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MATHEMATICAL MODELLING OF DISTANCE MEASURING MULTIFREQUENCY PHASE METHOD

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The article is developed algorithm of mathematical modelling of the formation process of the reflected monophonic signal in the presence of several reflection objects has been worked out. The algorithm consists of the following phases: setting the initial values, calculating the vectors values of the monophonic signals as a sum of signals reflected from each object, the vectors change by taking into account the amplitude error, the phase shift and the frequency of the probing signal. The mathematical modelling of the process of the objects distance measuring using multi-frequency phase method has been performed. In the process of modeling we have changed the basic parameters of the probing signal and the monophonic reflected signal, namely: initial frequency, frequency incremental step, frequency instability, amplitude designation error and monophonic signal phase shift error. Monte Carlo method has been applied in the process of modelling. Frequency instability was set according to normal distribution, and the amplitude and phase error were set with uniform distribution. The mathematical modelling of distance measuring using multi-frequency phase method has shown that distance measuring error is decreased if the probing signal frequency instability and the monophonic signal vectors measurement error are reduced. With regard to the abovementioned the mean square deviation of the distance is decreased. Calculations of the distance error coincide with the data obtained by the mathematical modelling. It has been found that it is appropriate, in the process of the objects probing at the depth of 50 meters, to use the frequency incremental step of 4 MHz, where the signal generator frequency instability is at least 10^{-6} f, the amplitude measurement error is $1/1024\, a_{\Sigma max}$, the phase shift measurement error does not exceed 0.1°. In this case, the distance measurement error does not exceed 0.6 m.

Keywords: mobile target, range, radar system, probe signal, rangometry, phase method.

Introduction

The problem of high-precision measurement of distance and radial velocity of moving targets such as surface, air and sea ones is not new. Various radars are used to solve the problem. Different types and kinds of problems can be distinguished depending on the problem to be solved by the radar station. Protection of the state borders turns out the most acute problem. In this case, identification of pinpoint targets at close distances from each other and their identification at considerable distances is undoubtedly a critical task.

The known methods for measuring distances in radar-location mainly use impulse-type signals and signal separation reflected from each object at time of their arrival. In this connection the probing signals which provide sufficient accuracy occupy a significant frequency range. This creates problems when constructing units of distance-measurement radar systems [1, 2].

The phase methods of distance measuring are the most accurate ones. They allow precision of the target distance measuring provided that the frequency range of probing signals is strictly limited, by virtue of the fact that we use harmonic signals and multi-scale approach [1].

Recently developed distance measuring multi-frequency phase methods allow to separate the signals reflected from many objects using limited frequency range of probing signals and measurements of the reflected signals vectors [1].

The theoretical material and methods of radar measurements can be used to develop fundamentally new radio systems of distance measuring, to measure the radial velocity of targets and conduct radar observation in the military sphere. This is especially true concerning development of radar systems which are to identify targets from each other at short distances in a single line. In order to set the limits of the distance measuring multi-frequency phase method using we have to perform mathematical modelling and specify major dependencies between the probing signals parameters and the parameters of accuracy and discrimination power.

Main body

Determining accuracy and discrimination power of the method is a multidimensional problem, in other words these values depend on many input parameters, namely: initial frequency, spectrum width, frequency incremental step, distance between adjacent objects, amplitude error, phase error. Let us consider the most important parameters that influence the potential accuracy and discrimination power of the method, namely initial frequency and frequency incremental step. The accuracy and discrimination power are important characteristics of distance measuring. They allow, knowing the results permissible accuracy, to set requirements for the measurement conditions, namely frequencies and instruments error. In this case, we consider the error as the difference between the true distance d and the measured one l with reference to the true distance, viz relative error:

$$\delta l = \frac{|d-l|}{d}, \tag{1}$$

where d – true distance; l – measured distance.

Discrimination power is the minimum distance between two adjacent objects Δd, wherein the method allows their identification as two separate objects, rather than as a single one. This can be expressed by the equation:

$$\Delta d = d_2 - d_1, \ \max\left(\Delta l_1, \Delta l_2\right) < \Delta d, \tag{2}$$

where Δl_1, Δl_2 – absolute errors of distances; d_1, d_2 – true distances to the objects.

The formula on the right side is the separability condition: if all absolute errors are less than the real distance between the adjacent objects then we separate them. Let us use mathematical modelling to determine the dependence character of accuracy and discrimination power on the initial frequency and frequency incremental step. To do this we must have the values of the "measured" vectors $\overrightarrow{B_k}$ at each probing frequency. Therefore, we will calculate these vectors analytically, setting the true values of the distances to the objects and the amplitudes of each reflected signal. These operations can be represented in the shape of the flow chart (Fig. 1).

