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RESEARCH

Methodical Approach to Using Acoustic Emission Method for Tribosystem Monitoring

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A B S T R A C T

The method of diagnosing various constructions of tribosystems by acoustic emission method is developed in the work. The development of the methodology is based on the following assumptions. The activity of acoustic emission during the operation of the tribosystem will depend on the rate of deformation of materials on the spots of actual contact. The total acoustic signal from the friction zone is formed as a result of the interference of the primary acoustic signals from the spots of actual contact with the friction surface, which correspond to the coherence condition. Based on these assumptions, the expression for calculating the informative frequencies that will be generated by the tribosystem in the process. The method of diagnosis contains the following steps: determination of informative frequencies on which it is necessary to register amplitudes; determining the magnitude of the amplitudes that carry the maximum information; distribution of the general acoustic signal on clusters and establishment of functional communication of values of a peak factor of clusters with values of coefficient of friction, speed of wear and time of running-in of tribosystems in an online mode. The use of the developed technique will increase the robustness of the method of diagnosing tribosystems and identify surface processes during wear.

1. INTRODUCTION

The first publications on the use of acoustic emission (AE) as a method of diagnosing friction joints appeared in the late 1970s [1-3] as a way to monitor friction and wear in real time. These works outline the prospects of this method and its possibility in diagnosing tribosystems. However, at that time the use of AE was hampered by the lack of high-speed electronic means of registration and signal processing. With the modern development of signal recording means, the use of this method allows to obtain information about the state of the friction surfaces online.

Acoustic oscillations generated by the tribosystem during operation occur due to the shock interaction of the roughness of the friction surfaces, their elastic-plastic deformation, the formation and destruction of friction joints (stick-slip mode [4]), structural-phase adjustment of materials, formation and the development of microcracks in the surface layers of contacting bodies, the separation of wear particles.

Currently, acoustic emission means a secondary process that is a superposition of signals from a huge number of elementary sources of AE, ie acoustic radiation is the result of collective processes of structural units (defects in the structure of the material). Moreover, it is believed that this secondary process is the result of interference of primary acoustic waves that meet the coherence condition.

2. MAIN HEADING

In works [5,6] it is noted that the classification and prediction of the wear rate in tribosystems is a real industrial problem that has not been solved today. The authors conclude that an online monitoring system capable of categorizing wear rate can be critical for many industries as it can help prevent catastrophic failures. The authors note that frictional failures are a common cause of catastrophic damage to mechanical systems, resulting in significant repair costs or operational delays. Therefore, a system for monitoring such failures in real-time is in great demand. In works [5,6] a probabilistic analysis of acoustic signals is proposed, with their division into levels, synchronously recorded with the wear rate and the friction coefficient in real experiments.

In work [7] to diagnose tribosystems, the recorded signals from the friction zone were processed using the fast Fourier transform, and then parameters such as power, rms amplitude, mean frequency, and signal energy were determined. The correlation coefficient between the obtained parameters and the wear rate and the coefficient of friction is determined. The authors of the work found that some acoustic frequencies reflect friction, while others reflect the wear rate. In this work, a conclusion is made about the separation of informative frequencies that characterize the wear rate and the coefficient of friction. According to the authors, this approach will increase the information content of the acoustic emission method when diagnosing tribosystems.

A similar approach is expressed by the authors of the work [8], where the acoustic signals from the friction zone were studied during the tribosystem test. The authors note two emission mechanisms at frequencies of 0,2 MHz and 1 MHz. According to the authors, these frequencies are informative. In work [9], on the basis of the tribosystem tests carried out, it is stated that the informative frequency range does not exceed 800 kHz. At the same time, the authors varied the values of the roughness of the friction surfaces and, on the basis of this, conclude that intermittent slippage in the contact of roughness has great importance on acoustic radiation.

The results of the research of the frequency component of the signal are presented in the work [10]. The authors claim that the frequency of AE correlates with the type of wear of the friction surfaces, such as adhesive, abrasive. The authors make a platoon that the mechanisms of wear can be determined by the frequency spectrum of AE signals.

The role of slip of roughness in contacting friction surfaces and the effect of sliding velocity on acoustic radiation is discussed in the work [11]. The authors of the work conclude that an increase in the sliding speed increases slip in the contact, and this, in turn, increases the values of information frequencies from the friction zone.

