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METHOD FOR DETERMINING PHASE SHIFT USING TWO-PHASE INTERPOLATION TRANSFORMATION

This ***study*** *focuses on a method for accurately determining the phase shift between two harmonic signals. The proposed technique compares the waveform of the combined signal, which is obtained by applying a two-phase interpolation transformation, with a set of predefined reference functions. This* ***study aims*** *to develop a method for accurately measuring the phase shift between two harmonic signals to reduce the measurement errors caused by phase asymmetry in signal transmission channels and minimize the costs associated with parameter control. The sources of error in the proposed measurement method are identified and addressed. The* ***task*** *involves setting up the measurement objective to determine the phase shift between two harmonic signals. This section presents the analyses of known methods for measuring phase shifts using of analog-to-digital conversion. The next step involves selecting indicators and criteria to determine how closely the investigated signal matches the reference function. Then, we propose the synthesis of an algorithm to find the extremum of the sum of squares deviations for the set of reference functions and the investigated signal, relying on the golden ratio method. Finally, the paper will analyze possible sources of error that could affect the measurement outcome. The* ***methods*** *used are the following: methodology for conducting digital signal processing and measuring error estimation, numerical methods for extremum search, and methodology for single-factor experiments. The following* ***results*** *were obtained. A proposed compensation method for measuring phase shift is based on comparing the shape of the normalized signal, which is obtained as a result of the summation of harmonic signals after their semiperiodical transformation, with a set of normalized reference functions synthesized by computational means. A list of measurement and auxiliary operations, which should be ideally conducted to implement this measurement method, has been determined. An analysis of the components of measurement errors was conducted.* ***Conclusions****. The scientific novelty of the obtained results lies in the following: a method for measuring the phase shift of a signal has been developed, which, in our opinion, should be classified as a compensatory measurement method. This will significantly reduce the error component caused by the phase asymmetry of signal transmission channels and reduce the costs of controlling parameters (up to 10%) without decreasing the quality of control; a list of the measuring and auxiliary operations necessary for the implementation of the proposed measurement method has been identified; sources of errors have been determined.*

Keywords: *harmonic signal; measurement; compensatory method; phase shift; error; extremum.*

Introduction

Motivation. Contemporary conflicts and geopolitical challenges highlight the importance of developing new and improving existing weapons and military equipment models for the Armed Forces of Ukraine and other military formations that are part of Ukraine's defense forces, to ensure national security. An important component of equipping Ukraine's defense forces is acquiring weaponry samples from our state's partner nations. According to [1], the decision on the admissibility of the supply of the newest weapons developed and manufactured by Ukraine's military-industrial complex or received from partners not part of the North Atlantic Treaty Organization (NATO) is made based on conducting tests by comparing the obtained technical characteristics during the tests with the corresponding values specified in normative and technical documents for the experimental sample (technical specifications, technical assignments, operational documentation, etc.).

Among the crucial indicators in developing the newest military equipment for the Ukrainian DF are high demands on operational and reliability characteristics. The most promising way to improve these characteristics is the application of modern diagnostic systems that incorporate state-of-the-art technologies, computer and telecommunications equipment, artificial intelligence technologies, and new approaches and methods for diagnosing the technical state. [2, 3]. It is necessary to use intelligent diagnostic systems [4, 5] and advanced high-precision measurement methods to reduce the time and improve the quality of control, with the further possibility of predicting the technical conditions of weapons and military equipment.

One of the important procedures for testing and diagnosing complex technical systems is measuring the physical quantities that characterize their parameters.

For example, when testing and operating unmanned aircraft systems to intercept air targets, it becomes necessary to measure accelerations and angles, the time delays of receiving and transmitting control channels and data transmission, and determine the distances to objects. The methods for measuring these values are based on the use of the phase shift between two harmonic signals as an intermediate value.

When developing and manufacturing the latest special wheeled military equipment, such as the BTR-4E, an important parameter is the strength of hulls. During the production of experimental or serial samples, the physical-chemical properties of materials and the quality of the sheets joining are measured during the input control of the components and user acceptance testing of the samples as a whole.

One of the most important characteristics of small arms, artillery, and rocket-artillery weapons is the degree of wear of the barrel (such as guides), its strength, the gunpowder condition, the degree of wear of metal, and protective coatings. The decision on the possibility of extending the service life is made based on the acceptance tests of a certain batch of products, considering the conditions of their previous operation.

The measurement of the above characteristics of small arms, artillery, and rocket-artillery weapons, and wheeled and tracked military equipment is based on non-destructive testing methods. Non-destructive testing methods include radiography, ultrasonic flaw detection, and magnetic resonance research methods. The measuring systems that implement these measurement methods widely use methods based on the phase shift measurement.

Structure of the article. An analysis of known methods for determining the stage shift was conducted; it was found that compensation methods and the method of changing the stage shift into other quantities, such as voltage, time interval, and geometric parameters of the oscillographic images of the studied signals are currently widely used. The disadvantages of the known methods, which significantly affect the quality of measuring control, are determined. Based on this analysis, the aim of this research was set.

In Section 1, “Methodology of the research”, the methodological basis for solving the measurement problem of determining a phase shift using the signal obtained by summing two-harmonic signals, after conducting a two-phase interpolation transformation using the compensation method, is determined.

