection and processing of natural data and the design of models for natural objects, as proposed in [4]. Also, the task of building object models uses additional sources of information. An example of developing a technology for the study of cultural heritage objects, which sunk underwater, is given in the source [5]. For moving objects (ships) the main source of information is the acoustic signature [6, 7].

Thus, for artificial but stationary objects or for objects that do not emit sound waves for one reason or another (including sunken ships) there are no reliable methods to determine the parameters and the fact of their artificial origin.

However, under visual inspection of the underwater part of an object, very often it is possible to make the conclusion about its artificial origin similarly to the definition of its parameters (size, shape, type).

The approach to the study is based on the construction of facet models similar to how it is done for radiodetection [8]. Based on the simulation of signals reflected from these models, it is possible to classify objects.

Thus, usually, the main element of such studies is the RCS [8-11]. However, as noted above, RCS and its variance are not always good sources of information. The study suggests that the reflection calculated from the facet model may provide enough information to identify both certain characteristics of the object and the complete identification of the object. For this purpose, a facet model of the object and a method of synthesis of the reflected signal were developed.

Accurate analysis of how the value of the amplitude of the reflected signal from the facet model is constructed was performed. For convenience, the system of the emitter and sensor is considered to be monostatic, i.e. the source of sound radiation and the receiver (microphone) are so close that the distance between them can be neglected.

The purpose of the paper is to create a method of acoustic research and determination of spatial characteristics of objects of complex shape, which contains the developed facet model of the object and the model of the reflected signal.

GEOMETRIC CHARACTERISTICS OF THE FACET MODEL SECTION

A simplified model of signal reflection from a surface section in space is considered. The section is represented by a triangle with a certain order of vertices $\{A,B,C\}$. The signal is represented by an arbitrary function $f(t)$. The spherical wave is most often considered. For sufficiently small areas, it is possible to consider a locally flat wave. Since the dimensions of the triangle are determined only by the choice of the surface partition, a wave with a flat front will be considered. Due to this interpretation a rectangular coordinate system is used. Let's carry out the translation of the coordinate system so that the observation point (source and receiver) is at the origin. Let the vertices of a triangle have the following coordinates: $A=\left(A_x, A_y, A_z\right)$, $B=\left(B_x, B_y, B_z\right)$, $C=\left(C_x, C_y, C_z\right)$. According to the condition it is known that the wave front moves in the direction of the vector directed to the center of the triangle $I=\left(I_x, I_y, I_z\right)$, the coordinates of which are determined as follows:

$$a=\|B-C\| \text{ }, b=\|A-C\|,\; c=\|A-B\| \tag{1}$$

$$I_x=\frac{\left(aA_x+bB_x+cC_x\right)}{a+b+c}, \tag{2}$$

$$I_y=\frac{\left(aA_y+bB_y+cC_y\right)}{a+b+c}, \tag{3}$$

$$I_z=\frac{\left(aA_z+bB_z+cC_z\right)}{a+b+c}, \tag{4}$$

The next step is to choose a convenient basis. In order to obtain the first vector of the new basis, the vector of the direction of motion of the wave front $\overline{w}$ is fixed and normalized:

$$\overline{w}_{new}=\frac{\overline{w}}{\|\overline{w}\|}. \tag{5}$$

When passing the front of the wave cuts off the strips of the triangle in parallel lines. It is expedient to choose the second base vector as the directional for all such lines. Therefore, it must belong to the plane of the triangle and the front of the wave at the same time. Let $\overline{n}$ be the vector normal to the surface of the triangle, the orientation of which depends on the order of the vertices:

$$\overline{n}_1=\begin{bmatrix} B_x-A_x \\ B_y-A_y \\ B_z-A_z \end{bmatrix},\quad \overline{n}_2=\begin{bmatrix} C_x-A_x \\ C_y-A_y \\ C_z-A_z \end{bmatrix}, \tag{6}$$

$$\overline{n}=\overline{n}_1\times\overline{n}_2. \tag{7}$$

Then the second basis vector:

$$\overline{y}_{new}=\frac{\overline{x}_{new}\times\overline{n}}{\left\|\overline{x}_{new}\times\overline{n}\right\|}. \tag{8}$$

The vector constructed in this way is orthogonal to the vectors of the wave front's normal and the plane of the triangle at the same time.