In the works [12-14] analysis of publications on the use of AE to diagnose various tribosystems. They concluded that research on acoustic emission diagnostics of mechanisms is based on the use of signs of discrete emission. As for the continuous emission, it is characterized by the parameters: standard deviation; peak factor; the spectrum of oscillations [13]. In addition, use time parameters (duration of the front and the decline of the pulses) [13], parameters of pulse distribution by amplitude, and wavelet transform [14].

In the works [15-17] the analysis of the frequency component of the AE signal of various alloys under plastic deformation has been carried out. The authors have established the following frequency ranges in which the maximum values of the amplitudes are manifested: plastic deformation 50-200 kHz; twinning processes 200 - 500 kHz; martensitic transformations 250 - 400 kHz; jumps of cracks 250 - 600 kHz. Based on the studies performed, it is concluded that the maximum signal amplitudes are characteristic of twinning processes and the abrupt growth of cracks.

Further study of frequency ranges received in works [18,19]. A correlation has been established between the activity of acoustic emission and the rate of deformation. The authors conclude that when studying the flow of acoustic signals during plastic deformation, it is possible to limit the upper frequency boundary of 400 - 600 kHz. The data presented in the works indicate that the signal amplitude can characterize the density of nonrandom, interdependent elementary deformation events during plastic deformation of metallic materials and correlates with the deformation rate.

Based on the analysis of the works of Western scientists [20-25], in work [26] it is concluded that a promising direction is the substantiation of acoustic emission signs of defects that are invariant to signal amplitude scaling. This is due to the fact that signal fluctuations, differences in the amplitude-frequency characteristics of the sensors, affect the result of measuring the energy parameters of the emission, such as energy, average value of the amplitudes, spectrum and the result of the wavelet transform. The listed factors affect the parameters of the recorded acoustic emission signal. According to the author of the work [26] when measuring the temporal parameters of acoustic emission, it is advisable to choose the threshold level of amplitudes, which is determined from the condition of the minimum probability of the diagnosis error.

The work is devoted to the choice of informative parameters of AE for diagnosing tribosystems [27], where theoretically and experimentally it is established that informative frequencies depend on the following groups of factors: constructive; technological and operational. The degree of influence of the listed factors on change of a frequency range is established. Operational factors (sliding speed and load) change the frequency range from 106 to 584 kHz, technological factors (roughness of friction surfaces), change the frequency range from 118 to 618 kHz, design factors (the amount of friction area of a fixed triboelement), change the frequency range from 140 to 530 kHz. It is concluded that for effective diagnosis of tribosystems it is necessary to pre-determine the informative frequency range taking into account the above factors.

To substantiate the choice of informative amplitudes of AE in works [27,28] cluster analysis of AE signal frames from the friction zone of the tribosystem with signal distribution into groups of its generation sources is performed. Correlations between wear rate, friction coefficient and values of peak factor of different clusters are established. The author concludes that this analysis can be the basis for the development of methods for diagnosing tribosystems during their operation, which will measure the rate of wear at any time and calculate the resource of the tribosystem.

Based on the analysis of the work, we can conclude that to determine the wear rate and friction coefficient during the operation of tribosystems (online), it is necessary to pre-determine the informative frequency range and within this range to distribute the AE signal to components - clusters. Analysis of each cluster will provide information about a particular group of processes occurring in the surface layers of materials of the tribosystem.

3. THE AIM OF THE STUDY

The purpose of this study is to develop a methodological approach with a justification of the list of mandatory steps for monitoring various constructions of tribosystems by determining the informative frequencies and amplitudes of the friction zone and establishing their relationship with the processes of friction and wear.

In accordance with the purpose of the study, the following tasks were solved in the work:

1. Determination of the correlation between the calculated and experimental values of information frequencies from the friction zone, taking into account the constructive, technological and operational factors of tribosystems.
2. Determination of the correlation between the values of peak factors of different clusters and wear rate, friction coefficient and running-in processes of tribosystems.
3. Develop a methodological approach and justify the list of mandatory steps while using the method of acoustic emission for monitoring tribosystems in operation.

4. SECONDARY HEADING

In solving the first problem of the study – substantiation of the choice of informative frequency range for the analysis of frames of AE signals from the friction zone of the tribosystem with the distribution of the signal into groups of sources of its generation, we use the main conclusions of previously published works [27-31].

1. The activity of acoustic emission during the operation of the tribosystem will depend on the stress (Pa) and the rate of deformation (1/s) of the materials of the triboelements on the actual contact spots [27].
2. The total acoustic signal from the friction zone is formed as a result of the interference of the primary acoustic signals from the actual contact spots from the friction surface, which correspond to the coherence condition [4,11-16].

