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RECOGNITION OF THE TYPE OF MARINE SHIP BASED ON COMPARISON WITH NORMALIZED REFERENCE PARAMETERS OF RADIOLOCATION SIGNALS

Introduction. *The problem of marine ship types recognition becomes more relevant than previously as it primarily focuses on the safety of sea and inland navigation. The basis of the identification of the type of marine ship is the use of training samples — a set of reference normalized parameters of mathematical models of radar portraits of reflected signalsfor which the type of ship is reliably known.*

The purpose of the paper *is to develop a method for recognizing the type of marine ship by comparing the parameters of the radar portrait of the reflected signal of the radar object with the reference parameters of the signals of mathematical models of known types of marine ships.*

Methods*. The recognition method is based on comparison of the normalized parameters of the radar signal of the object with the normalized parameters of the mathematical models of the database references with the help of a full search, after which a decision is made in favor of the type of marine ship for which the overall measure of inconsistency or the identification criterion is minimal. The* *identification criterion is the sum of dimensionless features, which are a similarity measure of the parameters regarding reference object in the chosen metric.*

Results. *Testing of the developed recognition method on test samples made it possible to identify the type and real orientation angle of the ship at the level of 83 % as well as to identify the types and recognize the orientation angles of marine ships at the level of 96 %.*

Conclusions. *The new method for recognition of the type of marine ship is characterized by high computational efficiency and speed of analysis, compactness of the reference database, high reliability and accuracy of recognition. Determination of auxiliary alternative values of the identification of the type and orientation angle of the ship helps to statistically specify the characteristics of the recognition of the ship in the dynamic mode of observation. The developed method for recognizing the type of ship can be used in the military sphere, its use in radar systems will improve the safety of sea and inland navigation.*

Keywords: *recognition method, identification, type of marine ship, radar portrait of reflected signal.*

INTRODUCTION

This article presents the results of the development of a new approach to solving the problem of recognition and identification of marine ships (MS) by comparing the parameters of the radar portrait of the reflected signal (RPRS) with the reference parameters of signals of mathematical models of the RPRS of known types of marine ships. There are two groups of methods that allow for resolving this problem. The first group includes learning without a teacher, when recognition is performed automatically and is based solely on the analysis of observation data. The second group includes learning with a teacher which uses a priori information about objects. It should be noted that in most cases the results of identification of MS without a teacher are less accurate compared to methods based on training and the use of reference samples. Implementations of these two groups of algorithms are described in sufficient detail, for example, in [1, 2]. Meanwhile, the identification and recognition of marine ships remains an actual problem despite the fact that the use of deep learning methods with the help of neural networks could provide higher accuracy for resolution of such tasks. However, this requires significant computing power and a large volume of the training sample (several thousand or more samples), otherwise the recognition accuracy drops compared to traditional methods of learning with a teacher. Considering this, with a small number of samples typical for the task of MS recognition, it is necessary to apply classical methods such as discriminant and histogram analysis as well as the construction of comparison metrics. At the same time, the task of recognition with learning is connected with a direct transition to the space of features. The paper considers the details of the proposed algorithm for solving the given problem by constructing a metric that allows establishing the degree of correspondence between the MS observation data vector and the reference parameters in the space of dimensionless features for identifying the type of ship.

PROBLEM STATEMENT

The tasks of object recognition based on radio signals are quite relevant because they primarily concern the safety of sea and inland navigation [3–5]. Similar problems and specific mathematical methods for recognition are found in various fields, for example, in sonar [6–7] and geolocation [8], in solving the problems of acoustic direction finding and acoustic monitoring [9–11] performed by scientists of the International Center, as well as in problems of classification of aerial objects [12–13]. A large number of different approaches to the recognition of optical [14] and radar signals [11, 15–19] significantly complicates the development of a new method for types of marine ships recognition, especially when solving the problems of dynamic radiolocation. The requirements for the new method are quite strict — it is the speed of analysis, the compactness of the reference database, the reliability and accuracy of recognition.

The task of recognizing the type of marine ship can be solved by comparing the parameters of the radar portrait of the signal reflected from the object (RPRS) with the reference parameters of the signals of the mathematical models of the RPRS for known types of marine ships.

The sequence of development of the method for recognizing the type of ship by RPRS signals can be as follows:

– generation of mathematical models of signals for given types of ships and different angles of their orientation, for selected values of the distance to the NS and the height of the radar position (DHR);

– histogram normalization of signals of mathematical models of the training sample;

– formation of a database of reference parameters of known types of ships;

– construction of a classification method capable of recognizing the type and angle of orientation of a sea-going ship based on the RPRS signal;

– assessment of the quality of ship type classification based on the signals of examination samples.

The purpose is to develop a new method for the type of marine ship recognition by comparing the parameters of the radar portrait of the reflected signal of the radar object with the reference parameters of the signals of mathematical models of known types of marine ships.

PRINCIPLES OF THE NEW METHOD OF IDENTIFYING THE TYPES OF MARINE SHIPS

Assume that the duration of the RPRS signal of a marine ship depends only on the type and angle of orientation of the NS, as well as on the range and height of the radar location (DHR), which is true for radar recognition of single ships in static conditions.

The basis of the NS type classification is the use of training samples — a set of reference parameters of signals of mathematical models of RPRS, recorded in the database (DB), for which the type of *Ship*, the value of the orientation angle C (*Heading*) of the mathematical model of the RPRS signal, as well as the value distance D (*Distance*) and height A (*Height*) location of DHR are known. The recognition method is based on comparing the histogram-normalized parameters of the RPRS signal with the parameters of the DB standards by a full search, and the decision is made in favor of the type of MS for which the overall measure of dissimilarity or the identification criterion R is minimal. The identification criterion R is the sum of characteristics that serve as a measure of similarity in the selected metric for comparing the parameters of the RPRS with the reference parameters of the database.

Normalization allows you to obtain information about the shape or structure of the RPRS signal, regardless of the actual amplitude values, which allows you to use it in recognition tasks. Here normalization of signals means the application of the theory of reduction for a significant decrease of the input data of RPRS [2] and the formation of a vector of normalized parameters of the reference signal $\boldsymbol{P} = (T, S, Fc_1, Fc_2, \ldots Fc_{if}, \ldots Fc_{Nf})$, where T is the duration of the RPRS signal; S is the unit of normalized signal amplitude; $Fc_1, \ldots, Fc_{Nf}$ — discrete values of histogram-normalized amplitudes; N_f is the number of duration intervals of the normalized RPRS signal.

The most important characteristic in this recognition method is the parameter T, which is the duration of the RPRS signal, that functionally depends on the orientation angle of the mathematical model C and to a large extent on the type of *Ship*. In order to reduce the volume of a full search of DB references, the value of the coefficient k_T is introduced in the recognition method that determines the range of the duration of the RPRS signal when compared with the values of the duration of signals of references' mathematical models, which allows not to analyze reference signals with very small values or with very large values of signal duration.