In Section 2, “Problem formulation”, the procedure for obtaining the signal by summing two-harmonic signals after conducting a two-phase interpolation transformation is described, offering the following: to use a normalized vector of instantaneous values to its average value for determining the phase shift; a set of vectors of reference standard normalized functions as a benchmark measure of the phase shift; and to use the method of the least squares as a determining method of the degree of the coincidence.

In Section 3, “Optimization”, an algorithm for determining the phase shift by the compensation method with the use of the golden ratio method is developed.

Section 4, “Results and Discussion”, contains a list of measuring and additional operations necessary to implement the propone method for determining the phase shift. Sources of errors in the proposed method of determination are determined.

The article is concluded by the conclusions, which highlight the main scientific and technical results and outline directions for further research in this area.

State of the art. At present, phase-measurement methods are employed in various fields, including radar and radio navigation, aviation and space technology, geodesy, mechanical engineering, communications, and non-destructive testing [6, 7]. The transformation of various physical quantities and their values into the phase shift of two harmonic signals facilitates a simple execution procedure and achieves a high degree of accuracy. Methods for converting physical quantities into the phase shift of two harmonic signals have moved beyond traditional applications and are frequently used in experimental physics, radiophysics, non-destructive testing, experimental medicine, and cutting-edge science and technology fields during research [8, 9]. Phase measurement methods and information-measurement systems created based on these methods allow solving many scientific and technical tasks related to the accurate measurement of distances, time intervals, and angles and analysis of signal field characteristics of different physical natures (electromagnetic, optical, acoustic).

In solving specific practical tasks, there arises the need to measure phase shifts in a frequency range from infra-low to ultra-high frequencies, in the presence of noise and interference across a wide dynamic range of amplitudes of the studied signals.

In measuring harmonic signals, concepts such as phase, initial phase, phase shift, and time delay are used. Currently, the greatest interest in phase measurements is determining the phase shift. As indicated in [10], according to existing normative documents, the phase shift is understood as the modulus of the difference between the initial phases of the frequencies of two harmonic signals.

Thus, in our opinion, the scientific and technical task of improving existing and developing prospective methods for measuring phase shifts is quite relevant.

The complete classification of the methods for measuring phase shifts was presented in the study [11].

Based on the principle of measuring the phase shift, compensatory methods and methods for converting the phase shift into other quantities, such as voltage, time interval, and geometric parameters of the oscillographic images of the studied signals, are distinguished.

The compensatory measurement method is based on balancing (compensating) the phase shift between two harmonic signals, i.e., reducing the phase shift of the signals to zero by adjusting the phase of one or both signals using a controlled measuring phase shifter (or phase shift measure) [11, 12]. Measurements were conducted at fixed intermediate frequencies to ensure the correct operation of the phase shifter and the phase drop-indication system of the signals. This method provides high measurement accuracy, which is close to the accuracy of phase shifter measurements.

The method of conversion into intermediate quantities allows determining the phase shift of signals after their previous conversion into another intermediate quantity, for example, voltage, current, displacement of the oscilloscope electron beam, and time interval. The main known methods of implementing this method are described below.

The additive method of signal voltage processing [11, 13] is based on the vector addition of signals. In the case of adding harmonic signals, a signal is obtained whose amplitude depends on the amplitude of the input signals and the phase shift between them. Because the phase-shift value is obtained from the measurement results of the amplitudes of the three-harmonic signals, this method is sometimes called the "three-voltmeter method."

To simplify the process of measuring the phase shift by adding voltages, a procedure for automatic adjustment of the input signal levels [14] was implemented. Then, the amplitude of the output signal depends exclusively on the magnitude of the phase shift.

The multiplicative method of signal processing (voltage multiplication method) [11, 15] is based on the fact that the multiplication of two-harmonic signals can produce a signal containing a constant component, the value of which depends on the amplitude values of the input signals and the phase shift between them, as well as a harmonic component. As with the voltage addition method, to simplify the process of measuring the phase shift, the automatic adjustment of the signal levels was performed.

When using the oscillographic method, as shown in the works [11, 16], the measured phase shift magnitude is determined by the nature and shape of the oscillograms. Phase shift measurement using the oscillographic method is carried out using a linear or sinusoidal sweep.

When measuring the phase shift of two-harmonic signals using a linear sweep, it is necessary to use a multichannel oscilloscope. When measuring the phase shift by a sinusoidal sweep, one of the measured signals is fed to the horizontal deflection channel, and the other signal is fed to the vertical deflection channel. Based on the action of these signals, an interference figure will appear on the screen, namely, an ellipse, whose axes are rotated by a certain angle relative to the horizontal and vertical axes of the screen. The magnitude of the phase shift is determined by measuring the dimensions of the ellipse edges.

The method for converting the phase shift of signals into a time interval is described in [24, 25]. The phase shift of signals is uniquely determined by the time delay between them. Determining the time delay between characteristic points of the signals, for example, between moments of zero-level crossing when the signs of the signal derivatives match, allows reducing the process of measuring phase shifts to the determination of time intervals based on the known frequency or period values of the input signals.

Considering the points mentioned, the following disadvantages can be attributed to the known methods:

– significant impact on the measurement accuracy of the phase shift due to error components caused by the phase asymmetry of the signal transmission channels;

– the presence of two channels for conducting analog-to-digital conversion of input signals, necessitating mutual synchronization of clock generators for each channel;

– considerable effect on the measurement accuracy of the phase shift due to external and internal noise;

– nonlinearity of the calibration characteristic.