Based on these conditions and restrictions in the work [27] the expression for calculation of the informative frequency which will be generated by a tribosystem in the course of work is presented:

$$f_{AE} = n_{acs} \cdot \dot{\varepsilon} \cdot (1+\mu) \cdot (1-2\mu), 1/s, \tag{1}$$

where f_{AE} – informative frequency of AE signals from the friction zone, dimension 1/s; n_{acs} – the total number of actual contact spots (ACS) on the friction surface of the triboelement with a smaller area of friction; $\dot{\varepsilon}$ - the value of the strain rate on a single actual contact spot, dimension 1/s; μ - Poisson's ratio.

Dependence (1) was obtained in work [27] on the basis of experimentally established correlation of the generated frequency of the AE signal from the friction zone and the number of actual contact spots, the deformation rate of the material of the surface layer of the triboelement on the actual spots of contact and the physical and mechanical properties of the material of the triboelement. The authors of work [27] provide experimental material that confirms this correlation.

The method of calculating the average area of a single actual contact spot, the average diameter of the contact spot, and the number of contact spots on the smaller friction surface of one of the triboelements is determined by the formulas given in the work [30].

The average area of a single actual contact spot:

$$A_a = \frac{\eta}{d_a}, \ \text{m}^2, \tag{2}$$

where η– relative actual contact area, calculated according to the work [30]; d_a – contact spot density, calculated according to the work [30].

The average diameter of a single ACS is determined by the expression:

$$d_{acs} = \sqrt{\frac{4A_a}{\pi}}, \ \text{m}. \tag{3}$$

Knowing the value of the smaller area of friction of one of the triboelements F_{min}, the average area of a single contact spot, formula (2) and the relative actual contact area [30], determine the number of actual contact spots on a smaller friction surface:

$$n_{acs} = \frac{F_{\min}}{A_a}\eta. \tag{4}$$

The rate of deformation of the material of the movable triboelement on a single actual contact spot is calculated by the formula:

$$\dot{\varepsilon}_{mov} = 75 \cdot (1+\mu_{mov})(0{,}86 - 1{,}05\mu_{mov})\frac{\sigma_{acs} \cdot \upsilon_{sl}}{E_{mov} \cdot d_{acs}} \ 1/\text{s}, \tag{5}$$

- for the material of the fixed triboelement:

$$\dot{\varepsilon}_{fix} = 75 \cdot (1+\mu_{fix})(0{,}86 - 1{,}05\mu_{fix})\frac{\sigma_{acs} \cdot \upsilon_{sl}}{E_{fix} \cdot d_{acs}} \ 1/\text{s}, \tag{6}$$

where μ_{mov} and μ_{fix} – Poisson's ratio of materials of movable and fixed triboelements; σ_{acs} – voltage on a single actual contact spot, Pa; E_{mov} and E_{fix} – modulus of elasticity of materials of movable and fixed triboelements, Pa; υ_{sl} – sliding speed, m/s.

From the above formulas (3) - (6) it follows that the voltage and rate of deformation of the surface layer material on the actual contact spots depends on the physical and mechanical properties of the triboelement material (Poisson's ratio and Young's modulus), as well as sliding speed. The deformation rate is included in expression (1), so the value of the information frequency is affected.

If the design of the tribosystem (movable and fixed triboelements) consists of materials with different modulus of elasticity E and Poisson's ratios м, then expression (1) to determine the informative frequency will have the following form:

- for a movable triboelement:

$$f_{AE(mov)} = n_{acs} \cdot \dot{\varepsilon}_{mov} \cdot (1+\mu_{mov}) \cdot (1-2\mu_{mov}), \qquad (7)$$

- for a fixed triboelement:

$$f_{AE(fix)} = n_{fix} \cdot \dot{\varepsilon}_{fix} \cdot (1+\mu_{fix}) \cdot (1-2\mu_{fix}). \qquad (8)$$

The obtained expressions (7) and (8) allow to calculate the informative frequencies in the frame of acoustic emission signals from the friction zone generated by the moving and stationary triboelements of the tribosystem. These frequencies depend on the number of actual contact spots, the rate of deformation of the material on the actual contact spots and the physical and mechanical properties of the material (Poisson's ratio), it follows from formulas (7) and (8). In this case, the rate of deformation of the material on a single ACS depends on the load, the sliding speed and the elastic properties of the materials of the triboelements. If the movable and fixed triboelements are made of different materials, they will generate different informative frequencies. This conclusion must be taken into account when placing the piezoelectric element on a stationary sample of the tribosystem to perform the diagnosis.