GENERATION OF MATHEMATICAL MODELS OF SIGNALS OF GIVEN TYPES OF SHIPS

Interpretation and identification of targets based on their radar images depends on the ability to distinguish between characteristic features of the object of observation. Such features can be values of the radar cross-section (RCS), spatial characteristics, for example, size and shape etc.

Currently, digital methods of modeling the secondary radiation of real objects using computer technology have become widely used. Conducting natural (physical) experiments to obtain radar information is associated with certain organizational, financial and time difficulties, which often complicates application of such methods. The main advantage of mathematical modeling is the possibility of obtaining a large number of radar portraits of the reflected signal, with a given accuracy, for different angles of objects in a short time when using relatively small computing power.

The calculation of the characteristics of scattering by complex-shaped radar objects is carried out on the basis of a mathematical description of their surface. The existing methods of numerical calculation of the RCS of complex radar objects make it possible to calculate the total scattering characteristics of a static object for each irradiation angle. The results of the analysis of the existing methods for modeling the surface of a radar object of a complex shape showed that the most adequate and widely used of them is the method based on the approximation of the surface of complex radar objects by elementary triangular sections (facets). The main advantage of the faceted representation of the surface of complex radar objects is the absence of restrictions on the geometry of the modeled object of complex shape, as well as the possibility of setting the electromagnetic reflection parameters of radar signals for each facet [20].

Exact methods for calculating the RCS of a radar object are based on Maxwell's equations in integral or differential form and include the method of moments, the method of finite elements, the method of finite differences in the time domain, the method of finite integrals and their hybrid modifications. Currently, the use of accurate RCS calculation methods is limited due to the necessity of the significant computing power usage in their implementation [21].

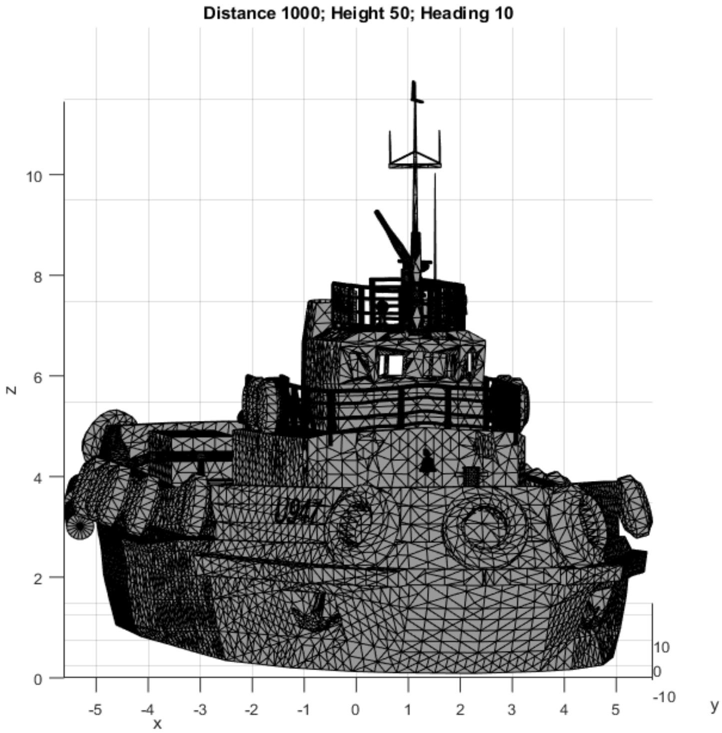

Fig. 1. View of the faceted 3D model of the Project 498, Saturn-type tugboat

From the asymptotic methods of calculating the secondary radiation of radar objects of a complex shape, the method of geometric optics, the method of physical optics, the geometric theory of diffraction, the physical theory of diffraction and their modifications can be distinguished. Among the asymptotic methods, the most acceptable, from the point of view of the required volume of calculations, are the methods of geometric optics, in which the behavior of the electromagnetic field between two neighbouring environments is described by the Snelius law, and the amplitude and phase of the reflected radiation is determined by the Huygens-Fresnel principle. The essence of the Huygens-Fresnel principle is that the real sources of the electromagnetic field are replaced by a surrounding (enveloping) radiating surface [12, 22].

Based on application of the Huygens-Fresnel principle the secondary electromagnetic field simulation technology was developed, which involves working with 3D models of ships to simulate reflected radar signals at probing signal frequencies in the range 1–10 GHz. The wavelength of electromagnetic radiation of this frequency range is much smaller than the linear dimensions of the 3D models of the ships that are supposed to be studied. In this regard, the Huygens-Fresnel method was used to solve the problems of simulating the secondary radiation of 3D models of ships with a complex spatial configuration, as the basis for solving the problems of simulating radar portraits of objects based on the use of superposition of elementary reflected radar signals of the secondary electromagnetic field.

In Figure 1 is shown an example of the image of the faceted 3D model of a project 498, Saturn-type tugboat, from the current DHR angle of observation.

DETERMINATION OF THE PARAMETERS OF THE NORMALIZED SIGNAL BY RADIO PORTRAIT OF THE REFLECTED SIGNAL

Normalization of the RPRS signal of the simulation model of the ship is performed in the following sequence:

- read the value of the reflected radar signal of the RPRS after amplitude detection;
- build a contour (envelope) of the simulation model of the reflected radar signal;
- form a rectangular "profile" [12] of the normalized signal by the number of signal duration intervals along the abscissa axis N_F and the number of intervals along the amplitude axis N_A;
- determine the average values of the amplitudes of the contour signal $y(t)$ for each interval of the duration of the signal t_{if} with a duration of $dt = T / N_F$ and find the maximum average value of the amplitude y_{max} among them;
- determine the discrete values of the form-codes of the normalized amplitudes Fc_{if} as the interval number according to the amplitude of the rectangular "profile" by normalizing the average value of the amplitude y_{if} in the interval i_f to the value y_{max} for the total number of amplitude intervals N_A;
- calculate the value of the unit of amplitude S (unit of power) of the normalized signal, as the ratio of the total power of the signal to the total sum of the values of the form-codes of the normalized amplitudes;
- obtain that the real amplitude of the normalized signal in the interval i_f has the value $y_{if} = S \cdot Fc_{if}$, at the same time, the minimum value of the amplitude will be 0 (zero), and the maximum value of the amplitude will be $y_{max} = S \cdot N_A$.

Unlike standard approaches to normalization [12], the obtained rectangular "profile" is invariant in size and with discrete values of the normalized signals. The results of the study proved that the number of normalization intervals along the abscissa axis $N_F = 16$ and the number of normalization intervals along the amplitude axis $N_A = 15$ are optimal for using the normalized signal in the tasks of recognizing ship types with the required accuracy. That is, 18 signal parameters: T (signal duration), S (amplitude unit) and 16 values of normalized form-codes ($Fc_1, Fc_2, \ldots Fc_{if}, \ldots Fc_{16}$) unambiguously and sufficiently describe the normalized signal.