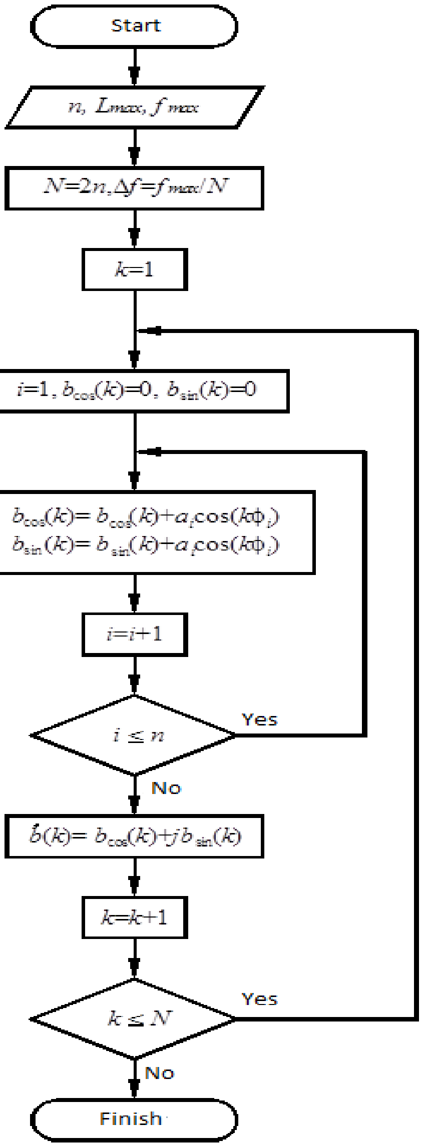

Fig. 1. Control flow chart for calculating vectors $\dot{b}(k)$ for mathematical modelling

According to the flow chart Fig. 1 we calculate the phase shifts of harmonic signals reflected from each object using the following expression:

$$\phi_k = \frac{4 \cdot \pi \cdot d_k \cdot f}{c}, \; k = 1 \ldots n, \tag{3}$$

where n – number of objects; d_k – true distances; f – initial frequency; c – wave-propagation velocity.

Calculation of the vectors of monophonic signals in the complex form is done in the following manner:

$$\dot{b}(k) = \sum_{i=1}^{n} a_i \cdot \left(\cos(k \cdot \phi_i) + j \cdot \sin(k \cdot \phi_i)\right), \; k = 1 \ldots N, \tag{4}$$

where a_i – true amplitudes of the vectors reflected from each object; *inc* – frequency incremental step; N – required number of frequencies.

We must take into account the fact that the calculation of the distance will depend on both the initial frequency and the incremental step of probing frequencies variation. The initial frequency is taken into account in the expression (4) by putting it in the calculation of the phase shift.

We use the following expression to take into account the incremental step of frequencies variation:

$$\dot{b}(k)=\sum_{i=1}^{n} a_i \cdot e^{j\cdot k\cdot inc\cdot\phi_i},\ k=1\ldots N, \tag{5}$$

where inc - frequency increment which takes the values from 0 to 1.

So, we have considered all the mathematical operations required for modelling. Before we start modelling, it should be noted that the characteristics under research, namely accuracy and discrimination power, can be divided into potential and real. Potential characteristics are the maximum characteristics that can be provided by the method not taking into account the errors of real devices. In this case the computation error (it cannot be excluded) is taken into account only. But this error can be minimized by increasing the capacity of calculations. The real characteristics take into account the errors of the real devices, namely the voltmeter and the phase meter (of course the computation error is present in this case). The reasons and nature of the device errors were discussed above. The research of potential accuracy and discrimination power of the distance measuring multi-frequency phase method was carried out in the preceding chapter. So let us not dwell on the conditions of the experiments performance but let's consider only the obtained results.

The accuracy and discrimination power is affected by the following parameters: initial frequency *f*, frequency incremental step Δf, measurement error of amplitude of monophonic signal Δa_Σ, measurement error of phase shift of monophonic signal $\Delta\phi_\Sigma$, instability of probing signal frequency δf. During the measurements this means that the objects probing frequencies are changed with a specific constant incremental step (increment) to be expressed in fractions of a unit and we will denote it by *inc*. The analysis of the determined parameters indicates that a number of parameters which influence the accuracy of measurement have determined character, and the rest of them are random in character. The first group includes initial frequency and incremental step of probing frequency variation. The second group includes the errors of amplitude and phase shift measurements and also instability of frequency of the probing harmonic signal. When performing the modelling it is necessary to take into account the determined nature of the first group of parameters and random nature of the second group.

Modelling of the determined parameters influence is carried out by their change from the initial value to the final value in some incremental steps. As a rule the initial value is taken at zero level. The upper value is limited by the capacity of receiving and transmitting equipment, measurement units, etc. By virtue of the fact that terminable parameters include frequency, then it is necessary to rely on the capability of harmonic signals generators, frequency range of transceivers, measuring devices of phase shifts and amplitudes. Since the harmonic signals can be generated, transmitted and received within a wide range of frequencies, then the measuring devices of the phase shifts and amplitudes are characterised by the limited frequency range. Thus, namely the frequency parameters will determine the modelling. The most common are the methods and technical means of measuring amplitude and phase shifts that are effective in the frequency range of 10 MHz [1-4]. Parameters that are random in character should be set given that they have their own probability characteristics i.e. distribution law, expectation function and mean square expectation.

To study the impact of various factors upon the accuracy of the distance measuring using the multi-frequency phase method with regard to their random nature it is necessary to develop appropriate mathematical models with introduced probability distributions. Let us consider the influence of each factor separately.

It is possible to use frequency generator with control option or frequency synthesizer to set the frequency grid. In both cases taking into account the impact of various factors frequency generation occurs with some instability i.e. long-term or short-term. The probability of frequency occurrence has normal distribution law that must be considered in the process of mathematical model development. Wherein the expectation function has the value of the required frequency, and the mean square expectation depends on the instability value of the generator. A quartz-crystal generator is characterised by a typical value of frequency instability, which vary from 10^{-4} до 10^{-8}. Taking into account the mathematical expression for the phase shift calculation of the harmonic signal reflected from the object located at some distance (3) we must introduce a random frequency value with provision for probability distribution:

$$\phi_k = \frac{4 \cdot \pi \cdot d_k \cdot normald\left[f + inc \cdot \Delta f, \sigma_f \right]}{c},\ k = 1 \ldots n. \tag{6}$$

where $normald\left[f + inc \cdot \Delta f, \sigma_f \right]$ is a coversine that sets the random value of the probing signal frequency with expectation function $f + inc \cdot \Delta f$ and mean square deviation σ_f.