When solving the second problem of the study, determining the correlation between the values of the peak factors of various clusters and the wear rate, the friction coefficient and the processes of running-in tribosystems, we will use the work [30]. The total signal AE is to be divided into clusters. This is a subset of the same type of pulses with the same magnitude of amplitudes A_i, associated with single generation sources.

The first cluster К1 - this is the base signal packet AE or the base frame. Sources of generation of the basic package of signals are: sliding of dislocations at deformation of surface layers on spots of actual contact; intergranular slip; rotation of blocks (grains); twinning; structural adjustment (phase transformations due to high temperatures at the spots of actual contact).

Based on work [30] write the formula for calculating the peak factor of the base cluster *K1*:

$$P_{AE}^{K1} = \frac{\left\langle \sum_{n=1}^{n}\sum_{m=1}^{m}(A_1 \cdot A_{\max,1}) \right\rangle}{\sum_{n=1}^{n}|A_1|^2}, \qquad (9)$$

where n – the total number of pulses of the AE signal that belong to the frame of the base cluster К1; m – the number of pulses of the AE signal that exceed the average value of the amplitudes of the base cluster К1 by 1.2 - 1.4 times; A_1 – the value of the amplitudes of all pulses AE, which belong to the frame of the base cluster К1; $A_{max,1}$ - the values of the amplitudes of the pulses AE, which belong to the frame of the base cluster К1, and exceed the average value of the amplitudes in the cluster by 1.2 - 1.4 times.

The second cluster К2 is a package of AE signals, which is characterized by emissions of amplitudes whose value exceeds the average value of the amplitudes of the first (base) cluster К1 by 1,6 - 2,3 times. Cluster signal generation sources К2 are: deformation jumps on spots of actual contact as a result of which sliding strips are formed; abrupt movement of roughness protrusions due to changes in adhesion forces, stick-slip mode.

Based on work [30] write the formula for calculating the peak factor of the cluster К2:

$$P_{AE}^{K2} = \frac{\left\langle \sum_{n=1}^{n}\sum_{m=1}^{m}(A_1 \cdot A_{\max,2}) \right\rangle}{\sum_{n=1}^{n}|A_1|^2}, \qquad (10)$$

where m – the number of pulses of the AE signal that exceed the average value of the amplitudes of the base cluster К1 by 1.6 – 2.3 times; $A_{max,2}$ - the values of the amplitudes of the pulses AE, which belong to the cluster frame К2, and exceed the average value of the amplitudes in the cluster К1 by 1.6 – 2.3 times. Substantiation of amplitude values is given in the work [29].

The third cluster is a package of AE signals, which is characterized by amplitude emissions, the value of which exceeds the average value of the amplitudes of the first (base) cluster К1 by 2.52 – 3.21 times.

Cluster signal generation sources К3 are: the development of fatigue cracks located parallel and perpendicular to the friction surface; separation of wear particles from the friction surface in the form of scales or petals by the mechanism of fatigue wear; separation of wear particles from the friction surface by the mechanism of "rolling" of oxide films or secondary structures.

Based on work [30] write the formula for calculating the peak factor of the cluster К3:

$$P_{AE}^{K3} = \frac{\left\langle \sum_{n=1}^{n} \sum_{m=1}^{m} (A_1 \cdot A_{\max,3}) \right\rangle}{\sum_{n=1}^{n} |A_1|^2}, \tag{11}$$

where m – the number of pulses of the AE signal that exceed the average value of the amplitudes of the base cluster К1 by 2.52 – 3.21 times; $A_{max,3}$ - the values of the amplitudes of the pulses AE, which belong to the cluster frame К3 and exceed the average value of the amplitudes in the cluster К1 by 2.52 – 3.21 times. Substantiation of amplitude values is given in the work [29].

The fourth cluster is a package of AE signals, which is characterized by emissions of large amplitudes, the value of which exceeds the average value of the amplitudes of the first (base) cluster К1 by 3.91 – 4.6 times.

Sources of cluster signal generation К4 are: microcutting and plastic deformation of protrusions of roughnesses of a surface of friction which is characteristic of the first stages of running-in [29].