Integer parameters Fc_{if} received the name "shape code" of the signal, because they characterize the shape of the normalized signal in a discrete form, regardless of the amplitude values. The use of both form-codes and normalized signal amplitudes when determining the features of the identification criterion R made it possible to build an effective method for recognizing types of marine ships by RPRS signals.

The value of the Fc_j signal form-codes can be written in symbolic form, where each value of Fc_{if} corresponds to a hexadecimal number with alphabet ‘0’…’*F*’, for example, 16 values of the vector $\boldsymbol{Fc}$ = (14, 14, 11, 7, 11, 10, 2, 7, 15, 6, 9, 9, 8, 8, 4, 2) is interpreted as the character form-code 'EEB7BA27F6998842', in which the hexadecimal letters correspond to the decimal numbers: 'A' = 10, 'B' = 11, 'C' = 12, 'D' = 13, 'E' = 14, 'F' = 15. The use of symbolic form-codes can be useful for significantly reducing the volume of the database of normalized signal parameters with little time spent on unpacking real values of form-codes.

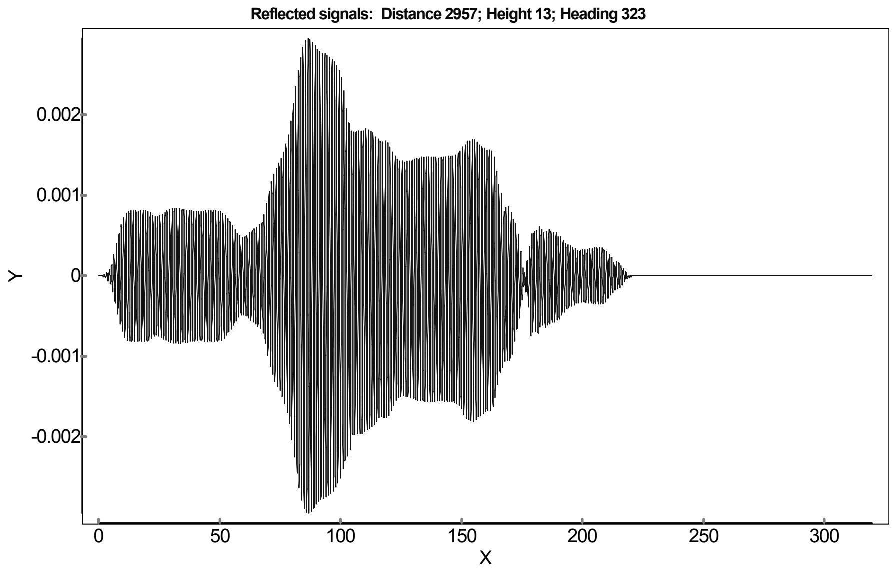

Fig. 2. Input signal of the mathematical model of the "498_Saturn" type ship

Determination of the average envelope of the input signal. We analyze the input signal of the RPRS, given in the form of a vector of amplitudes $\boldsymbol{Y}_i$, $i \in 1,\ldots,N$, where N is the number of vector points that belong to the mathematical model or the real MS signal. We begin with the formation of the abscissa vector $\boldsymbol{X}_i$, $i \in 1,\ldots,N$ with time discretization Δt_0.

As an example, we will analyze the signal of the mathematical model of the "498_*Saturn*" type ship without high-frequency noise for DHR parameters: range D (*Distance*) = 2957, height A (*Height*) = 13, ship orientation angle C (*Heading*) = 323°. The input signal $Y(x)$ is shown in Figure 2.

Let's find the average values (1) of the input signal with high-frequency modulation. To achieve this, successively analyze the amplitudes of the signal Y(x), determine the range of indices of the points $[i_1,i_2]$, for which ($y_i > 0$), and the coordinates of the middle point k of the lower envelope (x_{botj},y_{botj}), and calculate the total number j points of the average values of the lower envelope $N_{bot} = \max(j)$:

$$y_{botj} = \frac{\sum_{i=i_1}^{i_2} y_i}{i_2 - i_1 + 1}, x_{bot} = x_k, \quad k = (i_1 + i_2)/2, \tag{1}$$

Then, continue to analyze the amplitudes of $y(x)$ according to formula (1) under the condition ($y_i > 0$), and determine the coordinates of the points of the average values of the upper envelope $y_{top}(x_{top})$ and count the number of points of the average values of the upper envelope N_{top}. In Figure 3 a fragment of the input signal *Yisx* with the points of the average values of the lower envelope Y_{bot} and the upper envelope Y_{top} is shown.

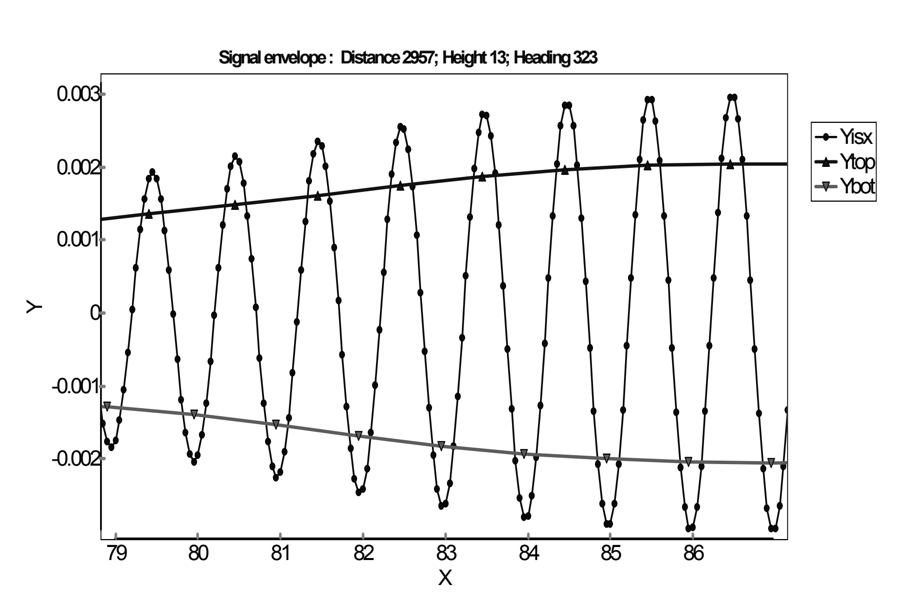

Fig. 3. Input signal and midpoints of the lower and the upper envelope

Real RPRS signals of marine ships are almost always noisy with high-frequency noise, so it is necessary to filter them out for further use. High-frequency filtering of signal $y_i(x)$ with the length N is performed by the three-point current average method

$$y_i = (y_{i-1} + y_i + y_{i+1}) / 3, \quad i = 2,..., \ N - 1, \qquad (2)$$

To combine the average values of the lower and upper envelope, it is necessary for the abscissas of their respective points to coincide. First, the signal of the lower envelope y_{bot} is filtered and the amplitudes $y_{\mathrm{sr}bot}$ of the received signal are linearly restored for a new abscissas vector $\boldsymbol{X}_{sr}$ of average values of the signal envelope with the length N_{sr} and an increased sampling step Δt. Then the process is repeated for the signal of the upper envelope y_{top} and the amplitudes $y_{\mathrm{sr}top}$ are linearly restored for the abscissas $\boldsymbol{X}_{sr}$.