The new basis is expanded as follows:

$$\bar{z}_{new} = \frac{\bar{x}_{new} \times \bar{y}_{new}}{\left\| \bar{x}_{new} \times \bar{y}_{new} \right\|}. \tag{9}$$

Then the coordinates of the vertices of the triangle can be obtained from the following equations:

$$\left[\bar{x}_{new} \middle| \bar{y}_{new} \middle| \bar{z}_{new}\right] \cdot \begin{bmatrix} A_{x_{new}} \\ A_{y_{new}} \\ A_{z_{new}} \end{bmatrix} = \begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} \tag{10}$$

$$\left[\bar{x}_{new} \middle| \bar{y}_{new} \middle| \bar{z}_{new}\right] \cdot \begin{bmatrix} B_{x_{new}} \\ B_{y_{new}} \\ B_{z_{new}} \end{bmatrix} = \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} \tag{11}$$

$$\left[\bar{x}_{new} \middle| \bar{y}_{new} \middle| \bar{z}_{new}\right] \cdot \begin{bmatrix} C_{x_{new}} \\ C_{y_{new}} \\ C_{z_{new}} \end{bmatrix} = \begin{bmatrix} C_x \\ C_y \\ C_z \end{bmatrix} \tag{12}$$

DESIGN OF THE REFLECTION MODEL

The projections will be considered in the next steps.

Let's project a triangle on a plane (fig. 1) $x_{new}Oy_{new}$:

Red lines represent the straight intersection of the wave front with the plane of the triangle at different points in time. We introduce the spatial step h and the moment in time t_0 at which the wave front first touches the triangle. Let the t_0 wave step pass for some time $t(h)$.

The purpose of the upcoming steps is to calculate the signal obtained by the receiver (microphone) at the time moments $2t_0$, $2t_0 + t(h)$, $2t_0 + 2t(h)$, $2t_0 + 3t(h), \ldots$ (starting from the moment of return of the first part of the reflected wave).

Given the flat front of the wave, let's assume that from the point of view of the source the triangle is visible in the projection on the front's plane. By definition, the new basis vectors are equivalent to the plane projection $z_{new}Oy_{new}$.

Where $z(t_0)$ is the coordinate of the peak closest to the wave's front. Note that the projection can always be oriented so that this vertex is on the left, without changing the area.