Based on work [29] write the formula for calculating the peak factor of the cluster К4:

$$P_{AE}^{K4} = \frac{\left\langle \sum_{n=1}^{n} \sum_{m=1}^{m} (A_1 \cdot A_{\max,4}) \right\rangle}{\sum_{n=1}^{n} |A_1|^2}, \tag{12}$$

where m – the number of pulses of the AE signal that exceed the average value of the amplitudes of the base cluster К1 by 3.91 – 4.6 times; $A_{max,4}$ - the values of the amplitudes of the pulses AE, which belong to the cluster frame К4 and exceed the average value of the amplitudes in the cluster К1 by 3.91 – 4.6 times. Substantiation of amplitude values is given in the work [29].

5. RESEARCH RESULTS

When solving the first research problem - determining the correlation between the calculated and experimental values of information frequencies from the friction zone and their dependence on the design, technological and operational factors of tribosystems, experimental studies were carried out on a friction machine, fig.1. Kinematic scheme of ring-ring tribosystems with the following combination of materials.

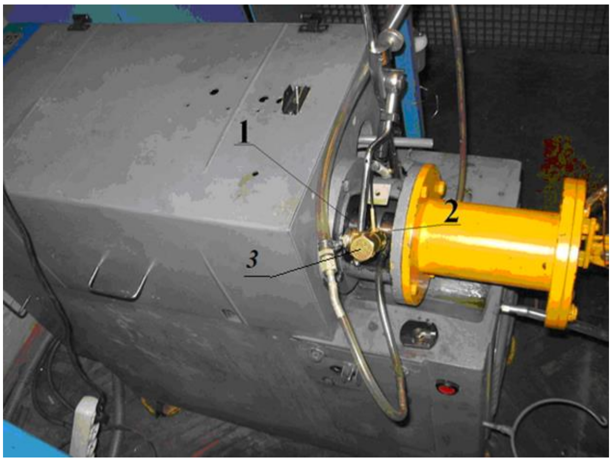

Fig. 1. Kinematic scheme of contact "ring-ring": 1 - moving ring; 2 - fixed ring; 3 - acoustic emission sensor.

Tribosystem №1: movable triboelement steel 40X (45 - 47 HRC), stable triboelement: Br.AZh 9-4 (90 - 110 HB);

Tribosystem №2: movable triboelement steel 40X (45 - 47 HRC),stable triboelement: gray cast iron SCH (HB 270);

Tribosystem №3: movable triboelement steel 40X (45 - 47 HRC), stable triboelement: steel 40X (45 - 47 HRC).

Lubricating medium - engine oil SAE 20W30. The overlap coefficient varied from 0.2 to 0.8, therefore the friction area of the stationary triboelement was F_{fr} = 0.00006 m²; 0,00015 m²; 0.00024 m², accordingly.

This choice of materials and their combination in the construction with simultaneous variation of friction areas allows to model different constructions of tribosystems of machines and mechanisms.

A block diagram of the experimental equipment for recording and processing AE signals from the friction zone is shown in fig.2.

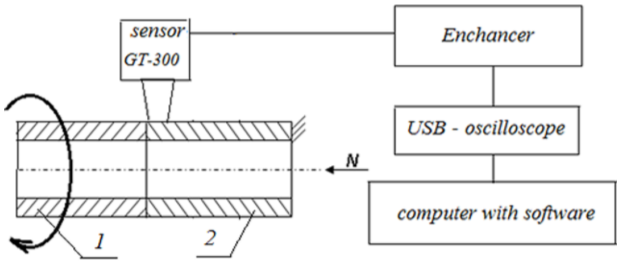

Fig. 2. Block diagram of experimental equipment for recording and processing AE signals: 1 - movable triboelement; 2 - fixed triboelement; N - load.

The AE signal from the friction zone is recorded by a broadband sensor GT300 (100 – 800 kHz), fig.2, which was installed on a stable triboelement 2 by means of a waveguide 3. The waveguide is made in the form of a ring. The GT300 sensor was fixed to the waveguide with glue, which provided a one-piece connection. The waveguide is made removable, fixed on a stable triboelement 2 with a screw and covered the entire surface of the triboelement. The generated signal was transmitted to the amplifier, then, in analog form, USB oscilloscope PV6501, which performs the functions of analog-to-digital converter and spectrum frequency analyzer simultaneously. After processing in a USB-oscilloscope, the signal in digital code enters the computer, where it is processed by special software.

