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ENHANCED PHASE METHOD OF SIGNAL DETECTION FOR ULTRASONIC MAGNETOSTRICTION DEFECTOSCOPY OF POWER EQUIPMENT

Abstract. *The magnetostrictive method of ultrasonic flaw detection has certain advantages, in particular, the ability to control objects with complex geometry, at their high temperature, the ability to control dry contact between the transducer and the object, difficult access to the controlled area, etc. The peculiarities of the generation of ultrasonic waves by magnetostrictive transducers and their distribution in control objects determine the low level of the signal/noise ratio, which limits the possibilities of practical application of this method. The aim of the paper is to improve the phase method for detecting signals of magnetostrictive receivers with a low signal/noise ratio and to check the effectiveness of the proposed technical solution for solving problems of non-destructive testing of energy equipment elements using magnetostrictive defectoscopes. The paper discusses the phase method of detecting radio pulse signals of magnetostrictive converters against the background of additive noise, which is based on a combination of the capabilities of the discrete Hilbert transformation, which makes it possible to determine the envelope and phase of signals, and methods of statistical processing of the results of phase measurements. The proposed signal processing algorithm was studied both in a model experiment and when processing real magnetostrictive defectoscope signals. The proposed method makes it possible to detect radio pulse signals with a signal/noise ratio close to 1. The reliability of the obtained data is confirmed by the results of computer simulation. The considered method of detecting signals can be used in ultrasonic magnetostrictive defectoscopes and other diagnostic systems operating in conditions of reduced signal/noise ratio.*
Keywords: magnetostrictive defectoscope, ultrasonic defectoscopy, phase methods of signal processing, Hilbert transform, envelope, phase, sample resulting length of the vector.

1. Introduction

Ensuring stable trouble-free operation of energy equipment, early detection of defects at the stage of initiation and monitoring of their development during operation requires constant improvement of means and methods of monitoring, diagnosis and control of separate elements and energy facilities a whole [1]. The variety of energy equipment monitoring tasks makes it impossible to cover the entire range of relevant issues using one or two methods of non-destructive testing (NDT). The constant complication of control tasks, the expansion of their scope, the use of new structural materials in power equipment stimulates the search for new methods and means of control, the improvement of both the hardware and the software-algorithmic part of modern NDT tools [2].

The magnetostriction method belongs to the circle of new methods for ultrasonic flaw detection, although this method has many other applications in control and measurement technology, hydrolocation, acoustoelectronics [3]. In general, the topic related to the study of magnetoelectric effects remains relevant, and the areas of these effects application are constantly expanding, as evidenced by a number of publications in leading scientific publications [4]–[8].

A significant part of magnetostrictive sensors (MS) include of sensors of linear movements based on magnetostrictive delay lines [9]. Magnetostrictive position sensors occupy a valid place among similar sensors, they implement other physical principles. First of all, this is due to their high reliability, resistance to vibrational influences, a significant range of transformations and low cost. Today, the world leaders in the development and production of magnetostrictive position sensors are such firms as MTS (USA), Balluff (Germany), Shlumberger Industries (France) and others [1]. Specialists of these companies indicate more than 1,500 areas of use of magnetostrictive position sensors. The sensors of these companies have a permissible error of measurement of movement of no more than 1 mm; operating temperature range – from –200 to +200 °C; measured movement – from 0 to 6000 mm; have high interference resistance and minimal power consumption.

MS are an electric coil with a core made of magnetostrictive material. In a magnetostrictive radiator, the energy of the variable magnetic field of the coil is transformed into the energy of mechanical oscillations of the core. This effect, known as the Joule effect or the linear magnetostriction effect, was discovered and studied in 1842 by the outstanding English physicist D.P. Joule [10]. In a magnetostrictive receiver, the energy of external mechanical vibrations transmitted by the core is transformed into the energy of a variable magnetic field, which induces a variable electromotive force in the coil. This magnetoelastic effect (Villari effect) was discovered in 1865 by the outstanding Italian physicist E. Villari [10]. It is these magnetostrictive effects that form the basis of the operation of the MS for defectoscopy.

Magnetostrictive emitters have a small area of the emitting surface, which is determined by the cross-sectional area of the core, thereby, such sensors are small-aperture [11]. This makes it possible to use them to solve a number of important control tasks inaccessible to other methods. In particular, it is control of stranded steel wires [12], waveguides in the form of pipes and plates [13], ultrasonic inspection of metal components at high temperature [14], control of objects through "dry" contact.