Linear restoration of the amplitude of the average values of the lower envelope $y_{\mathrm{sr}boti}$ at the point $x_{\mathrm{sr}i}$ consists in finding the interval between two consecutive abscissas of the points of the lower envelope (x_{botj}, y_{botj}) and (x_{botj+1}, y_{botj+1}), for which the condition (3) is fulfilled, and the value of $y_{\mathrm{sr}boti}$ is determined by linear interpolation (4) between two points for the abscissa $x_{\mathrm{sr}i}$

$$x_{botj} \le x_{sri} < x_{botj+1}, \qquad (3)$$

$$y_{srboti} = \frac{y_{botj+1} - y_{botj}}{x_{botj+1} - x_{botj}} (x_{sri} - x_{botj}) + y_{botj}. \qquad (4)$$

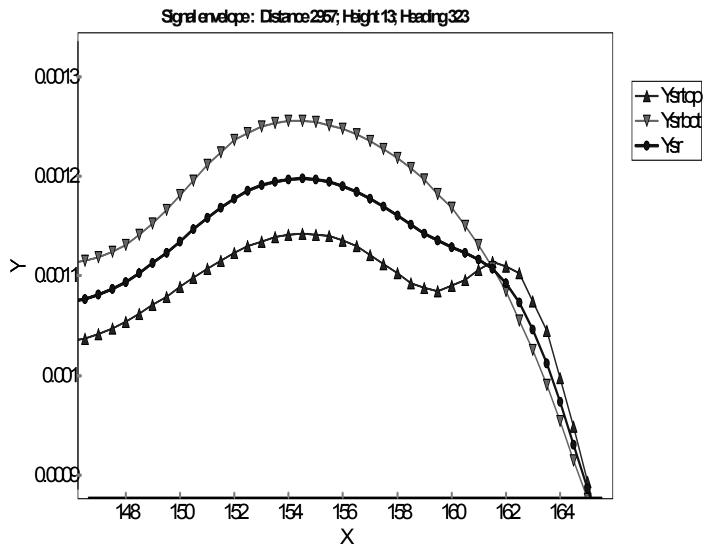

Fig. 4. Fragment of the signals of the upper, lower and middle envelope

Then, high-frequency filtering (2) of the signal of the upper envelope y_{top} is performed and linear restoration (4) of the average values of the amplitudes of the upper envelope y_{srtopi} for the same values of the abscissa x_{sri} is carried out.

Next, the average absolute values of the amplitudes of the signal envelope $y_{\text{sr}i}$ are determined for the points x_{sri} according to expression (5) and again high-frequency filtering (2) is performed

$$y_{sri} = (\left|y_{srtopi}\right| + \left|y_{srboti}\right|) / 2, \quad i \in 1,...,N_{sr} . \tag{5}$$

Figure 4 shows a fragment of the signals of the average absolute values of the amplitudes of the lower envelope Y_{srbot} and upper envelope Y_{srtop} and the average values of the envelope Y_{sr}.

DETERMINATION OF NORMALIZED SIGNAL PARAMETERS

The duration T of the average envelope signal $y_{sr}(x_{sr})$ is defined as the discrete value of the maximum abscissa $T = x_{sri}$, $i = N_{sr}$. The duration of the signal is divided into $N_f = 16$ intervals, then the duration of the time interval will be $\Delta T = T / N_f$.

Then, calculate the average values of the amplitudes of the signal envelope $F_{\text{sr}j}$ in each j interval and determine the maximum value of the amplitude $F_{\max}$ among them.

Next, carry out discrete normalization of the average amplitudes of the envelope signal $F_{\text{sr}j}$ by the maximum value of $F_{\max}$ for N_A amplitude intervals and determine the integer values of the form-code of the signal Fc_j in the j interval

$$Fc_j = round(\frac{F_{srj} \cdot N_A}{F_{max}}), \quad j \in 1,...,N_f , \tag{6}$$

where *round* is a function that converts value to the nearest higher integer.

Discrete integer values of the vector ***Fc*** in each interval, or "form-codes" of the signal, indicate the number of units of amplitude S that correspond to the normalized signal of the envelope, i.e., the real amplitude of the normalized signal in the interval j has the value $y_j = S \cdot Fc_j$, while the minimum amplitude value will be 0 (zero) and the maximum amplitude value will be $y_{max} = S \cdot N_A$. This actually means that a histogram of the amplitude distribution of the normalized signal is constructed [22].

The value of the unit amplitude of the normalized signal S is refined by the value of the total signal power of the average amplitudes of the envelope U_{sum} and the sum of the values of Y_{sum} of the form-codes Fc_j in all intervals, while U_{sum} is defined as the sum of the values of the amplitudes y_{sr}

$$U_{sum} = \int_{x_{sr1}}^{x_{srN}} y_{sr} dx = \sum_{i=1}^{N_{sr}} y_{sri}, \quad Y_{sum} = \sum_{j=1}^{N_f} Fc_j , \tag{7}$$

$$S = \frac{U_{sum}}{Y_{sum}} . \tag{8}$$

Then, assume that the abscissas t_j of the normalized signal $F(t)$ are the middle of each j interval, the amplitudes are the value $f_j = S \cdot Fc_j$, the coordinate of the first point is (0,0), and the end point is $(T,0)$, where $j \in 0,\ldots,N_f+1$, that is

$$t_j = (j + 0,5) \cdot \Delta T, \quad f_j = S \cdot Fc_j . \tag{9}$$

Figure 5 shows the envelope of the signal Y_{sr}, the average values of the amplitudes in the intervals F_{sr} and the normalized signal F.

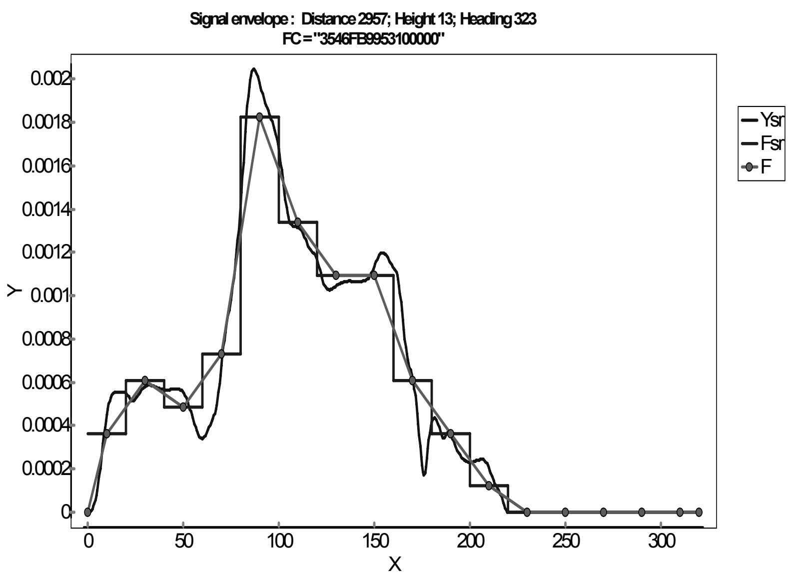

Fig. 5. Signal envelope, average values of the intervals' amplitudes and normalized signal of the mathematical model of the "498_Saturn" type ship

Output parameters of the signal normalization are the duration of the signal *T*, the unit of amplitude of the normalized signal *S* and the vector of normalized values of the form-code ***Fc***.