To calculate the vectors of monophonic signals the resulting expression must be substituted in the expression (5). Frequency instability is changed through the values of 10^{-5} до 10^{-8}. We use Monte Carlo method to carry out mathematical modelling. We produce at least 1000 calculations for adequate modelling. After calculating we perform statistical processing of the received values of the objects distance. We construct histogram of the frequency of the data occurrence, reveal the nature of the distribution function, find expectation function, and values dispersion.

The results of mathematical modelling of the impact of the frequency instability upon the measurement result of the objects distance are shown in Table 1.

Fig. 2 and 3 show the dependence of the distance measuring error on the frequency instability.

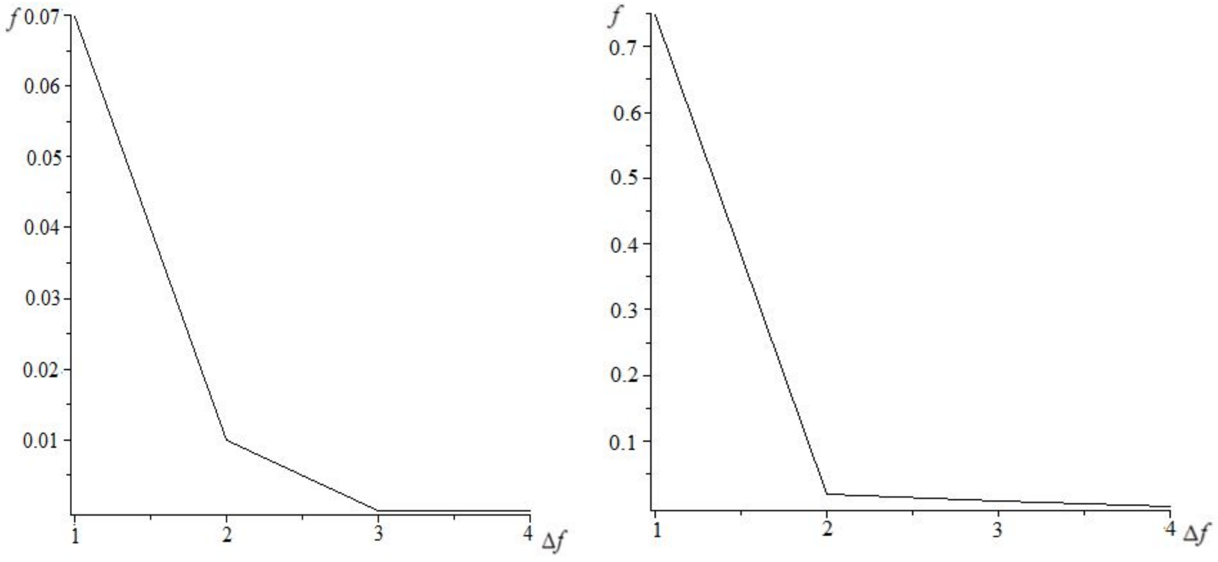

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Fig. 2. Dependence of the distance measuring error on the frequency instability for:
a – $\Delta f / f = 10^{-5}$; b – $\Delta f / f = 10^{-6}$

Table 1.

The research of influence of frequency instability upon the error of the objects distance measuring

Instability of frequency, $\Delta f/f$	10^{-5}				10^{-6}			
True value	10	17	25	35	10	17	25	35
Expectation function, m	10.07	16.25	26.32	34.96	9.99	16.98	25.05	34.99
Expectation function of function deviation from average deviation, m	0.31	1.78	2.35	0.32	0.03	0.15	0.32	0.02
Mean square deviation, m	0.15	4.45	6.87	0.19	0.002	0.039	0.12	0.0009
Distance error, m	0.07	0.75	1.32	0.04	0.01	0.02	0.05	0.01
Instability of frequency, $\Delta f/f$	10^{-7}				10^{-8}			
True value	10	17	25	35	10	17	25	35
Expectation function, m	10.00	16.99	24.99	35.001	9.999	16.999	24.999	34.9999
Expectation function of function deviation from average deviation, m	0.003	0.015	0.029	0.002	$1\cdot10^{-4}$	$8\cdot10^{-4}$	0.001	0.0001
Mean square deviation, m	$1\cdot10^{-5}$	0.0003	0.0014	$8\cdot10^{-6}$	4.10^{-8}	$8\cdot10^{-8}$	$3\cdot10^{-6}$	$1.7\cdot10^{-8}$
Distance error, m	$1\cdot10^{-4}$	0.01	0.01	0.001	$1\cdot10^{-5}$	0.001	0.001	0.0001