In the case of using small-aperture MS, an ultrasonic wave in the shape of a hemisphere is emitted into the object of control, therefore the amplitude of the ultrasonic signal decreases rapidly with increasing distance from the emitter and, accordingly, the signal/noise ratio at the output of magnetostrictive receivers decreases. Under such conditions, detection of signals from the signal-noise mixture becomes difficult. In part, this problem can be solved due to the use of constructive methods of increasing the power of the emitting and the sensitivity of the receiving sensors [15]–[16]. Another way to solve this problem is to improve methods of processing signals of magnetostrictive receivers. In [17], the phase method of detecting signals of ultrasonic thickness gauges, which is based on statistical processing of the phase of information signals, is considered. This method involves the detection of signals based on the maximum of the mean resultant length, which is determined in the sliding mode of processing the results of the signal phase measurement. But this technical solution does not take into account part of the information contained in the signal envelope. This leads to a partial loss of the accuracy of the received estimates of the signal parameters and, ultimately, to a decrease in the ability to detect signals and a loss of accuracy in estimating their position in time.

The aim of the paper is to improve the phase method for detecting signals of magnetostrictive receivers with a low signal/noise ratio and to check the effectiveness of the proposed technical solution for solving problems of NDT of energy equipment elements using magnetostrictive defectoscopes.

2. Statement of the research problem

A probing ultrasonic signal is emitted into the object of control (OC), the model of which is represented by the formula:

$$u_P(t) = U_P(t)\sin 2\pi ft, \quad t \in [0, T_P], \tag{1}$$

where $U_P(t)$, f – respectively, the Gaussian envelope and frequency of the carrier signal; t, T_P – the current time and the time interval at which the signal is set $u_P(t)$, $T_P = (1...5) f^{-1}$.

The electrical signal $u_{MS}(t)$ received at the output of the magnetostrictive receiver is analyzed, which is an additive mixture of the signal (1) that has passed a certain section of the OC (informational component), and Gaussian noise realizations (noise component):

$$u_{MS}(t) = k_{EAT} u_P(t-\tau) + \xi(t),\ t \in [0, T_a], \tag{2}$$

where $k_{ект}$ – coefficients of the electroacoustic tract, $k_{ект} << 1$, τ – the delay of the received signal relative to the emitted one; $\xi(t)$ – implementation of additive Gaussian noise with zero mathematical expectation and dispersion σ^2; T_a – signal analysis time, $T_a >> T_P$.

It is necessary to improve the phase method of detecting signals of magnetostrictive receivers due to more complete use of the information contained in the signal envelope of the sensor and to evaluate the effectiveness of the method by conducting model and physical experiments.

3. Research methodology

The methodology of the phase method of detecting signals against a background of noise is based on a combination of the capabilities of the integral Hilbert transformation of signals [18]–[19], which makes it possible to determine the envelope and phase of signals, and methods of statistical processing of the results of phase measurements, the theoretical basis of which is also statistical methods of angular data analysis [20]–[21].

The main stages of signal formation and processing according to the improved phase method of detecting signals of magnetostrictive receivers are considered below.

3.1. Formation of signals in a physical experiment with MS.

The process of formation and processing of MS signals is reflected in the scheme presented in Fig. 1.

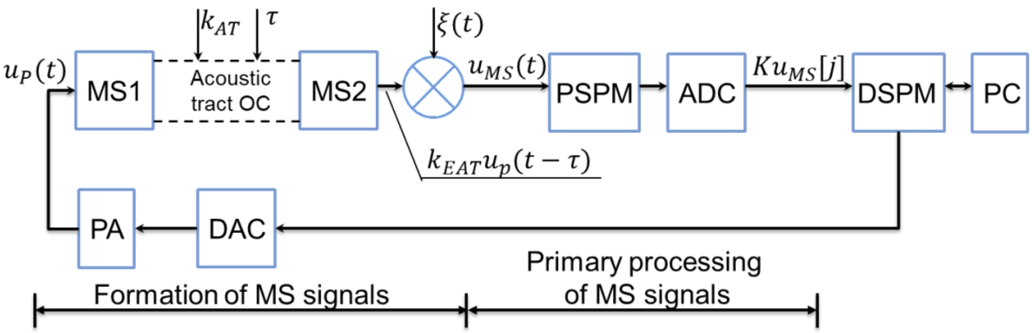

Fig. 1. Structural and logical scheme of formation and processing of MS signals

In Fig. 1 are marked: MS1,2 – magnetostrictive sensors, PA – power amplifier, DAC – digital-to-analog converter, PSPM – primary signal processing module, ADC – analog-to-digital converter, DSPM – digital signal processing module, PC – personal computer.