FORMING DATABASE OF REFERENCE PARAMETERS OF NORMALIZED SIGNALS

The use of a DB of normalized reference parameters of mathematical models of various types of ships allows solving the problem of recognizing the type of marine ship by comparing the obtained normalized parameters of the RPRS signal with the parameters of the signals stored in DB.

The main database variables are the DHR parameters: range *DData* and altitude *AData* and MS parameters: ship type *ShipData* and the orientation angle of the model *CData*.

The database is a set of values of 18 parameters of normalized RPRS signals (T, S, $Fc_1 \ldots Fc_{16}$), where T is the duration of the signal; S is the unit of normalized signal amplitude; $Fc_1 \ldots Fc_{16}$ are normalized signal form-codes, which are defined for a given list of values of the main variables of the training sample: *AData*, *ShipData*, *CData* reference signals of mathematical models of reflected radar portraits recorded in the database.

Parameter value sets are formed as four-dimensional arrays for each *DData* distance value. The formed four-dimensional arrays are recorded as binary files with the same type of data in the "*Real*" format (4 bytes) by successive line recording of the values of parameters T, S, $Fc_1 \ldots Fc_{16}$. Before the recognition procedure, the values of the binary files are read into four-dimensional arrays for each *DData* range value and combined by a function that allows you to access the database as an array element by index.

The main variables of the training sample of reference signals of mathematical models of reflected radar portraits recorded in the database have the values given in the Table 1.

Table 1. Values and indices of the main database variables

Index	Main database variables			
	Distance, m *DData*	**Height, m *AData***	**Ship type *ShipData***	**Model orientation angle, degrees *CData***
0	1000	10	498_Saturn	0
1	2000	20	1164	2
2	2900	40	Giurza	4
3	3000	60	Nevsky	6
4	3100	80	r-51e	8
5	-	100	Sagaydachniy	10
6	-	-	ship1_8k	12
7	-	-	Voskhod	14
…	-	-	-	…
179	-	-	-	358

We will indicate with the suffix “*Data*” the names of the main variables and parameters (*DData, AData, ShipData, CData, TData, SData, FcData* etc.), which refer to the references of the mathematical models of the DB, in order to distinguish them from the main variables and parameters of the marine ship RPRS signal, which will be designated with the suffix "*Radar*" (*DRadar, ARadar, ShipRadar, CRadar, TRadar, SRadar, FcRadar* etc.).

The database formation algorithm is as follows:

Step 1. Loop through the values of the main variables *DData, AData, ShipData, CData*.

Step 2. Determine the parameters of the normalized signal (*TData, SData,* vector *FcData*) based on the radar portrait of the reflected signal of the mathematical model.

Step 3. Form a 4-dimensional array of PData parameters with dimensions (N_A, N_{Ship}, N_C, N_P) and write the normalized signal parameters into it, where $N_A = 6$ — the number of *AData* height values with the *iA* index, $N_{Ship} = 8$ — the number of ship types with the iShip index, $N_C = 180$ – the number of *CData* model orientation angle values from 0^o to 358^o in steps of 2^o with the *iC* index, $N_P = 18$ – the number of normalized parameters with the *iP* index:

$PData_{iA,\, iShip,\, iC,\, 0} = TData$

$PData_{iA,\, iShip,\, iC,\, 1} = SData$

$PData_{iA,\, iShip,\, iC,\, 2} = FcData_1$ ...

$PData_{iA,\, iShip,\, iC,\, NP-1} = FcData_{NP-2}$

Step 4. Finish looping through the main variables *AData, ShipData, CData*.

Step 5. Write the formed 4-dimensional *PData* array into a binary file with the same type of data in the “*Real*” format (4 bytes), by sequentially writing the values of the normalized signal parameters.

Step 6. Finish looping through the main variable *DData*.

A database binary file has an internal structure consisting of "header" and "data". In the "header" the dimension values of the 4-dimensional array are written, and in the "data" — the same type of parameter values.

When reading a database file, the dimension values are first read and a 4-dimensional array is formed, then the data values from the database file are written into the array elements. This approach to the use of multidimensional arrays ensures the preservation of information about the structure and dimensions of the array in the file itself, which is very important for long-term use and modification of these files.

IDENTIFICATION OF THE TYPE OF MARINE SHIP

Recognition of the type of marine ship is carried out by a complete search of the database, comparison of the normalized parameters of the RPRS signal with the reference parameters and determination of the minimum value of the identification criterion $R = R_{\_min}$. The identification criterion R is the sum of features that are a measure of similarity in the selected metric for comparing normalized signal parameters.

Before starting the recognition of the MS type, the RPRS signal is normalized, as a result of which we obtain the following parameters: the duration of the *TRadar* signal, the amplitude unit of the normalized *SRadar* signal, and the vector of normalized values of the ***FcRadar*** form-code. These parameters are compared to the corresponding *TData*, *SData* and ***FcData*** vectors of the database.

The identification criterion R is the sum of four dimensionless values of comparison features

$$R = R_T + R_{FR} + R_{FL} + R_{DF}, \quad (10)$$

where R_T is a sign of comparing the duration of signals; R_{FR} is a sign of comparison of real signal amplitudes; R_{FL} is a sign of comparison of the distance between real amplitudes; R_{DF} is a feature for comparing derivative form-codes of normalized signals.

To determine the minimum identification criterion $R_{\_min}$, the repeated voting procedure [12] is used, the essence of which is that a table of results of *ParamA* determination of features *R* is first formed by comparing the object with standards for a specific value of the parameter *A* (height) taking into account the coefficient k_T, which allows not to analyze references with very small values or with very large values of signal duration: $(1–k_T)\cdot TRadar > TData > (1+k_T)\cdot TRadar$.

In the *ParamA* table, the minimum value of the R_{min} criterion is determined by primary voting. In the next stage, a table of *ParamResult* results of predefined minimum identification criteria R_{min} is formed for each type of *Ship* and height *A*, in which the minimum value of the $R_{\_min}$ criterion is determined by secondary voting.

The minimum value of $R_{\_min}$ in the table of results *ParamResult* and the corresponding parameters of the type of marine ship are taken as the result of the recognition algorithm.

By re-voting in the *ParamResult* result table, the minimum value of the R_{Altmin} criterion, which is greater than $R_{\_min}$, is determined. The parameters corresponding to R_{Altmin} are taken as an alternative result of the recognition algorithm, which can confirm or refute the previous statistical recognition result during the dynamic movement of the MS.