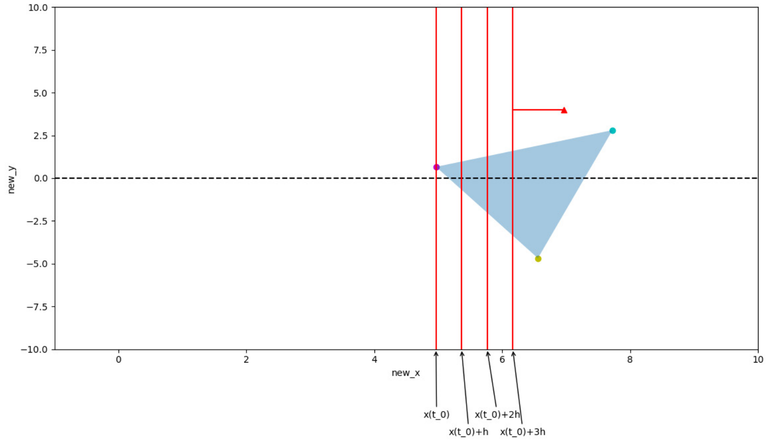

Fig. 1. Steps of wave propagation by projections

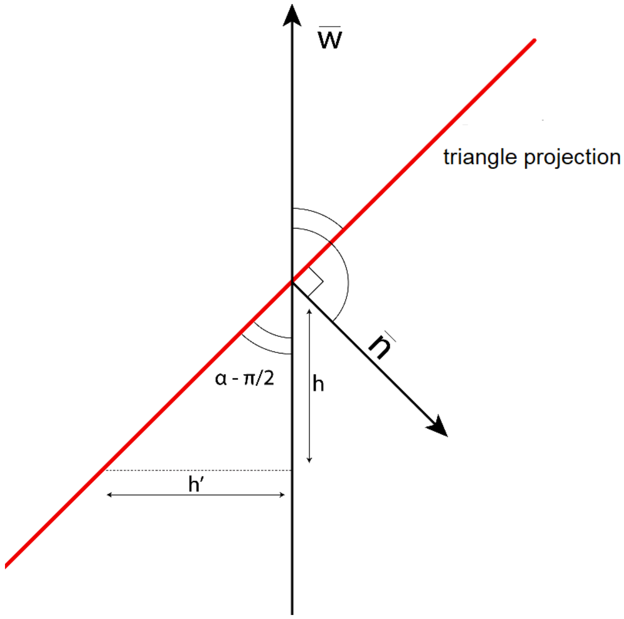

Fig. 2. The wave propagation step and its angles

Thus, during the elementary steps of time $t(h)$ in the plane $y_{new}Oz_{new}$ the wave will be reflected from the bands of the width triangle h'. Therefore, it is necessary to establish a correspondence between h and h'. To do this, first enter the angle between the normal vector to the plane of the triangle and the wave propagation vector α. Given the condition of visibility of the triangle, only the case $\frac{\pi}{2} < \alpha < \pi$ is considered. By construction, the vector of the normal $\overline{n}$ lies in the plane $x_{new}Oz_{new}$. Therefore, the projection of the triangle on this plane will be a segment (Fig. 2).

According to fig. 2 we have:

$$h' = h \cdot \tan\left(\alpha - \frac{\pi}{2}\right). \tag{13}$$

Therefore, formula (13) establishes a correspondence between the step of wave propagation in space h, the step of changing the value of the function $h' = h \cdot \tan\left(\alpha - \frac{\pi}{2}\right)$ and the step of calculating the area of the triangle.

CONSTRUCTION OF THE INTEGRAL FORMULA OF THE REFLECTED SIGNAL

At any given time, the total reflected signal is the sum of all reflected signals from all bands. This approach, with explicit construction of the integral, differs significantly from the sum of the shiny dots, as done in [11].

Assume that from each band of a triangle of width h' some part of the signal is returned to the receiver. Denote this part of the reflected signal $g(f(t))$. Let the wave front correspond to the value $f(t_0)$. Thus, the part of the reflected signal that returned first corresponds to the value $g(f(t_0))$. Further, the receiver will record the return $g(f(t_0 - n \cdot h))$, $n \in N$. At each point in time, the superposition of signals reflected from the strips of the triangle with weights corresponding to the area of each section will be processed. Our goal in this step is to obtain a formula for the superposition of the signals received by the receiver at any given time.

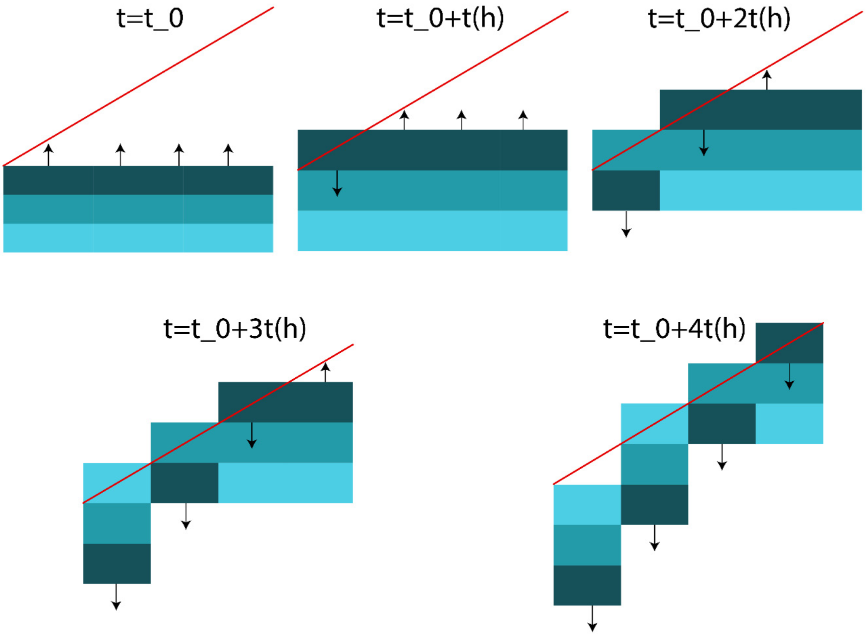

Fig. 3. The process of wave reflection

Again, consider the projection on the plane $x_{new}Oz_{new}$ and depict the stages of reflection of the wave with a time step $t(h)$ (Fig. 3).

In fig. 3 different colors of the oncoming wave correspond to different values $f(t)$. In order to simplify the illustration the condition $g(f) \equiv f$ was assumed.