The DSPM generates samplings of the excitation signal, which are converted into voltage by the DAC, amplified by the PA and sent as an excitation signal $u_P(t)$ of the MS1 – an emitter of ultrasonic vibrations. These vibrations, having passed through the Acoustic tract OC, is converted by the receiving sensor MS2 into an electrical signal $k_{EAT} u_P(t-\tau)$. A noise component is added to this signal – the implementation of Gaussian noise, which is considered as an integral result of the action of the internal noise of the electronic units and the noise of the electroacoustic path. Model (2) corresponds to such a signal.

To transmit the informational harmonic component of the signal (2) in the ADC, a limited frequency band is sufficient. This gives reason to consider signal (2) as narrow-band, and accordingly, to present it as:

$$u_{\mathrm{MS}}(t)=k_{\mathrm{EAT}}U_P(t)\sin 2\pi f(t-\tau)+\xi(t)=U_S(t)\cos\left(2\pi ft-\varphi_{\mathrm{S}}-\frac{\pi}{2}\right)+\xi(t)=$$
$$=A(t)\cos\left(2\pi ft-\varphi_{\mathrm{S}}-\frac{\pi}{2}+\varphi(t)\right)=A(t)\cos(\Phi(t)),\qquad t\in[0,T_{\mathrm{a}}], \tag{3}$$

where $\varphi_{\mathrm{S}}=(2\pi f\tau)\bmod 2\pi=2\pi\cdot(f\tau)\bmod 1$ – the initial phase of the signal, $A(t)$, $\Phi(t)$ – respectively, the envelope and phase of a narrowband signal, $\varphi(t)\in[0,2\pi)$ – the modulation component of the narrowband signal phase caused by noise. The transition in (3) to the "cos" function is due only to the convenience of presenting the signal (3) in a complex form and does not change the essence of the phase method of signal detection.

3.2. Initial processing of MS signals.

This stage of signal processing is performed by PSPM and ADC. PSPM provides coordination of electronic units with MS2, signal amplification and frequency filtering. The signal is transmitted to the output of the module with the overall transmission coefficient *K*. The ADC forms a digital signal $Ku_{\mathrm{MS}}[j]$, $j\in[1,J]$, $J=[T_{\mathrm{a}}/T_{\mathrm{D}}]^{+}$, where T_{D} – signal sampling period, $T_{\mathrm{D}}<<f^{-1}$, $[\cdot]^{+}$ – designation of the operation of selection of an integer part of a number. Sequence $Ku_{\mathrm{MS}}[j]$ considered as embedded in an analog signal $Ku_{\mathrm{MS}}(t)$. In Fig. 2, as an example, a fragment of the signal is shown $Ku_{\mathrm{MS}}(t)$ as a radio pulse with a Gaussian envelope (red curve) and samplings of a discrete sequence $Ku_{\mathrm{MS}}[j]$ after converting the signal into an ADC (graphs are presented in relative units) are marked with circles.

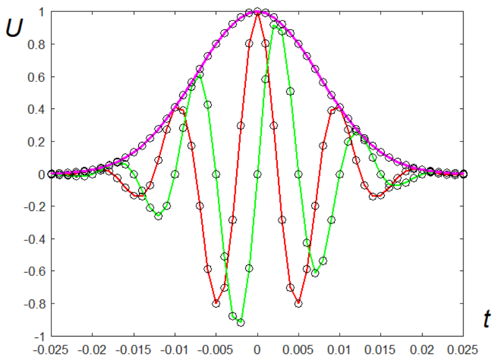

Fig. 2. An example of graphs of a signal $Ku_{\mathrm{MS}}[j]$ (red curve), its Hilbert image (green curve) and envelope (lilac curve) and their discrete values (marked by circles)

3.3. Formation of discrete signal characteristics.

This action is implemented in DSPM in two stages. On the first, a discrete Hilbert transformation of sequences $Ku_{\mathrm{MS}}[j]$, $j\in[1,J]$, $J=[T_{\mathrm{a}}/T_{\mathrm{D}}]^{+}$ is performed and a quadrature sequence $K\tilde{u}_{\mathrm{MS}}[j]$, $j\in[0,J)$ is obtained, all frequency components of which are shifted by an angle $\pi/2$ elative to the corresponding components $Ku_{\mathrm{MS}}[j]$. In Fig. 2 discrete values $K\tilde{u}_{\mathrm{MS}}[j]$ are marked by circles on the green curve. In general, the possibilities and features of using the Hilbert transformation in energy informatics for the analysis of information signals and obtaining their discrete characteristics were discussed in the papers [22]–[23].