The aim of the work. To propose methodological principles for using the composite signal obtained by summing two harmonic signals, after conducting a two-half-period transformation, to measure the phase shift between them. To consider the possibility of implementing a compensation method for determining the phase shift using the indicated signal.

The proposed approach for determining the phase shift will reduce the component of deviation caused by the metrological characteristics of the multi-valued measure by 10...15% compared to known compensation methods for determining the phase shift from one hand. Additionallynaly, it will reduce the costs of creating and maintaining such measurement systems by 5...7%.

Compared to known measurement systems for determining the phase shift that implement amplitude-time analog-to-digital signal conversion, the measurement deviation for determining the phase shift can be reduced to 5% by shortening the length of the measurement channel. Moreover, the costs for creating and maintaining the metrological system can be reduced by up to 10% by using a single amplitude-time analog-to-digital converter.

Overall, the proposed approach for implementing the compensation method for phase-shift measurements enhances the effectiveness of diagnosing weaponry and military equipment by ensuring a specified level of parameter control reliability and reducing the cost of measurement equipment in intelligent diagnostic systems.

1. Methodology of the research

To address the proposed measurement task, it is suggested to use a signal obtained by summing two harmonic signals that have a phase shift relative to each other. The use of this signal ensures a significant reduction in the measurement error component caused by the asymmetry of the signal transmission channels.

This measurement method is based on the use of a single-factor experimental design and, in our view, can be classified as a compensatory method for measuring phase shifts.

As an informational parameter concerning the magnitude of the phase shift, the shape of the signal obtained because of summing two harmonic signals after their two-half-period transformation is used. For this purpose, an amplitude-time analog-to-digital conversion of the indicated signal is carried out, and a vector of instantaneous values is formed. To improve the sensitivity of the measurement method, it is proposed to normalize the obtained vector to the average value.

As a multifaceted measure of the phase shift, a set of normalized vectors of reference standard functions is used, assuming equality of the amplitudes of harmonic functions for the entire set of phase shift values between them, which are synthesized by computational means. The use of this approach allows, on the one hand, to solve the measurement task and, on the other hand, to significantly simplify the algorithm for its resolution.

The magnitude of the phase shift is proposed to be determined by comparing the normalized vector of the signal with a set of vectors of reference standard normalized functions.

As a criterion for matching the obtained vector after analog-to-digital conversion with vectors of reference standard functions, it is proposed to use the minimal value of the sum of squares of discrepancies between them.

An algorithm was developed to find the minimal discrepancy value of the sum of squares between the vectors to be compared using the golden ratio method.

2. Problem formulation

Let's consider in more detail the procedure of conducting the measurement and a list of operations that are appropriate for measuring the phase shift between two harmonic signals using a two-half-period transformation.

To achieve increased accuracy in measuring the phase shift, it may be necessary to carry out auxiliary operations, such as the instrumental filtering of input signals, to reduce the impact of interference, the presence of which is due to the influence of external factors and their amplification, to the level at which the amplitudes of the signals differ by no more than 20%, to improve the sensitivity of measuring the magnitude of the phase shift of the input harmonic signals.

After completing the above procedures, it can be asserted that there exist two harmonic signals $u_1(t)$ i $u_2(t)$, which have a phase shift relative to each other equal to $\Delta\varphi$, which belongs to the interval from 0 to 2π.

Given that phase shift measurements are relative measurements, let us express the changes in the signals $u_1(t)$ i $u_2(t)$, in the form:

$$u_1(t) = U_{m1}\cos(2\pi f t), \tag{1}$$

$$u_2(t) = U_{m2}\cos(2\pi f t + \Delta\varphi), \tag{2}$$

where. U_{m1}, U_{m2} - signal amplitude $u_1(t)$ and $u_2(t)$ accordingly;

$f = \frac{1}{T}$ - the frequency of the signals;

T - the period of signal repetition.

A time diagram for these signals $u_1(t)$ i $u_2(t)$, that have a certain phase shift relative to each other by an angle $\Delta\varphi$ н is shown in Fig. 1a and Fig. 1b.

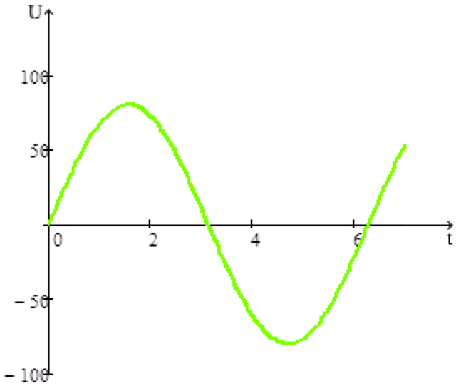

Fig. 1a. Time diagram of the signal $u_1(t)$

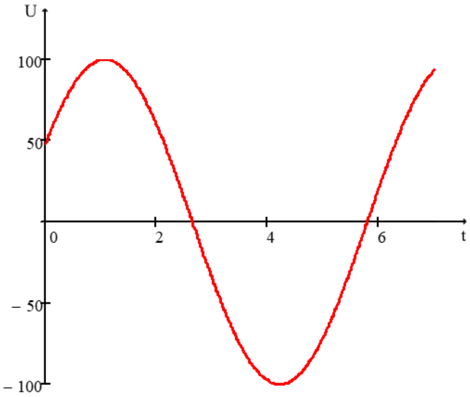

Fig. 1b. Time diagram of the signal $u_2(t)$

After completing the above procedures, the signals $u_1(t)$ i $u_2(t)$ are fed into two-half-period converters. The outputs of the converters provide the following signals:

$$u_1^{/}(t) = |u_1(t)| = |U_{m1}\cos(2\pi ft)|, \qquad (3)$$

$$u_2^{/}(t) = |u_2(t)| = |U_{m2}\cos(2\pi ft + \Delta\varphi)|, \qquad (4)$$

A time diagram of these signals is shown in Fig. 2, a and Fig. 2, b.