ASSESSMENT OF THE QUALITY OF SHIP TYPE CLASSIFICATION

Testing of the developed method for the type of marine ship recognition and determining the classification quality was carried out in several stages: first, an examination sample of 10 arbitrary values of the main variables for the ship type "498_Saturn" was tested, both with and without high-frequency noise, then the reference sample of mathematical models of the DB was used as an examination sample for a specific height value of the missile homing head.

Recognition of examination sample signals without noise. We will apply the developed method for the type of marine ship recognition to an examination sample of 10 signals of mathematical models of RPRS without noise for the type of ship "498_Saturn" with arbitrary specific values of the main variables: *DRadar* distance, *ARadar* DHR height and *CRadar* ship orientation angle.

In Figure 2 is shown the signal of the mathematical model of the "498*_Saturn*" type ship without noise for the DHR parameters: *DRadar* distance = 2957, *ARadar* height = 13, and *CRadar* ship orientation angle = 323, and in Figure 5 — signal envelope, average values of amplitudes in intervals and the normalized signal of the mathematical model.

It should be noted that the values of the duration of the signal T are very close in value for symmetrical angles of orientation of the model relative to the coordinate axes, and this leads to the fact that the recognition procedure actually determines not the real angle of orientation of the model, but the direction of the angle. Therefore, during recognition, the orientation angle of the model C is reduced to an angle in the range of 0–90° according to the conditions and written after the value of the orientation angle of the model in round brackets:

Given angle:		Conditions:
$(0^o \ldots 90^o) = C,$	for	$0^o \le C \le 90^o$
$(0^o \ldots 90^o) = 180^o - C,$	for	$90^o < C \le 180^o$
$(0^o \ldots 90^o) = C - 180^o,$	for	$180^o < C \le 270^o$
$(0^o \ldots 90^o) = 360^o - C,$	for	$270^o < C < 360^o$

Recognition of signals of the examination sample with noise. Real RPRS signals after amplitude detection Y(t) may contain high-frequency interference of the radar system. We will test the developed method for recognizing the type of marine ship on the same test sample of 10 signals with the addition of high-frequency white noise with a zero average value and with a noise/signal ratio = 0.1.

Let's add high-frequency interference to the signal of the mathematical model of the "498_*Saturn*" type ship without noise (Fig. 2), the graph of the received input signal is shown in Figure 6.