At the second stage, the sequences $Ku_{\mathrm{MS}}[j]$ and $K\tilde{u}_{\mathrm{MS}}[j]$ are used to calculate the estimates of the discrete characteristics of the output signal – envelope and phase within the interval $[0,2\pi)$, which are carried out according to the formulas:

$$\hat{U}_{\text{MS}}[j] = K\sqrt{\left(u_{\text{MS}}[j]\right)^2 + \left(\tilde{u}_{\text{MS}}[j]\right)^2},\ j \in [0,\ J), \tag{4}$$

$$\hat{\varphi}_{\text{MS}}[j] = \operatorname{arctg} \tilde{u}_{\text{MS}}[j] / u_{\text{MS}}[j] + 0{,}5\pi\left\{2 - \operatorname{sign} \tilde{u}_{\text{MS}}[j]\left(1 + \operatorname{sign} u_{\text{MS}}[j]\right)\right\},\ j \in [0,\ J). \tag{5}$$

In Fig. 2 values $\hat{U}_{\text{MS}}[j]$ are represented by circles on the lilac-colored curve – envelope of the MS signal.

Function (5) represents the so-called unexpanded discrete phase of the signal. The expanded discrete phase is calculated from (5) as:

$$\hat{\Phi}_{\text{MS}}[j] = \hat{\varphi}_{\text{MS}}[j] + 2\pi q\left(\hat{\varphi}_{\text{MS}}[j]\right),\ j \in [0,\ J), \tag{6}$$

where $q\left(\hat{\varphi}_{\text{MS}}[j]\right)$ – a step function that increases by one each time the function $\hat{\varphi}_{\text{MS}}[j]$ jumps from values around 2π to 0.

The phase shift between the signal $u_{\text{MS}}[j]$ and the carrier signal of the excitation signal $u_{\text{P}}[j]$ at discrete times is defined as:

$$\hat{\varphi}[j] = \hat{\Phi}_{\text{MS}}[j] - 2\pi f T_{\text{o}} j, \quad j \in [0,\ J). \tag{7}$$

Therefore, the discrete Hilbert transformation makes it possible to obtain and analyze the discrete characteristics of informational radio pulse signals – their envelope, phase, and phase shift as functions of time given by samplings of a certain volume.

4. Results

4.1. Justification of the improved phase method of detection of MS information signals.

The phase method of detecting radio pulse signals against a noise background is given in [17]. It includes the determination of the unfolded phase $\hat{\Phi}_{\text{MS}}[j],\ j \in [0,\ J)$ of the studied additive mixture of the information signal and noise, the calculation of the difference $\hat{\varphi}[j]$ between the received unfolded phase and the phase of the signal-carrier of the information signal, sliding window processing of the difference in the phases of the signals by a window with an aperture $(M+1) << J$, calculation of the sample resulting length of the vector $r[j]$ as a result of summation on the unit circle of the values selected by the window phase differences, determination of the position in time of the information component of the signal by the maximum of the function $r[j]$. The current value $r[j]$, for an even value of *M*, is calculated according to the expression:

$$r[j] = \frac{1}{M+1}\sqrt{\left(\sum_{k=j-M/2}^{j+M/2} \cos\hat{\varphi}[k]\right)^2 + \left(\sum_{k=j-M/2}^{j+M/2} \sin\hat{\varphi}[k]\right)^2},\ \ j = \overline{\frac{M}{2},\left(J - \frac{M}{2}\right)}. \tag{8}$$

The mean resultant length (8) was initially introduced in the statistical analysis of angular data [20]–[21] as a circular statistic characterizing the dispersion of a sampling of volume angles $(M+1)$. The area of values of this characteristic belongs to the interval $(0,1]$, and its values are invariant to the selection of the beginning of the angle count. In the basic method, this statistic is calculated in the sliding mode, which makes it possible to detect the presence of radio pulses based on the fluctuations of the phase difference dispersion $\hat{\varphi}[j]$. When expression (8) was obtained, it was assumed that the probabilistic model of angles sampling $\left(\hat{\varphi}[j-0.5M],....,\hat{\varphi}[j],....\ \hat{\varphi}[j+0.5M]\right)$ was a vector of random angles $\left(\psi_{j-0.5M},....,\psi_j,....\ \psi_{j+0.5M}\right)$, all components of which have the same probability distributions and, accordingly, the same numerical characteristics.