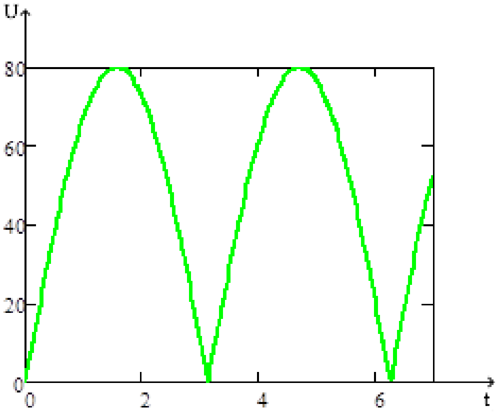

Fig. 2a Time diagram of signals $u_1^{/}(t)$

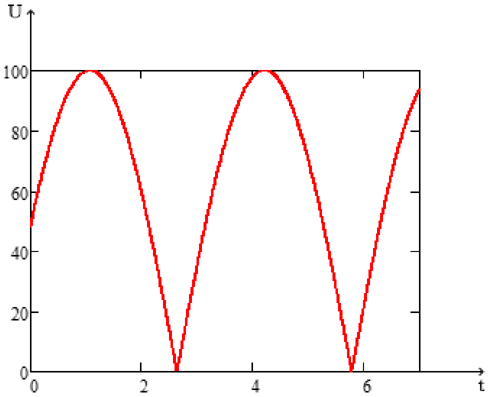

Fig. 2b Time diagram of signals $u_2^{/}(t)$

Summing $u_1^{/}(t)$ i $u_2^{/}(t)$ we will obtain the signal $u_\Sigma^{/}(t)$, the time diagram of which is shown in Fig. 3:

Furthermore is described by the following relationship:

$$u_\Sigma^{/}(t) = \begin{cases} U_{1min} + \frac{U_{1min} - U_{2min}}{t_{1.2}} t + \\ + \left(U_{1max}^{/} - \frac{U_{1min} + U_{2min}}{2}\right) \times \\ \times \sin(f_{1.2} t) \\ \quad for\ t_1 \le t < t_2 \\ U_{2min} + \frac{U_{2min} - U_{1min}}{t_{2.1}} t + \\ + \left(U_{2max}^{/} - \frac{U_{2min} + U_{1min}}{2}\right) \times \\ \times \sin(f_{2.1} t) \\ \quad for\ t_2 \le t < t_1 \end{cases} \qquad (5)$$

where U_{1min} and U_{2min} – points of discontinuity of the function in the interval from 0 to $\frac{T}{2}$;

$U_{1max}' = (U_{m1} + U_{m2})\cos\frac{\Delta\varphi}{2}$ – local maximum on the time interval $t_{1.2} = T(1 - \frac{\Delta\varphi}{\pi})$;

$U_{2max}' = (U_{m1} + U_{m2})\sin\frac{\Delta\varphi}{2}$ – local maximum on the time interval $t_{2.1} = T\frac{\Delta\varphi}{\pi}$;

$f_{1.2} = \frac{1}{t_{1.2}}$ - frequency of the signal on the interval $t_{1.2}$;

$f_{2.1} = \frac{1}{t_{2.1}}$ - frequency of the signal on the interval $t_{2.1}$.

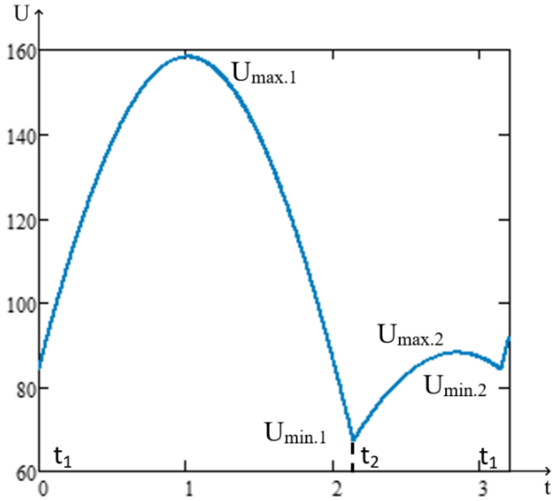

Fig. 3 Time diagram of signals $u_\Sigma^{/}(t)$

The signal $u_\Sigma^{/}(t)$ is input into an analog-to-digital converter that converts the amplitude to time. In this context, we assume that the amplitude-time conversion begins under the condition $u_1(t) = 0$ when transitioning from a negative value to a positive value and ends under the condition $u_1(t) = 0$ when moving from a positive value to a negative value. In this case, the minimum number of samples is selected considering the maximum portion of the signal and the Nyquist frequency. After performing the specified operation, according to [10], the signal $u'_{\Sigma}(t)$ il be represented by the vector $u'_{\Sigma\,d}(t_i)$ with instantaneous values corresponding to specific moments in time t_i.

$$u'_{\Sigma\,d}(t_i) = (U_1, U_2, \ldots U_i \ldots U_n), \qquad (6)$$

where U_i – instantaneous values of the signal $u'_{\Sigma}(t)$ at the i-th moment in time, obtained as a result of analog-to-digital conversion;

n – the number of counts received during the analog-to-digital conversion of the signal $u'_{\Sigma}(t)$ in the interval from 0 to $\frac{T}{2}$.