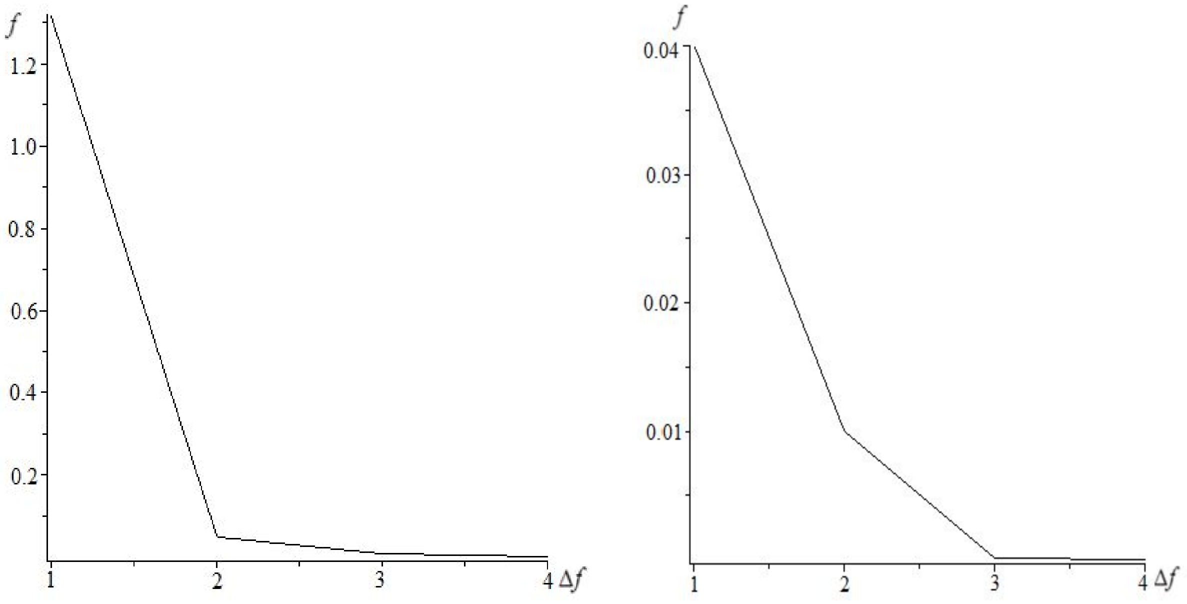

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Fig. 3. Dependence of the distance measuring error on the frequency instability for: a – $\Delta f/f = 10^{-7}$; b – $\Delta f/f = 10^{-8}$

The obtained dependencies show that the distance measurement error using multi-frequency phase method decreases by the exponential relationship.

Let us perform mathematical modelling in order to study the impact of measuring error of the monophonic signal amplitude and phase shift upon the distance measuring error using multi-frequency phase method. Let us make use of the common mathematical modelling algorithm. Its main stages are the following: setting the initial conditions; introducing measurement errors; carrying out calculations according to the method of measurement; repeated calculations in order to apply Monte Carlo method to receive a sample of the given size; statistical analysis of the obtained modelling results.

Let us introduce the restrictions of initial conditions in order to perform mathematical modelling. Let us assume that the values of distance are within the range of 50 m. Let us set four distances: 10 m, 15 m, 30 m and 35 m. If the maximum distance is 50m then according to the expression:

$$l_{max} \le \frac{c}{2f_{min}}, \tag{7}$$

the minimum frequency should not exceed 3 MHz Let us set the frequency incremental step less than 3 MHz In order to introduce the signals measurement errors in the results of the calculations let us define the parameters of the probing signals to be measured. The values of the vectors of the probing signals are measured according to the analytical multi-frequency method. Each vector of the signal is set by the signal amplitude and initial phase. When the probing signals are used we carry out measurements of the phase shift between the reflected monophonic signal and the reference probing signal. Let us use the following expression to model the monophonic signal:

$$a_{\Sigma}(f) = \sum_{i=1}^{n} a_i e^{\frac{f_j}{f_{min}}\phi_i}, \tag{8}$$

where a_i – signal amplitude reflected from *i* object; ϕ_i – signal phase shift reflected from *i* object; f_j – current frequency; f_{min} – initial frequency.

Adding the error into the mathematical model is carried out by superposition of random values upon the monophonic signal amplitude and the phase shift. To do this we used the tools of MatLab R 2013 mathematical software. Accordingly the expression (8) will be the following:

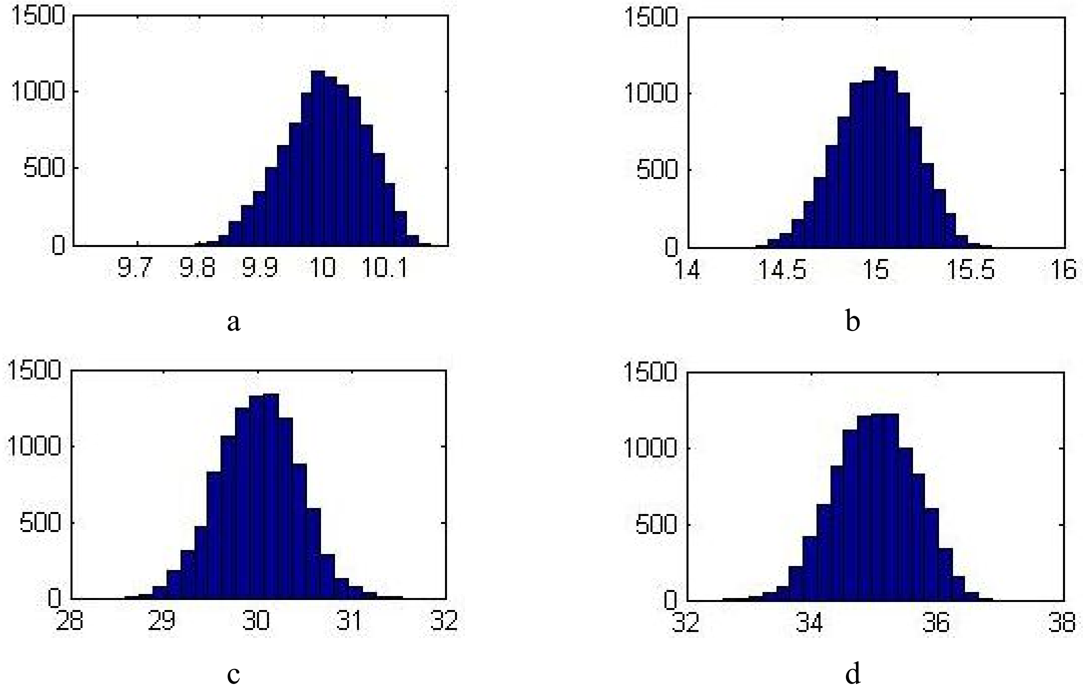
$$a_{\Sigma}(f) = \sum_{i=1}^{n} a_i e^{\frac{f_j}{f_{min}}\phi_i} + \Delta a_j e^{\frac{f_j}{f_{min}}\Delta\phi_j}, \tag{9}$$