In the case of conducting phase measurements of radio pulse signals with a Gaussian envelope (Fig. 2) in the presence of interference, it should be expected that with smaller signal amplitudes, and therefore with smaller signal/noise ratios, phase difference values with larger dispersions are obtained. It is obvious that this fact must be taken into account when determining vector $r[j]$ (8). At the qualitative level, such a conclusion can be substantiated by the following considerations. Because the values $r[j]$ are obtained from the results of measurements of phase shifts of signals, it is obvious that the accuracy of the latter affects the accuracy of the determination of $r[j]$. At the same time, it is known from statistical radio engineering [24] that the envelope and phase of a narrowband signal at coincident moments of time are statistically dependent. Therefore, taking into account information about the signal envelope makes it possible to increase the accuracy of determining the phase and vice versa.

It is advisable to take into account the instantaneous values of the amplitude of the radio pulse using the defined envelope $\hat{U}_{\mathrm{MS}}[j],\ j\in[0, J)$ (4). In the improved method of detecting radio pulse signals against a background of noise, it is proposed to use sampling envelope value $\hat{U}_{\mathrm{MS}}[j],\ j\in[0, J)$ as weighting coefficients when determining the weighted mean resultant length. This procedure is performed according to the formula:

$$r_w[j]=\frac{1}{M+1}\sqrt{\left(\sum_{k=j-M/2}^{k=j+M/2}\hat{U}^{*}_{\mathrm{MS}}[k]\cdot\cos\left(\hat{\varphi}[k]\right)\right)^2+\left(\sum_{k=j-m/2+1}^{j+m/2}\hat{U}^{*}_{\mathrm{MS}}[k]\cdot\sin\left(\hat{\varphi}[k]\right)\right)^2},\quad j=\frac{M}{2},\left(J-\frac{M}{2}\right), \quad (9)$$

where $\hat{U}^{*}_{\mathrm{MS}}[j]$ – the relative value of the envelope at the moment of time $jT_д$ is normalized by its maximum value.

4.2. Modeling of the process of detection of MS information signals according to the improved phase method.

In order to compare the known and improved method of detection of MS signals, a simulation of the process of a sequence of decaying radio pulses with a Gaussian contour was carried out. The simulation was performed in the Matlab. In the model experiment, the following output data were set: carrier signal frequency – 2.3 MHz; sampling frequency – 2.3 x 16 = 36.8 MHz; sampling size J = 6000; window aperture m = 32; the number of analyzed pulses is 5; aximum values of pulse signal amplitudes (in relative units) – 0.6; 0.36; 0.215; 0.13; 0.0775; root mean square noise (in relative units) $\sigma = 0{,}06$. The determined values of the signal/noise ratio (the ratio of the maximum values of the amplitudes of pulse signals to σ) were 10; 6; 3.6; 2.2; 1.3. The simulation results are shown in Fig. 3.

From the analysis of Fig. 3, b it can be seen, firstly, that the maxima of the sequence $r[j]$ coincide in time with the maxima of the information signals of the MS, secondly, the fifth pulse (with a signal/noise ratio = 1.3) is already comparable in magnitude to noise and cannot be reliably revealed. Instead, according to the sequence $r_w[j]$ (Fig. 3, c), the fifth pulse is detected. In addition, in this sequence, the noise level is significantly reduced in the interval from the first (signal/noise = 10) to the third (signal/noise = 3.6) pulse. Even better conditions for analyzing MS signals and determining their position in time are provided by the product graph $r[j]\cdot r_w[j]$ (Fig. 3, d) – the level of the noise component in this graph is much lower than in Fig. 3, b and Fig. 3, c.

4.3. Processing of MS signals obtained in the physical experiment.

For conducting the physical experiment the MS was used, the design of which is presented in [15]–[16]. The experiments used a probing ultrasonic radio signal (1) with a carrier signal f = 0.5 MHz and a duration of $T_P = 2f^{-1} = 4\,мкс$. The sampling frequency of the signal was 40 MHz (T_{D} = 25 ns), and the sampling volume J = 2000. The aperture of the window function was 75 counts (M = 74).

The results of two experiments with MS signals of different intensities are presented below. In Fig. 4, a the MS signal $u_{MS}[j]$ with a signal/noise ratio >> 1 (signal/noise = 100) is presented (the signal amplitude is given in relative units).