From fig. 3 it is evident that the parts of the returning wave are shifted by $2t(h)$ (taking into account the full path in both directions). So, we can write the following sequence:

$$t = 2t_0 + t(h):$$

$$t = 2t_0 + 2t(h): f(t_0)A(z(t_0)+h)$$

$$t = 2t_0 + 3t(h): f(t_0 - t(h))A(z(t_0)+h')$$

$$t = 2t_0 + 4t(h): f(t_0 - 2t(h))A(z(t_0)+h) + f(t_0)A(z(t_0)+2h')$$

$$t = 2t_0 + 5t(h): f(t_0 - 3t(h))A(z(t_0)+h) + f(t_0 - t(h))A(z(t_0)+2h')$$

$$t = 2t_0 + 6t(h):$$
$$f(t_0 - 4t(h))A(z(t_0)+h) + f(t_0 - 2t(h))A(z(t_0)+2h') + f(t_0)A(z(t_0)+3h')$$

$$\ldots$$

where $A(z(t_0)+it(h))$, $i \in N$ is the area of the corresponding projection band.

If the value of h is small enough it is convenient to replace calculation of the areas of trapezoids with calculation of the areas of rectangles. To do this, first perform a parallel translation of the projection of the triangle on the plane $z_{new}Oy_{new}$ so that the whole figure lay above the axis Oz_{new}. Next, we introduce a piecewise linear function $T(z)$, which is defined as the difference between the functions of the upper and lower sides of the triangle, and is identically equal to zero outside of it. So, the following generic formula is obtained:

$$S(\tau) := \sum_{i=0}^{\frac{t^{-1}(\tau)-h}{zh}-0.1} g(f(t_0 + 2(i+1)\cdot t(h) - \tau))\cdot h' \cdot T(z(t_0)+(i+1)h'). \tag{14}$$

Or, given the formula (13):

$$S(\tau) := \sum_{i=0}^{\frac{t^{-1}(\tau)-h}{zh}-0.1} g(f(t_0 + 2(i+1)\cdot t(h) - \tau))\cdot h \cdot \tan\left(\alpha - \frac{\pi}{2}\right)\cdot T\left(z(t_0)+(i+1)\cdot h \cdot \tan\left(\alpha - \frac{\pi}{2}\right)\right) \tag{15}$$

.

Finally, under $h \to 0+$ we get:

$$I(\tau):=\int_0^{t^{-1}(\tau)}\frac{1}{2}g(f(t_0+t(x)-\tau))\cdot\tan\left(\alpha-\frac{\pi}{2}\right)\cdot T\left(z(t_0)+\frac{x}{2}\tan\left(\alpha-\frac{\pi}{2}\right)\right)dx\,. \quad (16)$$

The resulting integral takes into account almost all characteristics of the signal.

CONSTRUCTION OF ANALYTICAL FORMULA FOR THE INTEGRAL FOR ONE OF THE CASES

Let's have a piecewise constant function as an input:

$$f(t):=\begin{cases}0 & , \quad t_0<t\\ C & , \quad t_0-length\le t\le t_0\\ 0 & , \quad t<t_0-length\end{cases} \quad (17)$$

The speed of propagation: $\upsilon : t(x)=x/\upsilon$. The integral takes the form:

$$I(x):=\int_0^t\frac{\upsilon\cdot\tan(\beta)}{2}f(t_0+x-t)T\left(\frac{x\upsilon}{2}\tan(\beta)+z(t_0)\right)dx \quad (18)$$

Perform the following transformations by replacing the variable:

$$\begin{aligned}&\int_0^t\frac{\upsilon\cdot\tan(\beta)}{2}f(t_0+x-t)T\left(\frac{x\upsilon}{2}\tan(\beta)+z(t_0)\right)dx=\\ &=\frac{C\cdot\upsilon\cdot\tan(\beta)}{2}\int_0^t I_{\{t-x\le length\}}T\left(\frac{x\upsilon}{2}\tan(\beta)+z(t_0)\right)dx=\\ &=\frac{C\cdot\upsilon\cdot\tan(\beta)}{2}\int_{t-length}^t T\left(\frac{x\upsilon}{2}\tan(\beta)+z(t_0)\right)dx=C\cdot\int_{z(t-length)}^{z(t)}T(u)du\end{aligned} \quad (19)$$

Replace the variable in the last two lines as follows: $z(t):=\frac{t\upsilon}{2}\tan(\beta)$, which in fact it means the transition to the projection plane of the triangle.