The vector $u'_{\Sigma\,d}(t_i)$ is fed into the computing device.

In the computing device, using the known values of the sampling frequency f_d and the number of samples n the period of the signal $u'_{\Sigma}(t)$ is determined by the following expression:

$$T_{\Sigma} = \frac{T}{2} = \frac{n}{f_d} = nT_d\,. \qquad (7)$$

To reduce computational operations and simplify the procedure for determining $\Delta\varphi$, it is reasonable to transition for $u'_{\Sigma\,d}(t_i) = (U_1, U_2, \ldots U_i \ldots U_n)$ from time samples to phase samples of the signal $u'_{\Sigma\,d}(\varphi_i)$. Then, given the known value of T_{Σ} the phase discretization step $\Delta\varphi_D$ is determined as

$$\Delta\varphi_D = \frac{\Delta t \cdot 2\pi}{T} \qquad (8)$$

To reduce the methodological component of the measurement error, it is proposed to normalize the instantaneous values of the signal $u'_{\Sigma\,d}(\varphi_i)$ to the average value $U'_{\Sigma mid}$, which can be determined using the following relationship:

$$U'_{\Sigma mid} = \frac{1}{n}\sum_{i=1}^{n} U_i. \qquad (9)$$

Then the normalized function $u'_{\Sigma\,dn}(\varphi_i)$ will have the following form:

$$\begin{gathered} u'_{\Sigma\,dn}(\varphi_i) = \\ = \left(\frac{U_1}{U'_{\Sigma mid}}, \ldots, \frac{U_i}{U'_{\Sigma mid}}, \ldots, \frac{U_n}{U'_{\Sigma mid}}\right) = \\ = (U_{1.n}, U_{2.n}, \ldots U_{i.n} \ldots U_{n.n}) \end{gathered} \qquad (10)$$

Given that the amplitudes of the signals $u_1(t)$ and $u_2(t)$ are close, the function of the total signal obtained after performing a half-wave conversion under the condition of equal amplitudes U_{me} is proposed as the reference function $u'_{\Sigma\,e}(\varphi_i)$ according to the phase samples

$$u'_{\Sigma e}(\varphi_i) = \begin{cases} U_{e.min} + (U_{e1max} - U_{e.min}) \times \\ \times \sin\left(\left(1 - \frac{\Delta\varphi}{\pi}\right)^{-1} \varphi_i\right) \\ \text{for } 0 \le \varphi_i < \pi - \Delta\varphi \\ U_{e.min} + (U_{e2max} - U_{e.min}) \times \\ \times \sin\left(\left(\frac{\Delta\varphi}{\pi}\right)^{-1} (\varphi_i - (\pi - \Delta\varphi))\right) \\ \text{for } \pi - \Delta\varphi \le \varphi_i < \pi \end{cases} \qquad (11)$$

where $U_{e.min} = U_{me}\sin\Delta\varphi$ – the discontinuity points of the reference function in the interval from 0 to π;

$U_{e1max} = 2U_{me}\cos(2\Delta\varphi)$ – the maximum value of the reference function over the interval $0 \le \varphi_i < \pi - \Delta\varphi$;

$U_{e2max} = 2U_{me}\sin(2\Delta\varphi)$ – the maximum value of the reference function over the interval $\pi - \Delta\varphi \le \varphi_i < \pi$.

After performing the calculation for each value of φ_i, with a certain value of phase shift $\Delta\varphi$ and normalizing to the average value of the reference function, we obtain the vector of the normalized reference function

$$u'_{\Sigma en}(\varphi_i) = (U_{1.e}, U_{2.e}, \ldots U_{i.e} \ldots U_{n.e}). \qquad (12)$$

Then, taking into account the above, the task of determining the phase shift of the harmonic signals $u_1(t)$ and $u_2(t)$ can be formulated as follows: from the entire set of normalized reference functions $u'_{\Sigma en}(\varphi_i)$ select such, j-th function

$$u'_{\Sigma enj}(\varphi_i) = (U_{1.e.j}, U_{2.e.j}, \ldots U_{i.e.j} \ldots U_{n.e.j}),$$

which most fully corresponds to the normalized signal

$$u'_{\Sigma\,dn}(\varphi_i) = (U_{1.n}, U_{2.n}, \ldots U_{i.n} \ldots U_{n.n}) \qquad (13)$$

The method of least squares (MLS), thanks to its wide range of applications, occupies a unique place among mathematical statistics methods. The MLS plays a particularly important role in solving measurement tasks. The task of the MLS is to estimate the patterns observed against the background of random fluctuations and to use this estimation for further calculations, in particular, to approximate the measured quantities.

Based on the fact that the amplitude-time conversion of the signal $u'_{\Sigma}(t)$ is conducted by a single analog-to-digital converter, under the same conditions, it can be asserted that the root mean square deviation of the error in determining the instantaneous values U_i of the signal $u^{/}_{\Sigma}(t)$ is constant ($\sigma_{U_i} = \text{const}$ for $i = 1 \ldots n$). Then, the instantaneous values U_i are considered equally precise measurements.