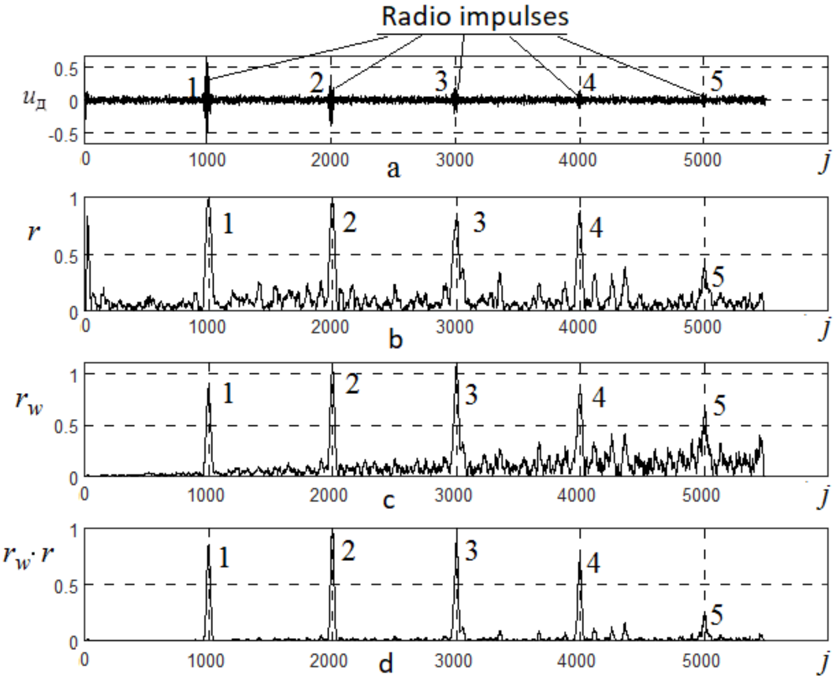

Fig. 3. Results of simulation of the process of detecting MS information signals: a – the analyzed signal; b – sequence $r[j]$; c – sequence $r_w[j]$; d – sequence $r[j]\cdot r_w[j]$

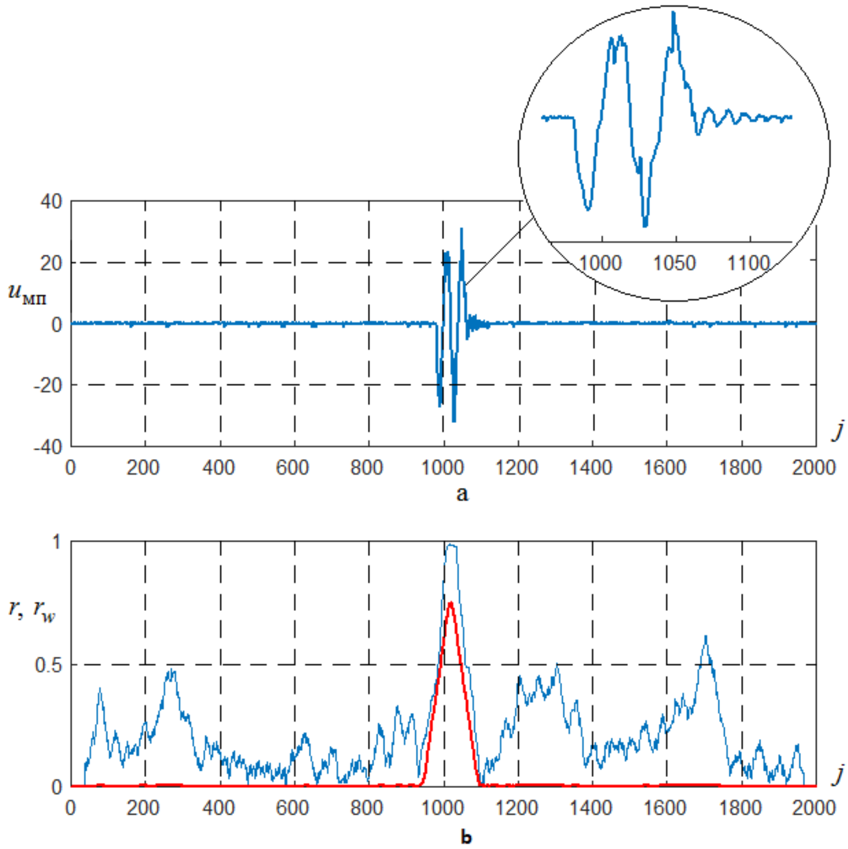

Fig. 4. Results of the physical experiment with a signal/noise ratio of ~ 100:
a – the graph of the sequence $u_{мп}[j]$; b – graphs of the sequences $r[j]$ (blue curve) and $r_w[j]$ (red curve)

In Fig. 4, b presents graphs of sequences $r[j]$ (blue curve) and $r_w[j]$ (red curve). From the analysis of the figure, it can be concluded that in this case, the use of the weighted mean resultant length (9) makes it possible to significantly reduce the noise level in the sequence $r_w[j]$ beyond the existence of the MS signal, although the peak value of the pulse decreased by ~ 25% – from unity to ~ 0.75. The detected pulse of the function $r_w[j]$ has the correct symmetrical shape, which makes it possible to estimate its position in time with a quantization error limited to $\pm 0,5T_д$.