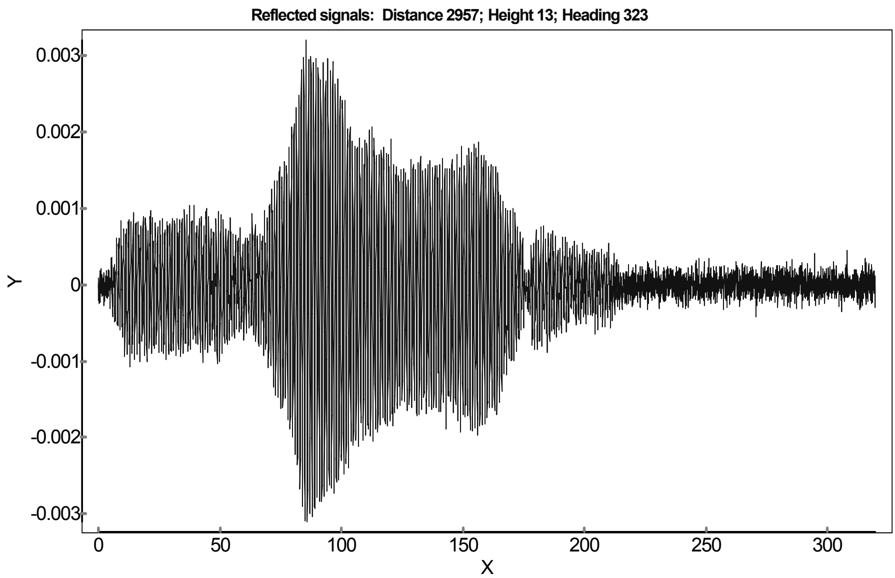

Fig. 6. Signal of the mathematical model of the ship "498_Saturn" with noise

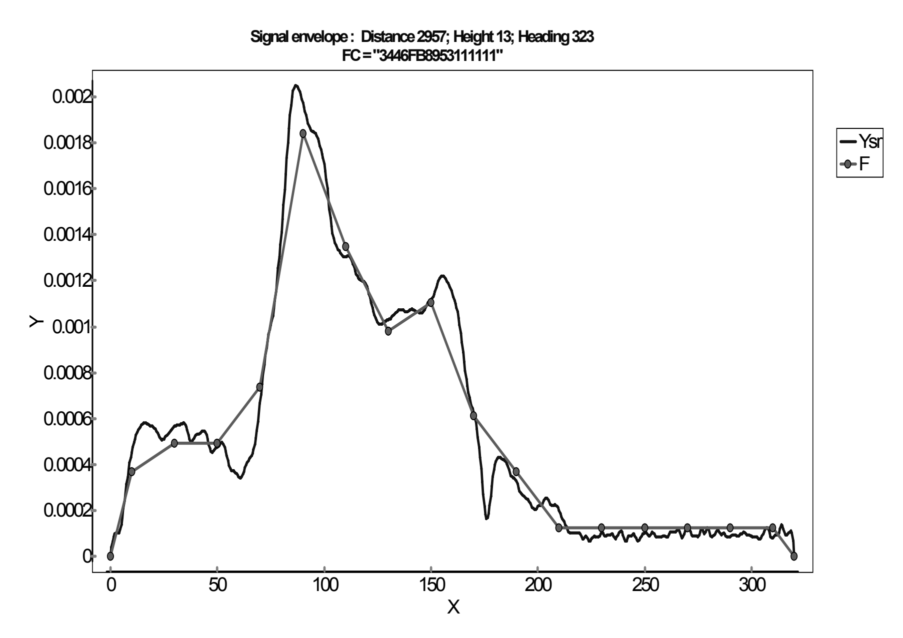

Fig. 7. Signal envelope with noise and normalized signal

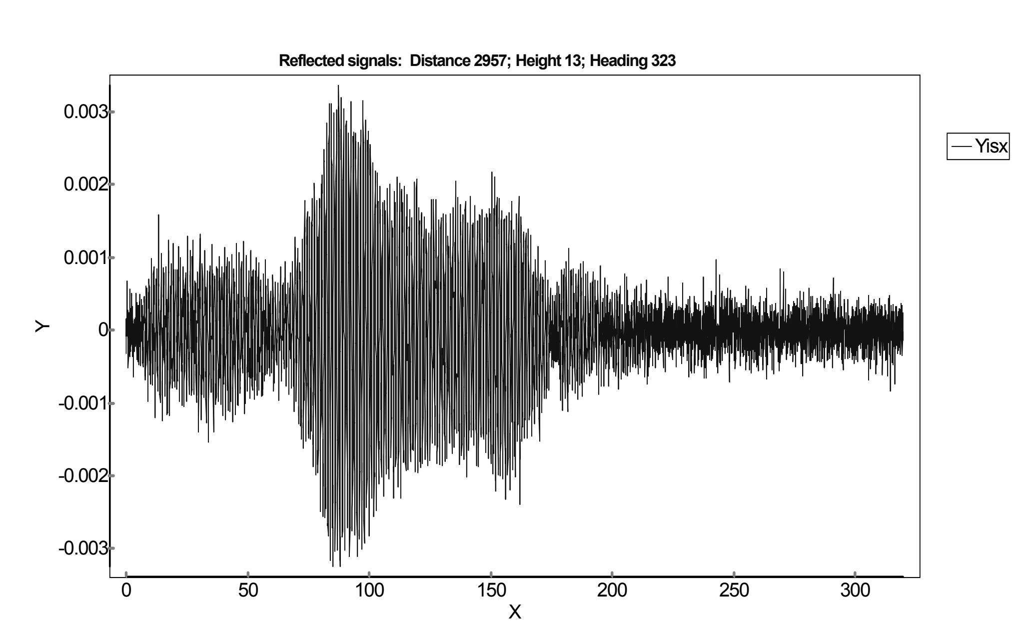

Fig. 8. Mathematical model signal of the ship "498_Saturn" with double noise

After determining the average envelope of the input signal Y_{sr}, the resulting normalized signal F for the mathematical model of the ship "498_*Saturn*" with noise will look as shown in Figure 7.

Recognition of double-noise test sample signals. We will test the developed method for recognizing the type of marine ship on the same test sample of 10 signals with the addition of double high-frequency white noise with a zero mean value and with a noise/signal ratio = 0.2. The graph of the input signal (Fig. 8) will be as follows.

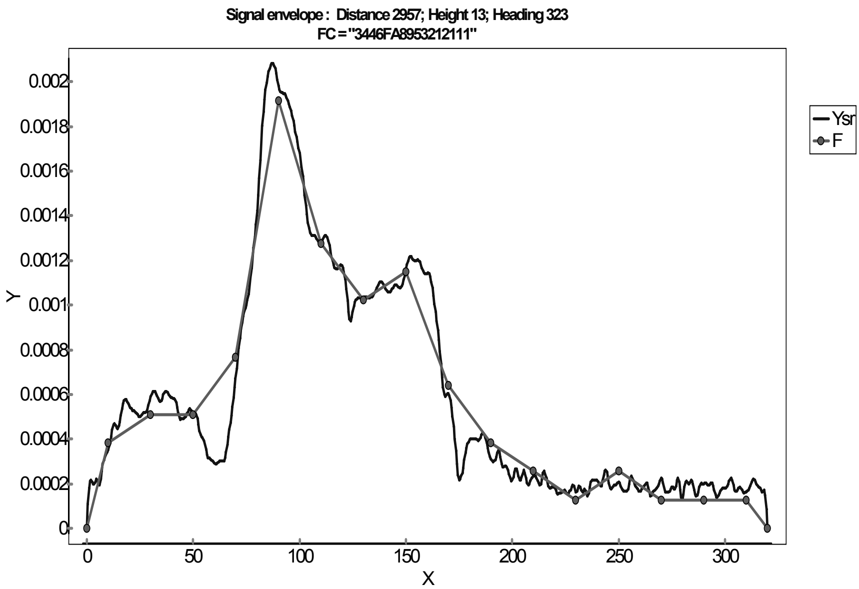

Fig. 9. Double noise envelope and normalized signal

Table 2. Testing the signal recognition method without noise, with noise and with double noise for ShipRadar = “498_Saturn”

Radar parameters			Signal type	Recognition option	*Data* identification parameters			
Dis-tance, M	Height, m	Orien-tatin angle, degrees			Ship type	Dis-tance, m	Height, m	Orienta-tion angle, degrees
DRa-dar	*ARadar*	*CRadar*			*ShipData*	*DDat a*	*AData*	*CData*
2957	13	323 (37)	Without noise	recognized	498_Saturn	3000	10	324 (36)
				alternative	498_Saturn	2900	10	324 (36)
			With noise	recognized	498_Saturn	3000	10	324 (36)
				alternative	498_Saturn	2000	80	326 (34)
			With double noise	recognized	498_Saturn	3000	10	324 (36)
				alternative	498_Saturn	3000	80	322 (38)

Table 3. Statistical data of ship type identification and orientation angle recognition of the model of 10 signals of the examination sample

Identified / Recognized	Signal without noise, %	Signal with noise, %	Signal with double noise, %
Ship type identified with real model orientation angle	50	60	50
Ship type identified correctly	90	90	80
Ship type identified alternatively	100	100	90
Model orientation angle recognized	70	80	90
Model alternative orientation angle recognized	80	90	90

After determining the average envelope of the input signal Y_{sr}, the resulting normalized signal F of the mathematical model of the ship "498_*Saturn*" with double noise is shown in Figure 9.

It should be noted that the symbolic values of the form-codes (FC) of signals without noise "3546FB9953100000" (Fig. 5), with noise "3446FB8953111111" (Fig. 7) and with double noise "3446FA8953212111" (Fig. 9) are very similar, and this testifies to the efficiency of the used procedures of high-frequency filtering of input signals and obtaining a normalized signal.

The results of testing the method for recognizing the type of ship "498_*Saturn*" of the given signals of the examination sample of mathematical models without noise, with noise, with double noise and DHR parameters: *DRadar* distance = 2957, *ARadar* height = 13 and *CRadar* ship orientation angle = 323 are displayed in the Table 2.

Table 3 shows statistical data of ship type identification and model orientation angle recognition of all 10 signals of the examination sample.

Statistical characteristics given in table 3 have the following meanings:

Ship type identified with real model orientation angle — the type is correctly identified and the real orientation angle of the ship is correctly recognized, which completely coincide with the type and orientation angle of the MS (0^o...358^o) within 8^o (according to the minimum value of the identification criterion);

Ship type identified correctly — the identified ship type completely matches the MS type (according to the minimum value of the identification criterion);

Ship type identified alternatively — the identified ship type or the alternatively identified ship type matches the MS type (according to the minimum and alternative identification criteria);

Model orientation angle recognized — the recognized orientation angle of the ship model (0^o...90^o) coincides with the orientation angle of the MS (0^o...90^o) within 8^o (according to the minimum value of the identification criterion);

Model alternative orientation angle recognized — recognized orientation angle of the model or alternative orientation angle of the model (0^o...90^o) coincides with the orientation angle of the MS (0^o...90^o) within 8^o (according to the minimum and alternative identification criteria).

Comparison of the results of testing the ship type recognition method based on an examination sample of 10 signals of mathematical models without noise, with noise and with double noise shows that there are no significant differences in the results, and this allows us to assert the ability of the proposed recognition method to analyze radar signals that are distorted by high-frequency obstacles.

It can be asserted that the quality of the type identification and recognition of the given orientation angle of the ship for the signals of the examination sample with arbitrary specific values of the distance, altitude, orientation angles of the ship and the presence of high-frequency noise is quite high.