where Δa_j – amplitude error on *j* frequency; $\Delta\phi_j$ – phase error on *j* frequency.

The errors of amplitude and phase are set with uniform distribution since modern digital measuring instruments are characterised with the measurement error exactly with such function. The amplitude error dispersion is set within 0.1% and 0.001%, the phase shift is set within 1° to 0.01° which corresponds to methodical and instrumental measurement errors of modern measuring instruments.

Let us estimate the impact of each factor upon the result of the distance measurement. Firstly, let us determine the impact of the frequency incremental step change. The frequency incremental step change is set within 1.5 MHz to 2.5 MHz. Increase in value is 0.5 MHz. Wherein we set the minimum value of amplitude determination errors (1/4096 a_{Σ}) and phase shift (0.01°).

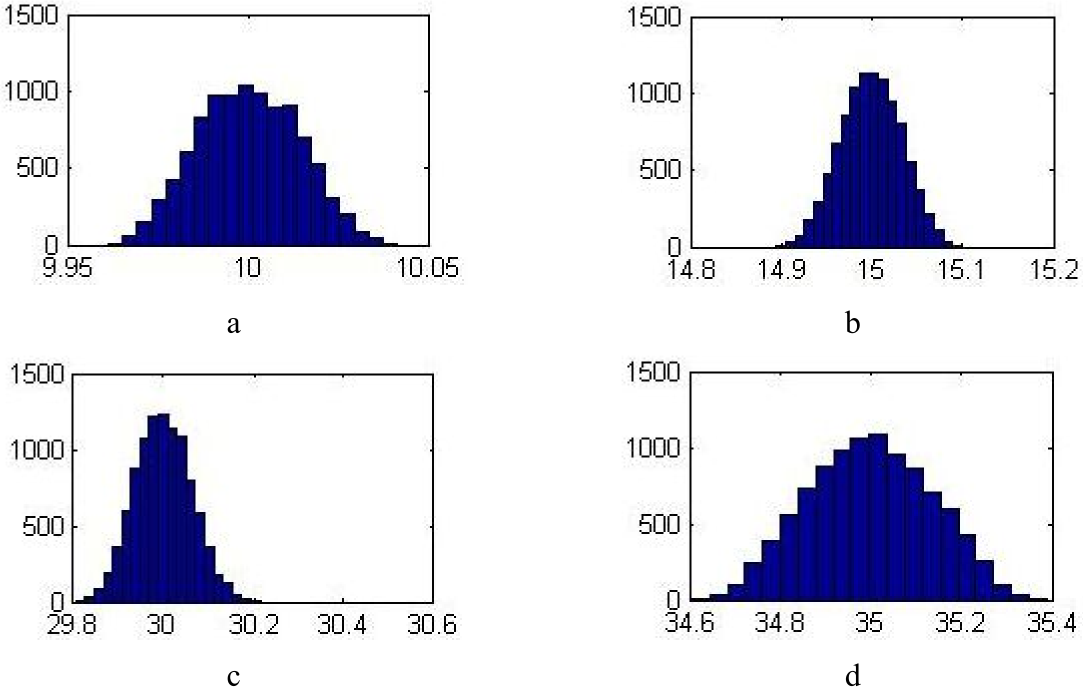
To illustrate the received sets of distance with random component the following histograms of frequency distribution of the values occurrence have been constructed (they are shown in Fig. 4 - 5).



a b

c d

Fig. 4. Histograms of distance distribution in case of initial frequency is f=2 MHz and minimum values of the phase shift and amplitude errors where: a – L=10 м, m=10.0005, sigma=0.064134; b – L=15 м, m=15.0001, sigma=0.20129; c – L=30 м, m=30.0024, sigma=0.42011; d – L=35 м, m=35.0011, sigma=0.6384



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c d

Fig. 5. Histograms of distance distribution in case of initial frequency is f=2.5 MHz and minimum values of the phase shift and amplitude errors where: a – L=10 м, m=10.0002, sigma=0.014017; b – L=15 м, m=14.9992, sigma=0.0333; c – L=30 м, m=29.9992, sigma=0.062326; d – L=35 м, m=34.998, sigma=0.13516

The analysis of the received histograms leads to the following conclusions. The laws of distance distribution at small values of the frequency incremental step are close to the Rayleigh law (Fig. 4). The law is normal for greater frequencies (Fig. 5). In this connection the deviation of the expectation function from the true value of distance is decreasing. This is also true for the mean square deviation.