In the second experiment, the MS signal was analyzed with a signal/noise ratio of ~ 2. In Fig. 5, a the probing signal $u_P(t)$ (blue curve) and MS signal $u_{MS}(t)$ (red curve) located on the time axis in the interval ~ (1.2–20) μs are presented. For more convenient determination of the time delay, the value $t = 0$ is artificially related to the first positive half-wave of the excitation signal. The low level of the informative pulse of the signal $u_{MS}(t)$ does not make it possible to reliably detect it by the envelope.

In Fig. 5, b presents graphs of sequences $r[j]$ (blue curve) and $r_w[j]$ (red curve). In this case, the use of the weighted mean resultant length of the vector (9) makes it possible to slightly reduce the noise level in the sequence $r_w[j]$ beyond the existence of the MS signal, and to increase the peak pulse value by ~ 30%, which is the positive effect of using the weighted mean resultant length of the vector.

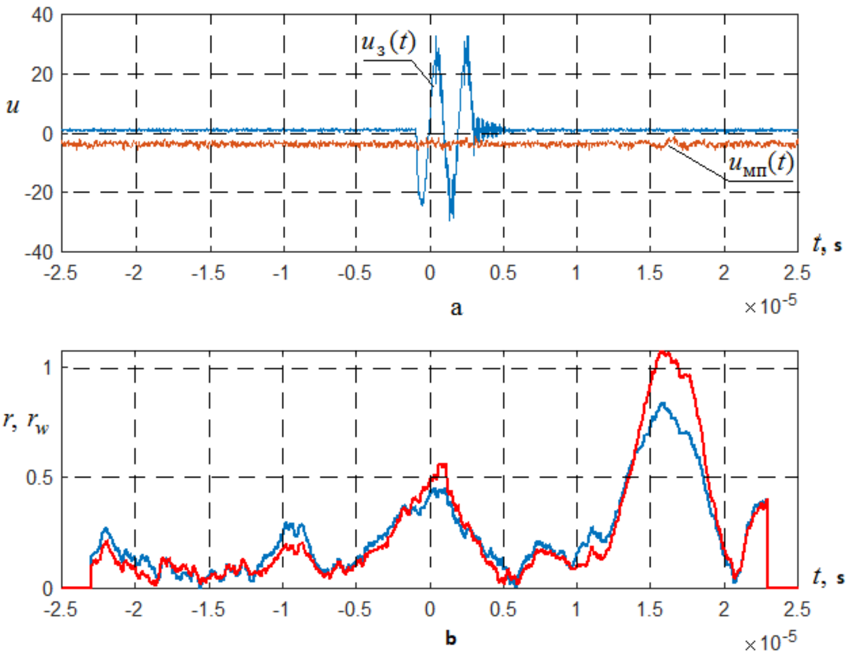

Fig. 5. Results of the physical experiment with a signal/noise ratio of ~ 2: a – graphs of the probing signal $u_3(t)$ (blue curve) and the MS signal $u_{МП}(t)$ (red curve); b – graphs of functions $r(t)$ (blue curve) and $r_w(t)$ (red curve)

The pulse of functions $r(t)$ and $r_w(t)$ presented in the vicinity of t = 0 is explained by the partial passage of the sounding radio pulse into the reception channel due to the influence of the electromagnetic field on the coil of the MS receiver.

5. Discussion of results

MS signals are generally represented by an additive mixture of a radio pulse and noise. In magnetostrictive defectoscopes, such signals can be represented by a model of narrow-band signals of type (3). The application of discrete Hilbert transformation to such models makes it possible to obtain samplings of the phase and evelope of such signals of significant volumes, which creates prerequisites for the application of statistical methods of their processing. Conducted studies on models of narrowband signals and received real MS signals confirmed the effectiveness of using information about the evelope to detect MS signals based on the weighted mean resultant length $r_w[j]$ (9). This function is obtained in sliding mode. Its maximum coincides in time with the middle of the MS signals.