As a parameter for the degree of match between the normalized signal $u'_{\Sigma\,dn}(\varphi_i)$ and the $j-$th normalized reference function $u^{/}_{\Sigma enj}(\varphi_i)$, by MLS, we use the sum of the squares of discrepancies for the i-th elements of the corresponding characteristics:

$$S\left[u'_{\Sigma\,dn}(\varphi_i), u^{/}_{\Sigma enj}(\varphi_i)\right] = \sum_{i=1}^{n}\left(U_{i.n} - U_{i.e.j}\right)^2 \quad (14)$$

Given the above remark, let's define the measurement task of determining the phase shift $\Delta\varphi$ of signals $u_1(t)$ and $u_2(t)$ as follows: from the entire set of reference phase shift functions, we choose such a j-th function $u^{/}_{\Sigma enj}(\varphi_i)$, that will ensure the minimum value of the deviation sum of squares between the discrete normalized signal $u'_{\Sigma\,dn}(\varphi_i)$ and it, namely

$$\begin{gathered} S\left[u'_{\Sigma\,dn}(\varphi_i), u^{/}_{\Sigma enj}(\varphi_i)\right] = \\ = \sum_{i=1}^{n}\left(U_{i.n} - U_{i.e.j}\right)^2 \rightarrow \min \end{gathered} \quad (15)$$

3. Optimization

From the description of the measurement task, this task involves searching for the minimum value of the sum of the deviations of squares. These problems can be solved either analytically or numerically.

An analysis of known software tools [17, 18], which are widely used today, shows that they use numerical methods to find the extremum.

In turn, numerical methods for finding the function extremum can be divided into gradient methods, second-derivative methods, and direct methods.

As a rule, when solving the problem of searching for an extremum using gradient methods and second-derivative methods, they achieve faster convergence than when using direct methods.

However, applying methods that use derivatives to solve this task is difficult because of the functional dependence of the function under study.

Direct methods do not require the following conditions of regularity and continuity of the function under study and the existence of a derivative.

The analysis of the change in the deviation sum of squares' values when determining the phase shift shows that this function is quasi-convex [19, 20].

To determine which reference function ensures the minimum deviation of the sum of squares, we use the golden ratio method. The choice of this method compared to known methods, such as the dichotomous method, is due to its fewer iterations.

The proposed algorithm for determining $\Delta\varphi$ using the golden ratio method is outlined below:

Preliminary stage.

Determine the acceptable final length of uncertainty l.

The selection of the minimum value of this indicator is supposed to be conducted based on the requirements for the measurement task's error margin, taking into account the precision characteristics of the technical means involved in the process of analog-to-digital conversion of the signal and additional operations, and the rounding errors during calculations [21, 22].

As evident from the conditions for conducting the phase shift measurement and the list of operations for converting the input harmonic signals $u_1(t)$ and $u_2(t)$ the initial uncertainty interval is equal to $[0, \pi[$ radians.

The length of the new uncertainty interval for the first iteration is determined by the following relation [23]:

$$\Delta\varphi_{\lambda 1} = (1 - \alpha) \cdot \pi, \quad (16)$$

$$\Delta\varphi_{\mu 1} = \alpha \cdot \pi, \quad (17)$$

where α – a coefficient that lies in the interval $0 < \alpha < 1$.

For conducting calculations, it is recommended $\alpha = 0.618$.

Calculate the deviation of the sum of squares $S_{\lambda 1}\left[u'_{\Sigma\,dn}(\varphi_i), u^{/}_{\Sigma en\lambda 1}(\varphi_i)\right]$ between the vector $u'_{\Sigma\,dn}(\varphi_i)$ and the reference function $u^{/}_{\Sigma enj}(\varphi_i)$, assuming the phase shift is equal to $\Delta\varphi_{\lambda 1}$ and the value $S_{\mu 1}\left[u'_{\Sigma\,dn}(\varphi_i), u^{/}_{\Sigma en\mu 1}(\varphi_i)\right]$ assuming the phase shift is equal to $\Delta\varphi_{\mu 1}$ using equations (11) and (14).

Let's calculate $S_{\lambda 1}\left[u'_{\Sigma\,dn}(\varphi_i), u^{/}_{\Sigma en\lambda 1}(\varphi_i)\right]$ and $S_{\mu 1}\left[u'_{\Sigma\,dn}(\varphi_i), u^{/}_{\Sigma en\mu 1}(\varphi_i)\right]$, assuming $k = 1$ and move to the main stage.

Main stage.

Step 1. If $\Delta\varphi_{b.k} - \Delta\varphi_{a.k} \leq l$, then stop and accept that the value of the phase shift equals

$$\Delta\varphi = \frac{\Delta\varphi_{b.k} - \Delta\varphi_{a.k}}{2} \quad (18)$$

where $\Delta\varphi_{a.k}$ – is the start of the uncertainty interval at the k-th iteration;

$\Delta\varphi_{b.k}$ – is the end of the uncertainty interval at the k-th iteration.

Otherwise, if

$$\begin{aligned} &S_{\lambda 1}\left[u'_{\Sigma\,dn}(\varphi_i), u'_{\Sigma en\lambda 1}(\varphi_i)\right] < \\ &< S_{\mu 1}\left[u'_{\Sigma\,dn}(\varphi_i), u'_{\Sigma en\mu 1}(\varphi_i)\right] \end{aligned} \tag{19}$$

proceed to step 3. If

$$\begin{aligned} &S_{\lambda 1}\left[u'_{\Sigma\,dn}(\varphi_i), u'_{\Sigma en\lambda 1}(\varphi_i)\right] \geq \\ &\geq S_{\mu 1}\left[u'_{\Sigma\,dn}(\varphi_i), u'_{\Sigma en\mu 1}(\varphi_i)\right] \end{aligned} \tag{20}$$

then proceed to step 2.