Let us explore the impact of the monophonic signal amplitude determining error as the next stage. The amplitude error is set from the minimum value of $1/4096\,a_{\Sigma}$ to its maximum value of $1/256\,a_{\Sigma}$. Change of error is carried out in two times that corresponds to one discharge of the analog-to-digital converter. The phase shift measurement error is set to the lowest (0°). The incremental step of frequency change is 2.5 MHz. The analysis of the received data shows that the distribution laws for small errors are similar to the normal law. The distribution law is similar to Rayleigh law in case of the great values of the amplitude error. Deviation of the expectation function from the true value and mean square deviation increases in case of error increase.

Let us explore the impact of the phase shift measurement error upon the distance measuring error as the next stage. In the process of modelling we will change the phase shift within 0.01° to 0.5° with the error change by 5 times. The amplitude measurement error is set for $1/4096\,a_{\Sigma}$. The incremental step of frequency change is 4 MHz. The analysis of the received data shows that the error of the phase shift identification affects the value of the expectation function deviation from the true value and mean square deviation. When the phase shift error increases the distance error and mean square deviation also increase. However, the greatest distance error observed does not exceed two thousandths of a meter. That is why, the phase shift measurement methods and devices with an accuracy of 0.5° or greater are enough for measuring purposes. This conclusion is particularly important taking into consideration the fact that the presence of noise can significantly impact the values of the phase shift measurement error.

The peculiarity of the multi-frequency phase method is solving the system of linear equations as one of the stages of the distance finding. In this case, the accuracy of the distance measurement is affected by the conditioning number of the system matrix of linear equations of the multi-frequency phase method. It has been shown that the value of the monophonic reflected signal vector is different at different frequencies. Thus, changing the frequency values of the probing signals results in changing of the conditioning number and therefore the objects distance measuring error.

The results of mathematical modelling. The general trend is that the conditioning number decreases to a certain minimum value with the increase of the initial probing frequency. Then it increases to its maximum value with the following decreasing. This dependency is periodically repeated with the frequency increasing. With the increase of the probing frequency change incremental step the periodicity of the dependency is preserved, however, the minimum value is changed. The performed modelling shows that the change incremental step value of 4 MHz of the probing frequency preserves the minimum value of the conditioning number 13.5 for the initial frequency of 35 MHz. But the conditioning number is 16 for zero initial frequency. The lowest value of the conditioning number is observed when the frequency change incremental step value is 3.9 MHz. Dependency graph for this frequency incremental step is shown in Figure 6.

On the other hand, when a smaller probing frequency change incremental step was set within 2.5 to 3.5 MHz the conditioning number was 3-5 times bigger comparatively to its minimum value. Thus, the following conclusion can be drawn. Probing with less frequency incremental step does not significantly increase the matrix conditioning number so there is a transfer of the amplitude and phase shift measurement errors with their slight increase into the distance measuring error. Thus we can narrow the frequency range of probing signals. To reduce the distance measuring error we should use more accurate methods of amplitude measuring and it will allow simplifying measurement instrumentation.

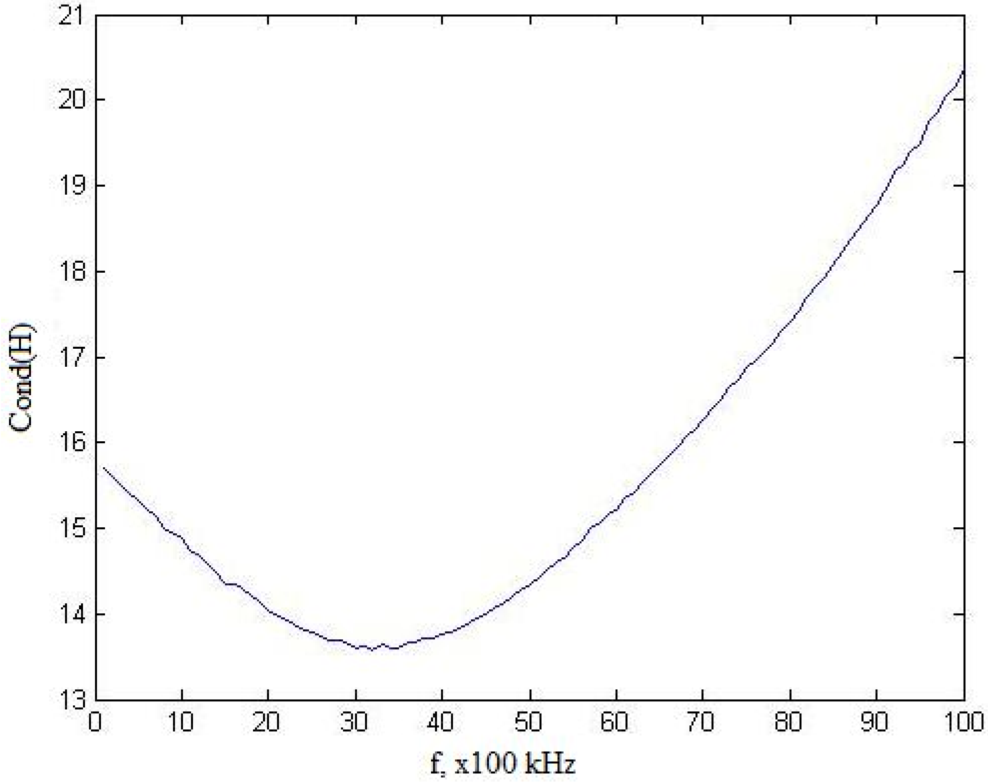

Fig. 6. Dependence of the conditioning number of the system matrix of linear equations on the initial probing frequency for the frequency incremental step of 3.9 MHz

The other values of distance result in a change of dependence. When the distance of one object is changed, the value of the conditioning number and the frequency it is observed at is changed.