From the previous stages we know the structure of the function for calculating the area of a triangle $T(z)$. It is guaranteed to have a bend at the midpoint of the triangle along the axis Oz_{new}. Let's mark this point as z_{mid}. Respectively, the beginning of the integration of the triangle and the end are denoted by $z_{left}=z(t_0)$ and z_{right}. It is necessary to investigate the location $z(t)$, $z(t-length)$ relative to z_{left}, z_{mid}, z_{right}. Since the integrand is of the form $T(z)=0$, $z\notin\lfloor z_{left},z_{right}\rfloor$, simplify limits of integration:

$$\begin{aligned}b&:=\min\{z(t)-z_{right}\}\\ a&:=\max\{z(t-lenght),z_{left}\}\end{aligned} \quad (20)$$

Therefore, it is necessary to consider only the following cases:

$$b < z_{left}$$
$$b < z_{mid}$$
$$a < z_{mid} < b$$
$$z_{mid} < a < b$$
$$z_{right} < a$$

Denote the two nonzero components of the function $T(z)$:

$$f_1(z) = T(z), z \in \lfloor z_{left}, z_{mid}) \tag{21}$$

$$f_2(z) = T(z), z \in \lfloor z_{mid}, z_{right} \rfloor \tag{22}$$

Selecting and fixing two arbitrary corresponding antiderivatives $F_1(z)$ and $F_2(z)$ we get:

$$I(b) = \begin{cases} 0 & , \quad b < z_{left} \\ C \cdot (F_1(b) - F_1(a)) & , \quad b < z_{mid} \\ C \cdot (F_2(b) - F_2(z_{mid}) + F_1(z_{mid}) - F_1(a)) & , \quad a < z_{mid} < b \\ C \cdot (F_2(b) - F_2(a)) & , \quad z_{mid} < a < b \\ 0 & , \quad z_{right} < a \end{cases} \tag{23}$$

The final model is obtained by summarizing over time of all the models of individual sections.

MODEL OF A SUNKEN SHIP AND ITS REFLECTED SIGNAL

In fig. 4. shown a simplified facet model of a sunken ship, and in fig. 5 and fig.6 shown the shape of the reflected signal, for two different angles: on the bow-stern axis and on the starboard side. This model is obtained as the sum of signals from individual sections.

As can be seen from fig. 5 and fig. 6 there is a certain interdependence between the angle of the upcoming scanning wave and the shape of the reflected signal.

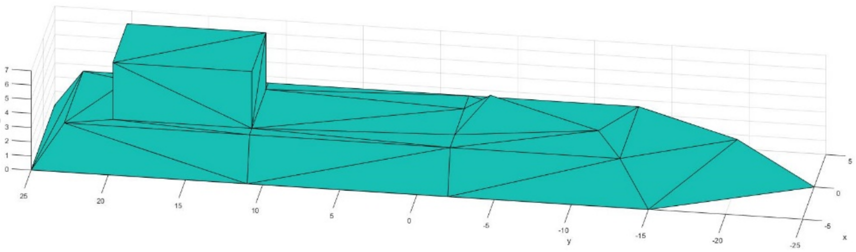

Fig. 4. Model of the ship.

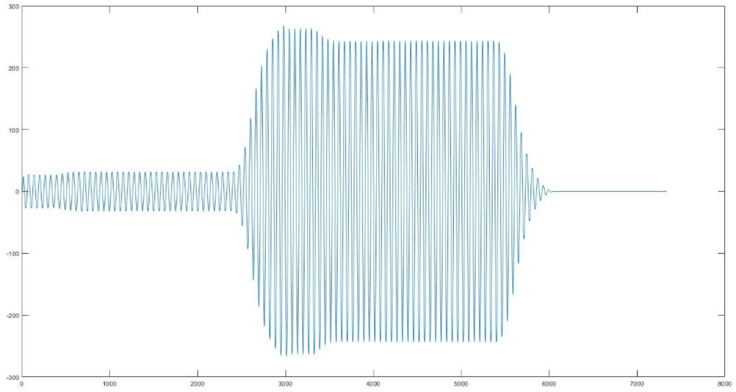

Fig. 5. The structure of the reflected signal when irradiated along the axis on the bow-stern axis

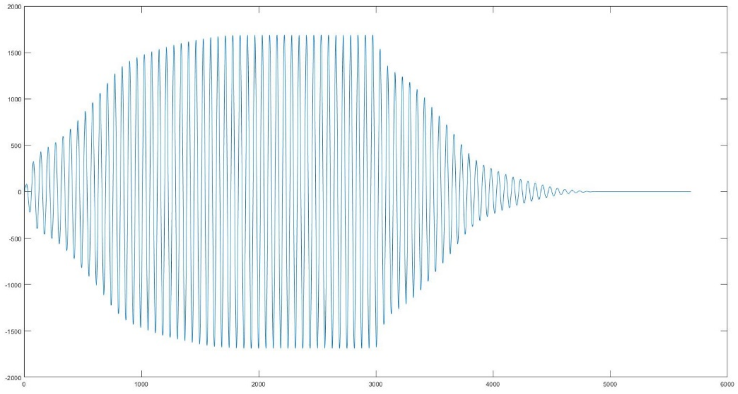

Fig. 6. The structure of the reflected signal when irradiated from the starboard side

Of particular interest are the sections corresponding to the following:

1. for a time interval until the wave has covered the ship completely and,
2. for a time interval when the wave no longer covers the ship completely.