Step 2. Determine:

$$\begin{aligned} \Delta\varphi_{a.(k+1)} &= \Delta\varphi_{\lambda.k}, \\ \Delta\varphi_{b.(k+1)} &= \Delta\varphi_{b.k}, \\ \Delta\varphi_{\lambda.(k+1)} &= \Delta\varphi_{\mu.k}, \\ \Delta\varphi_{\mu(k+1)} &= \Delta\iota_{a.k} + \alpha(\Delta\varphi_{b.(k+1)} - \Delta\varphi_{a.(k+1)}). \end{aligned} \tag{21}$$

Calculate $S_{\mu(k+1)}\left[u'_{\Sigma\,dn}(\varphi_i), u'_{\Sigma en\mu(k+1)}(\varphi_i)\right]$ and proceed to step 4.

Step 3. Determine:

$$\begin{aligned} \Delta\varphi_{a.(k+1)} &= \Delta\varphi_{a.k}, \\ \Delta\varphi_{b.(k+1)} &= \Delta\varphi_{\mu.k}, \\ \Delta\varphi_{\mu.(k+1)} &= \Delta\varphi_{\lambda.k}, \\ \Delta\varphi_{\lambda(k+1)} &= \Delta\varphi_{a.(k+1)} + (1-\alpha) \times \\ &\times (\Delta\varphi_{b.(k+1)} - \Delta\varphi_{a.(k+1)}). \end{aligned} \tag{22}$$

Calculate $S_{\lambda(k+1)}\left[u'_{\Sigma\,dn}(\varphi_i), u'_{\Sigma en\lambda(k+1)}(\varphi_i)\right]$ and proceed to step 4.

Step 4. Replace k with $k+1$ and proceed to step 1.

4. Results and Discussion

Based on the above, the following sequence of auxiliary and measuring operations is proposed, which implements the proposed method for measuring the phase shift:

1 – filtering of input signals $u_1(t)$ and $u_2(t)$ to reduce the impact of external noise,

2 – amplification of input signals $u_1(t)$ and $u_2(t)$,

3 – conducting a two-half-period conversion of input signals $u_1(t)$ and $u_2(t)$,

4 – summing of the signals after conducting two-half-period conversion of input signals $u_1(t)$ and $u_2(t)$,

5 – generating the start and end signals of the analog-to-digital conversion operation,

6 – performing analog-to-digital conversion of the signal obtained because of summing the signals after conducting the two-half-period conversion of input signals $u_1(t)$ and $u_2(t)$,

7 – synthesis of a set of reference functions

8 – calculation of period and average value of signal under study

9 – conducting the normalization of the vector of instantaneous values of the signal,

10 – conducting a comparison of the normalized vector of instantaneous values with the reference function to determine the degree of non-coincidence,

11 – Determining the direction of change of the reference function and a new search interval for the phase-shift value.

12 – an indication of the determined phase-shift values of the input signals $u_1(t)$ and $u_2(t)$.

The main components of error in the proposed measurement method include an error component caused by amplitude-time conversion; an error component due to the formation of the start and end of amplitude-time conversion; the influence of external noises and noises from the measuring device's internal environment; an error in rounding when searching for the minimum deviation value of the sum of squares; and an error caused by the discreteness of generating reference functions.

Based on the fact that the use of two-half-period transformation to solve the measurement problem of determining the phase shift is a fairly new direction in the field of phase measurement, the main task of this work is to offer a methodological approach to determining the phase shift using this transformation, which can be used in the construction of information-measuring systems.

In the work [16], the possibility of using the two-half-period transformation of harmonic signals to determine the phase shift was considered. However, a significant disadvantage of oscillographic measurement methods is the need for visual reading. This drawback does not allow the use of the proposed method in information-measuring systems without additional modifications.

Let's conduct a comparative analysis of the known methods for implementing the compensation method for measuring with the proposed method. The main measuring operations implemented in known methods of the compensation measurement technique involve the generation of a phase shift using a multi-valued phase shift measure and the indication of the phase signal alignment, provided that one of the signals has passed through a reference phase shifter. These measurement operations are the main sources of deviations in the known methods of implementing the compensation measurement technique.

The proposed phase-shift measurement method uses a set of functions, synthesized by a computational device, as a reference set of phase shifts with the coincidence indicator implemented virtually. Based on the characteristics of well-known software packages widely used for modeling, such as Mathcad, MATLAB, and Electronics Workbench, it is known that they can perform calculations with precisions of up to 16 digits. From the above, it can be concluded that the total deviation in determining the phase shift will decrease by 10...15 % compared to known compensation methods for determining the phase shift, while the costs of creating and maintaining measurement systems will be reduced by %.

In the case of comparing the proposed method for determining the phase shift with methods such as the additive signal voltage processing method, the multiplicative signal processing method, and Hilbert transform phase meters, it can be stated that the measurement deviation will decrease to 5 %, and the costs for creating and maintaining the measurement system will be reduced by 5...10 %. This conclusion is based on the fact that the above methods require the operation of automatic signal-level adjustment for each measurement channel. This operation significantly complicates the measurement channels and introduces a component of deviation due to phase mismatches in the signal transmission channels, as well as the need for synchronization of the analog-to-digital conversion operation for each measurement channel. The proposed method does not require automatic signal level adjustment, and the phase-shift value information is transmitted by a single signal.