As well as the accuracy of the distance measuring depends on the frequency range of the probing signals, the discrimination power of the distance measuring multi-frequency phase method depends on the frequency of harmonic signals the scanning of the objects is accomplished by. It is necessary to establish the relationship between the minimum distance between the objects which can be identified and the initial frequency.

Based on theoretical provisions laid down in the previous works of the authors, if the objects are located in close proximity, the vectors of the signals reflected from two objects at the beginning of the frequency range are close to each other. In this connection the increase of the probing frequency results in the increase of the monophonic signals vectors. To separate the two vectors it is necessary that the angle between the vectors is not less than the minimum value that can be separated. This condition may be met by different ways. Firstly, it is possible to measure the phase shift and amplitude of the monophonic signal with a given accuracy according to which the signals reflected from each object are separated by the results of solving the system of linear equations. Secondly, it is possible to increase the frequency change incremental step of the probing signal. It results in the increase of the angle between the vectors and thus the phase difference between them, which allows you to separate the signal reflected from each object. In this case, it is possible to measure the phase shifts and amplitudes of the signals reflected from each object with greater error. Thirdly, the discrimination power depends on the conditioning number of the matrix.

The practice of radar distance measurement says that identification capability is determined by the distance measuring error. And it is determined by its doubled value Δl. Therefore, in order to determine the distinguished capability we can use the expression (2).

Let us perform mathematical modelling in case of near location of the objects and establish relationships with a precision measurement of the phase shift and amplitude of the monophonic signals and the conditioning number of the system matrix of linear equations.

Let us take the initial conditions for the modelling as follows. We set four objects like in the previous modelling. The distance between two objects is from 2 to 1 m. The distance of 10 m is used as a reference one. We also will change the incremental step of the frequency from 2.5 MHz to 4 MHz, the original frequency from 0 to 1 MHz and the phase shift measuring errors from 1° to 0.1° and amplitude from $1/256\,a_{\Sigma\max}$ to $1/2048\,a_{\Sigma\max}$ of the monophonic signal. The result of the mathematical modelling is to establish the basic laws of various factors influence upon the probability characteristics of the objects distance.

The obtained data show that identification is improved with frequency increasing. With regard to the above mentioned the smaller is the distance between the objects, the greater frequency incremental step is to be set. Moreover, there is some critical frequency which provides the possibility of the objects identification. The change of the initial frequency does not result in any significant changes in the objects distance distribution histogram. In the same way the change of accuracy in determining the amplitude of the monophonic signal within a number of discharges also dos not result in the improvement of the objects identification.

The change of the phase shift measuring accuracy results in the change of identification indicators. It has been determined above that the identification capability depends on the phase shift measurement error of the monophonic signal. Similarly, the discrimination power depends on the value of the error.

Conclusions

1. The algorithm of mathematical modelling of the formation process of the reflected monophonic signal in the presence of several reflection objects has been worked out. The algorithm consists of the following phases: setting the initial values, calculating the vectors values of the monophonic signals as a sum of signals reflected from each object, the vectors change by taking into account the amplitude error, the phase shift and the frequency of the probing signal.

2. The mathematical modelling of the process of the objects distance measuring using multi-frequency phase method has been performed. In the process of modeling we have changed the basic parameters of the probing signal and the monophonic reflected signal, namely: initial frequency, frequency incremental step, frequency instability, amplitude designation error and monophonic signal phase shift error. Monte Carlo method has been applied in the process of modelling. Frequency instability was set according to normal distribution, and the amplitude and phase error were set with uniform distribution.

3. The mathematical modelling of distance measuring using multi-frequency phase method has shown that distance measuring error is decreased if the probing signal frequency instability and the monophonic signal vectors measurement error are reduced. With regard to the abovementioned the mean square deviation of the distance is decreased. Calculations of the distance error coincide with the data obtained by the mathematical modelling. It has been found that it is appropriate, in the process of the objects probing at the depth of 50 meters, to use the frequency incremental step of 4 MHz, where the signal generator frequency instability is at least $10^{-6} f$, the amplitude measurement error is $1/1024\,a_{\Sigma\max}$, the phase shift measurement error does not exceed 0.1°. In this case, the distance measurement error does not exceed 0.6 m.

4. The research results of influence of the probing signal initial frequency and incremental step change in the distance measuring error has revealed that the changes in these two parameters result in the system matrix of linear equations with different values. The result is the matrixes with equal values of the conditioning number. The initial frequency increase

results in reducing the conditioning number from the values of tens of thousands to 15-20. The probing signal frequency change incremental step also results in the change of the conditioning number, but in a smaller range. Lower distance measuring errors are observed at small values of the conditioning number, due to the fact that the matrixes with such conditioning numbers less propagate the monophonic signal vector error onto the resulting error in distance.

5. The research of the identification capacity of the distance measuring multi-frequency phase method has been carried out. It has been shown that the identification of two objects located at a close distance depends on all the factors affecting the measurement accuracy and have the same dependencies.