Recognition of signals of all types of ships from the reference database. We will test the recognition of all types of ships according to the reference parameters of signals of mathematical models, which are recorded in the reference database.

The procedure for testing recognition of ship types based on the signals of mathematical models of the reference database begins with reading the files of the reference database and forming 4-dimensional arrays in which parameter values from the database files are written. We will perform testing by sorting the values of the variables *ShipRadar, DRadar, CRadar* (Table 1) for a fixed value of the variable *ARadar* = 20.

During the identification of the current Radar model, we will not take into account cases when (*ShipRadar* = *ShipData*) & (*DRadar* = *DData*) & (*ARadar* = *AData*), because in these cases, for all orientation angles of the CData model, the value of the identification criterion is identical to $R \equiv 0$.

In Table 4 listed statistical data of testing the method for recognizing the type of marine ship *ShipRadar* = "498_*Saturn*", for all distance values of *DRadar* and *ARadar* = 20. The names of columns 3–7 in Table 4 and their decoding is described in the comments to Table 3.

Table 4. Statistical data of testing the method for recognizing the type of marine ship "498_Saturn" according to the reference normalized parameters of reflected signals of mathematical models for ARadar = 20

Ship name	**Dis-tance, m**	**Ship type identified with real model orientation angle, %**	**Ship type identified correctly, %**	**Ship type identified alterna-tively, %**	**Model orientation angle rec-ognized, %**	**Model al-ternative orientation angle rec-ognized, %**
1	2	3	4	5	6	7
498_Saturn	1000	63,3 (66)	91,7 (15)	96,7 (6)	93,3 (12)	97,2 (15)
	2000	73,9 (47)	92,8 (13)	96,1 (7)	94,4 (10)	96,7 (6)
	2900	98,9 (2)	100 (0)	100 (0)	100 (0)	100 (0)
	3000	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)
	3100	99,4 (1)	100 (0)	100 (0)	100 (0)	100 (0)

Notes:
Columns 3–7 indicate the percentage of correctly identified ship types (recognized model orientation angles) for all 180 *CRadar* orientation angles (with a step of 2^{o}), and the number of recognition errors in round brackets.

Table 5. *Average statistical data of testing the method for recognition of all types of marine ships according to the reference normalized parameters of reflected signals of mathematical models for* ARadar *= 20*

Criterion	**Dis-tance, m**	**Ship type identified with real model orienta-tion angle, %**	**Ship type identified correctly, %**	**Ship type identified alterna-tively, %**	**Model orientation angle rec-ognized, %**	**Model al-ternative orientation angle rec-ognized, %**
1	2	3	4	5	6	7
Average value for all types	1000	55,0	87,5	93,3	90,3	95,0
	2000	74,2	95,2	97,4	96,2	98,1
	2900	93,8	99,0	99,7	99,1	99,7
	3000	96,3	99,1	99,7	99,2	99,6
	3100	95,3	99,5	99,8	99,4	99,7
Total average value		82,9	96,1	98,0	96,8	98,4

The test results indicate that the application of a denser grid of changes in the main variable *DData* (DHR distance) with a step of 100 m allows to achieve for some ships an absolute result of identifying the type of ship and recognizing the real orientation angle of the model.

Table 5 shows the average and general statistical data of testing the method for recognition of all types of marine ships based on the reference normalized parameters of reflected signals of mathematical models for *ARadar* = 20.

According to the test results given in the Table 5, it can be stated that the developed method allows to recognize the type and real orientation angle of the ship at the level of 83%, as well as to identify the types of marine ships and recognize the given orientation angles of the models at the level of 96%.

CONCLUSIONS

The method for recognizing the type of marine ship by comparing the normalized parameters of the radar portrait of the reflected signal with the reference parameters of signals of mathematical models of known types of marine ships is characterized by the use of insignificant computing power, high speed of analysis, compactness of the reference database, high reliability and accuracy of recognition.

Determination of auxiliary alternative values of the identification of the type and orientation angle of the ship helps in the dynamic mode of observation to statistically specify the characteristics of the recognition of the ship.

The results of testing the new recognition method showed that the accuracy of identifying the type and orientation angle of the ship does not depend on the distortion of radar signals by high-frequency noises at the level of the noise/signal ratio of less than 0.2.

Testing of the developed recognition method on examination samples made it possible to identify the type and real orientation angle of the ship at the level of 83 % as well as to identify the types and recognize the orientation angles of marine ships at the level of 96 %.

The use of a new method for recognition in radar systems will improve the safety of marine and inland navigation and can also be used in the military sphere.

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РОЗПІЗНАВАННЯ ТИПУ МОРСЬКОГО КОРАБЛЯ НА ОСНОВІ ПОРІВНЯННЯ З НОРМОВАНИМИ ЕТАЛОННИМИ ПАРАМЕТРАМИ РАДІОЛОКАЦІЙНИХ СИГНАЛІВ

Вступ. *Проблема розпізнавання типів морських кораблів залишається актуальною, тому що вона стосується, насамперед, безпеки морського та внутрішнього судноплавства. В основі ідентифікації типу морського корабля лежить використання навчальних вибірок – набору еталонних нормованих параметрів математичних моделей радіолокаційних портретів відбитих сигналів, записаних у базі даних, за якими достовірно відомо тип корабля.*

Мета статті. *Розроблення методу розпізнавання типу надводного морського корабля шляхом порівняння параметрів радіолокаційного портрету відбитиго сигналу радіолокаційного об'єкта з еталонними параметрами сигналів математичних моделей відомих типів морських кораблів.*

Методи. *Метод розпізнавання полягає в порівнянні нормалізованих параметрів радіолокаційного сигналу об'єкта з нормованими параметрами математичних моделей еталонів бази даних шляхом повного перебору і приймається рішення на користь типу морського корабля, для якого загальна міра невідповідності, або критерій ідентифікації є мінімальним. Критерій ідентифікації — це сума безрозмірних ознак, які є мірою подібності у вибраній метриці параметрів об'єкта з еталонами.*

Результати. *Тестування розробленого методу розпізнавання на екзаменаційних вибірках дало змогу ідентифікувати тип та реальний кут орієнтації корабля на рівні 83%, а також ідентифікувати типи та розпізнати кути орієнтації морських кораблів на рівні 96%.*

Висновки. *Новий метод розпізнавання типу морського корабля відзначається використанням незначних обчислювальних потужностей, великою швидкістю аналізу, компактністю еталонної бази даних, високою надійністю та точністю розпізнавання. Визначення допоміжних альтернативних значень ідентифікації типу та кута орієнтації корабля допомогає в динамічному режимі спостереження статистично уточнити характеристики розпізнавання корабля. Розроблений метод розпізнавання типу корабля може бути використано у військовій сфері, його застосування у радіолокаційних системах підвищить безпеку морського та внутрішнього судноплавства.*

Ключові слова: *метод розпізнавання, ідентифікація, тип морського корабля, радіолокаційний портрет відбитого сигналу.*