The disadvantages of the proposed method of implementing the compensation measurement method include that the phase-shift measurement range is within $[0, \pi[$ radians, limited frequency range is limited, which will be determined by the characteristics of the two-half-period converter.

Further research, in our opinion, should be aimed at synthesizing a mathematical model for the error estimation of the phase shift, offering an algorithm for determining the length of the uncertainty interval for the first iteration, taking into account the characteristics of the signal $u'_{\Sigma}(t)$, and synthesizing a methodology for calculating the requirements for filtering input signals $u_1(t)$ і $u_2(t)$, analog-to-digital conversion, computer technology, and software.

After carrying out the above work, it is advisable to conduct computational experiments using simulation modeling, for example, in the MATLAB and Electronics Workbench packages to determine the correctness (adequacy) of the offered models and the feasibility and type of use of digital filtering of the vector of instantaneous values $u'_{\Sigma d}(t_i)$ as when influencing a measuring system for electromagnetic interference from the outside, as well as simulating internal noise.

The use of this measurement method is planned for monitoring the parameters (time delays) of leading communication lines in data transmission systems.

Conclusions

A method has been proposed for determining the phase shift between two harmonic signals, which is based on comparing the shape of the normalized signal resulting from the summation of the harmonic signals after performing their double-half-period transformation with a set of standardized reference functions synthesized by computational means.

As a criterion for matching the shapes of the investigative signal and reference function, the proposed method uses the minimum deviation value of the sum of squares between them. To address this task, an algorithm for finding the extremum of the deviation value of the sum of squares for a set of reference functions and the investigated signal is proposed based on the golden ratio method.

Compared to existing methods based on analog-digital amplitude-time conversion, this method can: reduce the error component caused by the phase asymmetry of the signal transmission channels, thanks to shortening their length; substantially lowering the requirements for the quality of the automatic gain control operation of input signals; synthesize a single analog-digital conversion channel for the signal under analysis instead of two, thereby obviating the need for synchronizing analog-digital conversion for each signal processing channel; and significantly cut costs involved in creating a multi-value phase shift reference by using a set of reference functions synthesized by a computational device.

The main sources of errors in this method for measuring the phase shift were identified. Future work will be dedicated to the synthesis of a mathematical model of measurement error and verify the obtained results using a physical model.

The adoption of the proposed principle for determining phase shifts will significantly reduce the complexity of measuring systems due to the simplification of circuit solutions. This, in turn, will allow for the saving of material resources for controlling the technical characteristics of electronic computing equipment and its components (about 10%) during the testing phases of development and manufacturing of a sample without compromising the quality of control. Moreover, this method can be considered as a methodological basis for creating diagnostic systems and measuring characteristics during the operation of complex technical systems.

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МЕТОД ВИЗНАЧЕННЯ ФАЗОВОГО ЗСУВУ З ВИКОРИСТАННЯМ ДВОХНАПІВПЕРІОДНОГО ПЕРЕТВОРЕННЯ

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Предметом вивчення в статті є метод вимірювання фазового зсуву двох гармонійних сигналів, в основі якого лежить порівняння форми сигналу отриманого шляхом підсумування після проведення їх двохнапівперіодного перетворення з набором еталонних функцій. **Метою** є розробка методу вимірювання фазового зсуву двох гармонічних сигналів, що дозволить знизити складову похибки вимірювання, обумовлену фазовою несиметрією каналів передачі сигналів, та зменшить витрати на проведення контроля параметрів, визначення джерела похибок запропонованого методу вимірювання. **Завдання:** постановка вимірювальної задачі визначення фазового зсуву двох гармонійних сигналів; аналіз відомих методів вимірювання фазового зсуву на підставі використання аналого-цифрового перетворення; вибір показників та критерію визначення ступеню збігу досліджуваного сигналу з еталонною функцією; синтез алгоритму знаходження екстремуму залежності значення відхилення суми квадратів для множини еталонних функцій та досліджуваного сигналу на основі методу золотого перетину; аналіз джерел похибок. Використовуваними **методами** є: методологія проведення цифрової обробки сигналів та оцінки похибок вимірювання, числові методи пошуку екстремуму, методологія однофакторного експерименту. Отримані такі **результати.** Запропонований компенсаційний метод вимірювання фазового зсуву, в основі якого лежить порівняння форми нормованого сигналу, отриманого в результаті складання гармонічних сигналів після проведення їх двохнапівперіодного перетворення та набору нормованих еталонних функцій, синтезованих обчислювальними засобами. Визначено перелік вимірювальних та допоміжних операцій, що доцільно виконати для реалізації даного методу вимірювання. Проведено аналіз складових похибок вимірювання. **Висновки.** Наукова новизна отриманих результатів полягає в наступному: розроблено метод вимірювання фазового зсуву сигналу, який на наш погляд доцільно віднести до компенсаційного методу вимірювання, що дозволить суттєво знизити складову похибки, обумовлену фазовою несиметрією каналів передачі сигналів та знизити витрати на проведення контролю параметрів (до

10 %) без зниження якості виконання контролю; визначено перелік вимірювальних та допоміжних операцій, необхідних для реалізації запропонованого методу вимірювання; визначені джерела похибок.

Ключові слова: гармонійний сигнал; вимірювання; компенсаційний метод; фазовий зсув; похибка; екстремум.

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