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МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ БАГАТОЧАСТОТНОГО ФАЗОВОГО МЕТОДУ ДАЛЬНОМЕТРІЇ

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Задача високоточного вимірювання дальності та радіальної швидкості рухомих цілей, як наземних, повітряних так і морських, є неновою. Для її розв'язання застосовують різноманітні радіолокаційні засоби. В залежності від задачі, яку мають вирішувати радіолокаційні системи, розрізняють їх різні типи і види. Найбільш гостро постає завдання охорони кордонів держави. В такому разі розрізнення малорозмірних цілей на невеликих відстанях та на значних дальностях є безсумнівно актуальною задачею. Відомі методи вимірювання дальностей в радіолокації, в основному, використовують імпульсні сигнали та розділення сигналів, відбитих від кожного об'єкту, за часом приходу. При цьому зондуючі сигнали, що забезпечують достатню точність, займають значний частотний діапазон. Це створює проблеми при побудові блоків дальномірних радіолокаційних систем. Найбільш точними є фазові методи дальнометрії. Вони дозволяють забезпечити високоточне вимірювання дальності цілей за умови чіткого обмеження частотного діапазону зондуючих сигналів, адже використовуються гармонічні сигнали та багатошкальність. Аналіз останніх досліджень показав, що розроблені в останні роки багаточастотні фазові методи дальнометрії дозволяють розділяти сигнали, відбиті від багатьох об'єктів, використовуючи обмежений частотний діапазон зондуючих сигналів та вимірювання значень векторів відбитих сигналів. Теоретичні положення та методи радіолокаційних вимірювань можна використовувати для розробки принципово нових радіосистем дальнометрії, вимірювання радіальної швидкості цілей та радіолокаційного спостереження у військовій сфері. Особливо це актуально при розробці радіолокаційних систем, що повинні розрізняти цілі на невеликих відстанях одна від одної на одній лінії. В статті проведене математичне моделювання процесу формування сумарного відбитого сигналу за наявності декількох об'єктів відбиття. Процес моделювання складається з етапів: встановлення початкових значень; розрахунок значень векторів сумарних сигналів як суми сигналів, відбитих від кожного об'єкту, зміна векторів шляхом врахування похибки амплітуди, фазового зсуву та частоти зондуючого сигналу. Проведено математичне моделювання процесу вимірювання дальності об'єктів за багаточастотним фазовим методом. При проведенні моделювання змінювались основні параметри зондуючого сигналу та сумарного відбитого сигналу, а саме: початкова частота, крок частоти, нестабільність частоти, похибка визначення амплітуди та фазового зсуву сумарного сигналу. При проведенні моделювання застосовано метод Монте-Карло. Нестабільність частоти задавалась з нормальним розподілом, похибка з амплітудою і фазою із рівномірним розподілом. Отримані результати свідчать, що математичне моделювання вимірювання дальності за багаточастотним фазовим методом показало, що при зменшенні нестабільності частоти зондуючого сигналу та похибки вимірювання векторів сумарних сигналів похибка вимірювання дальності зменшується.

Ключові слова: рухома ціль, дальність, радіолокаційна система, зондуючий сигнал, дальнометрія, фазовий метод.

МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ МНОГОЧАСТОТНОГО ФАЗОВОГО МЕТОДА ДАЛЬНОМЕТРИИ

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Задача высокоточного измерения дальности и радиальной скорости движущихся целей, как наземных, воздушных так и морских, является неновой. Для ее решения применяют различные радиолокационные средства. В зависимости от задачи, которую должны решать радиолокационные системы, различают их различные типы и виды. Наиболее остро стоит задача охраны границ государства. В таком случае различие малоразмерных целей на небольших расстояниях друг от друга и на значительных дальностях является несомненно актуальной задачей. Известные методы измерения дальностей в радиолокации, в основном, используют импульсные сигналы и разделения сигналов, отраженных от каждого объекта, по времени прихода. При этом зондирующие сигналы, обеспечивающие достаточную точность, занимают значительный частотный диапазон. Это создает проблемы при построении блоков дальномерных радиолокационных систем. Наиболее точными являются фазовые методы дальнометрии. Они позволяют обеспечить высокоточное измерение дальности целей при условии четкого ограничения частотного диапазона зондирующих сигналов, поскольку используются гармоничные сигналы. Анализ последних исследований показал, что разработанные в последние годы многочастотные фазовые методы дальнометрии позволяют разделять сигналы, отраженные от многих объектов, используя ограниченный частотный диапазон зондирующих сигналов и измерения значений векторов отраженных сигналов. Теоретические положения и методы радиолокационных измерений можно использовать для разработки принципиально новых радиосистем дальнометрии, измерения радиальной скорости целей и радиолокационного наблюдения в военной сфере. Особенно это актуально при разработке радиолокационных систем, которые должны различать цели на небольших расстояниях друг от друга на одной линии. В статье проведено математическое моделирование процесса формирования суммарного отраженного сигнала при наличии нескольких объектов отражения. Процесс моделирования состоит из этапов: установление начальных значений; расчет значений векторов суммарных сигналов как суммы сигналов отраженных от каждого объекта, изменение векторов путем учета погрешности амплитуды, фазового сдвига и частоты зондирующего сигнала. Полученные результаты свидетельствуют, что математическое моделирование измерения дальности данным методом показало, что при уменьшении нестабильности частоты зондирующего сигнала и погрешности измерения векторов суммарных сигналов погрешность измерения дальности уменьшается.

Ключевые слова: подвижная цель, дальность, радиолокационная система, зондирующий сигнал, дальнометрия, фазовый метод.