Potentially, these areas contain much more information compared to the criterion proposed in [11] based on the frequency correlation of fluctuations of the effective scattering surface of the target with a discrete adjustment of the emitter frequency. Because both radars and sonars create oscillating processes with the same mathematical description.

Certain inaccuracies that distort the overall model are in fact insignificant as long as the following conditions are met:

1. data of the same nature is used for recognition: either only real data, or only modeling data, if it is necessary to distinguish between natural and artificial objects;
2. to determine the characteristics of a particular type of object a neural network trained on all perspectives of the potential target is used.

CONCLUSIONS

In accordance with the stated task the method of model construction of objects and the sound signals reflected from them is presented, the general principles of a synthesis technique of reflective characteristics of difficult surfaces for small wavelengths were considered. The purpose and the approach of such a model construction are shown, and the presence of a significant difference in the signal characteristics for different angles is clearly demonstrated.

The developed method and models allow conducting experiments exclusively in digital form, without the need for expensive field experiments. The application of the proposed models does not corrupt the effectiveness of the features that will be used in the future for objects recognition.

The proposed method provides more information about the object in comparison with the criterion based on the frequency correlation of fluctuations of the effective scattering surface of the target with a discrete adjustment of the frequency of the emitter. And it is also insensitive to inaccuracies introduced by distortions into the general model.

Further research will continue in the direction of selecting or creating an optimal recognition system based on neural networks.

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РОЗРОБЛЕННЯ МЕТОДУ АКУСТИЧНОГО ДОСЛІДЖЕННЯ ПАРАМЕТРІВ ОБ’ЄКТА СКЛАДНОЇ ФОРМИ

Вступ. У статті розглянуто загальні принципи методу синтезу відбивних характеристик складних поверхонь для малих довжин хвиль. Проблема визначена для умов використання звукових хвиль та гідролокатора. Розраховані характеристики розсіювання отримані за допомогою фасетної моделі.

Метою роботи є створення методу акустичного дослідження параметрів об’єкта складної форми, який містить моделі об’єктів та моделі відбитого сигналу, з подальшим дослідженням та визначенням просторових характеристик об’єктів, розпізнаванням об’єктів тощо. На основі моделювання відбитих сигналів за цими моделями можна буде класифікувати об’єкти. Важливою відмінністю цієї роботи є низка припущень про те, що робити з моделлю і як обчислити результат, оскільки, як правило, основним елементом таких досліджень є лише поверхня відбиття.

Результати. У дослідженні розглянуто спрощену модель відбиття сигналу від площі поверхні у просторі. Встановлено відповідність між поширенням хвилі у просторі та зміною значення функції, яка подає відбиту хвилю. У будь-який момент часу загальний відбитий сигнал є сумою всіх відбитих сигналів від усіх поверхонь. Для цього запропоновано інтегральну форму запису. Аналітичну формулу, призначену для інтегрування, розроблено для одного конкретного випадку відображення. Щоб перевірити формулу на фасетній моделі корабля, проведено чисельні експерименти. Отримана форма сигналу має очікуваний вигляд.

Висновок. Відповідно до поставленого завдання в роботі демонструється метод побудови моделі об’єктів та відбитих від них звукових сигналів, розглянуто загальні принципи методу синтезу відбивних характеристик складних поверхонь для малих довжин хвиль. Показано, чому і як саме будується така модель і наочно продемонстровано наявність істотної різниці в характеристиках сигналу для різних кутів. Основною перевагою цієї моделі є можливість проведення експериментів виключно в цифровій формі, без необхідності проведення дорогих польових експериментів. Подальші дослідження стосуватимуться напряму вибору чи створення оптимальної системи розпізнавання на основі нейронних мереж.

Ключові слова: *фацетна модель; дистанційне зондування; підстилаюча поверхня; гідролокаторне зображення.*