With a low signal/noise ratio (from 1.3 to 5), such processing makes it possible to increase the impulse amplitude of the function $r_w[j]$ by at least ~ 30% relative to its unweighted prototype $r[j]$. In general, this makes it possible, with the constant power of the MS excitation signal, to perform ultrasonic studies of objects with lower coefficients of the electroacoustic tract $k_{\text{ект}}$, therefore, it makes it possible to detect smaller defects in the structure of the material of the studied objects and at greater distances.

With a high signal/noise ratio (from 5 or more), the main advantage of the considered signal processing method is that it provides a significant reduction (ten times) of the noise level in the sequence $r_w[j]$ beyond the existence of the MS signal. The detected pulse of the function $r_w[j]$ has the correct symmetrical shape, which makes it possible to reduce the error of estimating its position to values within $\pm 0,5T_{\text{D}}$.

6. Conclusions

The paper presents the results of research into the possibility of solving the problems of detecting and estimating the temporal position of MS signals, which are observed against a background of noise, by analyzing the weighted mean resultant length of the vector, which is determined by the phase characteristic of the investigated signal, taking into account its envelope. The implementation of such method does not require a complete copy of the signal. Only the frequency value of the carrier signal is sufficient a priori information. It is shown that it is possible to increase the efficiency of detection and the accuracy of positioning in time of MS information signals using the phase method of MS information signal detection by taking into account information about the signal envelope.

The proposed method makes it possible to detect radio pulse signals with a signal/noise ratio close to unity. The reliability of the obtained data is confirmed by the results of computer simulation. The considered method of detecting signals can be used in ultrasonic magnetostrictive defectoscopes and other diagnostic systems operating in conditions of reduced signal/noise ratio.

In general, the obtained results expand the possibilities of practical application of the magnetostrictive method of ultrasonic flaw detection of the relevant parts of electric power equipment and can be used in other information and measurement technologies for processing radio pulse signals in the presence of noise, particular, in the development of ultrasonic flaw detectors intended for working with materials with significant attenuation of ultrasonic vibrations. Further research in the direction of using circular statistics – themean resultant length, in the information and measurement technologies of MC signal processing, should be directed to a more detailed analysis of the effect of the window aperture and the possibility of multi-window processing of MC signals with a reduced signal/noise ratio.

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УДОСКОНАЛЕНИЙ ФАЗОВИЙ МЕТОД ВИЯВЛЕННЯ СИГНАЛІВ ДЛЯ УЛЬТРАЗВУКОВОЇ МАГНІТОСТРИКЦІЙНОЇ ДЕФЕКТОСКОПІЇ ЕНЕРГЕТИЧНОГО ОБЛАДНАННЯ

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Анотація. *Магнітострикційний метод ультразвукової дефектоскопії має певні переваги, зокрема, можливість контролю об’єктів зі складною геометрією за їх високої температури, можливість контролю за сухого контакту між сенсором та об’єктом, ускладненим доступом до контрольованої ділянки тощо. Особливості генерації ультразвукових хвиль магнітострикційними сенсорами та їх поширення в об’єктах контролю обумовлюють низький рівень відношення сигнал/шум, що обмежує можливості практичного застосування цього методу. Метою статті є удосконалення фазового методу виявлення сигналів магнітострикційних приймачів за низького відношення сигнал/шум та перевірка ефективності запропонованого технічного рішення для* *роз'вязання задач неруйнівного контролю елементів енергетичного обладнання за допомогою магнітострикційних дефектоскопів. У статті розглянуто фазовий метод виявлення радіоімпульсних сигналів магнітострикційних сенсорів на фоні адитивного шуму, який ґрунтується на поєднанні можливостей дискретного перетворення Гільберта, яке дає змогу отримати обвідну і фазу сигналів, та методів статистичного опрацювання результатів фазових вимірювань. Запропонований алгоритм опрацювання сигналів, який було досліджено як в модельному експерименті, так і при опрацюванні реальних сигналів магнітострикційного дефектоскопу. Дефектоскоп зберігає працездатність за відношення сигнал/шум близького до одиниці і вище. Достовірність отриманих даних підтверджена результатами комп'ютерного моделювання. Розглянутий спосіб виявлення сигналів може бути використаний в ультразвукових магнітострикційних дефектоскопах та інших діагностичних системах, що працюють в умовах зниженого відношення сигнал/шум.*

Ключові слова: магнітострикційний дефектоскоп, ультразвукова дефектоскопія, фазові методи опрацювання сигналів, перетворення Гільберта, обвідна, фаза, вибіркова результуюча довжина вектора.

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