The lower bandwidth of the signal is 50 kHz, which does not allow recording signals from test equipment (friction machine). The upper signal bandwidth is 1.5 MHz. This frequency range was selected based on an analysis of the works of other authors who are devoted to acoustic emission from the friction zone [4-19].

The bandwidth of the USB oscilloscope, fig. 2, is 20 MHz, which is many times higher than the selected operating signal bandwidth. Thus, using low and high frequency filters in the conducted studies, the AE signal from the friction zone was recorded and analyzed in the 50 - 1500 kHz band. In the applied measuring complex the registered frequency range can be changed by means of filters.

The USB oscilloscope operates in standby mode and is triggered by a command for registration time equal to 1000 μs. This time was chosen based on the analysis of the AE signal in the steady state using the autocorrelation function.

When checking the uniformity of the variances of the selected frames of the AE signals in the steady-state operation of the tribosystem, as well as the reproducibility of the results from frame to frame, the ISO 5725 standard recommends using the Cochran criterion. Cochran's criterion allows us to compare the uniformity of dispersion of signal analysis results from different frames of AE.

Experimental studies were carried out under the following friction modes: load N = 500 – 1500 N; sliding speed 0.2 – 0.8 m/s. During the experiments, the information frequencies were recorded at which the maximum values of the amplitudes were observed.

The results of experimental studies on the correspondence of theoretical and experimental informative frequencies from the friction zone are shown in fig. 3 – 6. Solid curves represent calculated values depending on various factors.

The points on the graph field represent the average values of the information frequencies in the steady-state operation of the tribosystem (after the completion of the running-in) at various loads. By information frequencies we mean the frequency band where the maximum values of the amplitudes are observed.

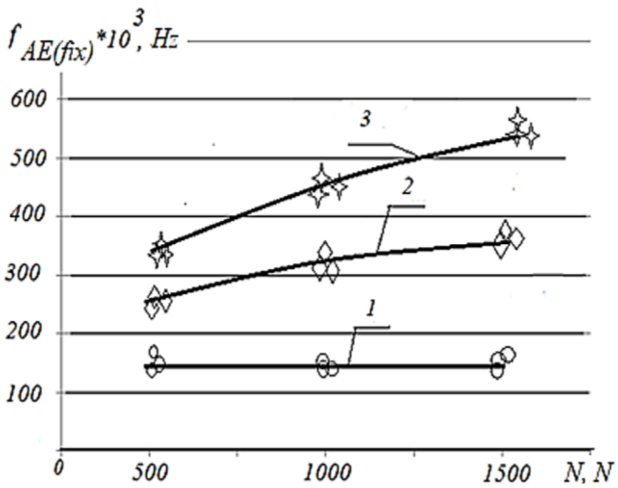

Fig. 3. Theoretical and experimental values of the change in the information frequency of the AE $f_{AE(fix)}$ a fixed triboelement with a change in the friction area F_{fr} at various loads: 1 – F_{fr} = 0.00006 m^2; 2 – F_{fr} = 0.00015 m^2; 3 – F_{fr} = 0.00024 m^2.

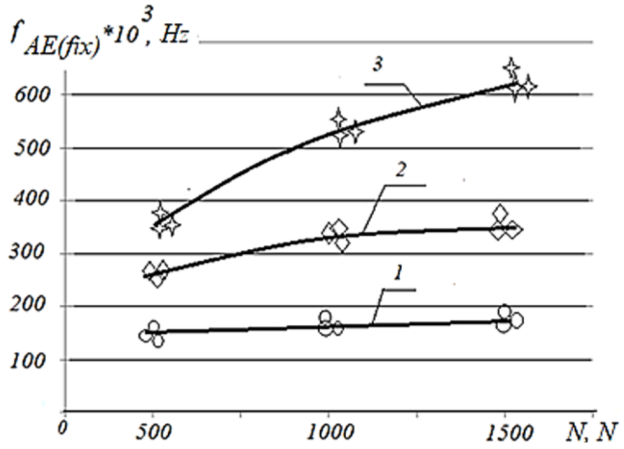

Fig. 4. Theoretical and experimental values of the change in the information frequency of the AE $f_{AE(fix)}$ fixed triboelement when roughness changes *Ra* friction surfaces at various loads: 1 – *Ra*=0,1 micron; 2 – *Ra*=0.2 micron; 3 – *Ra*=0.4 micron.

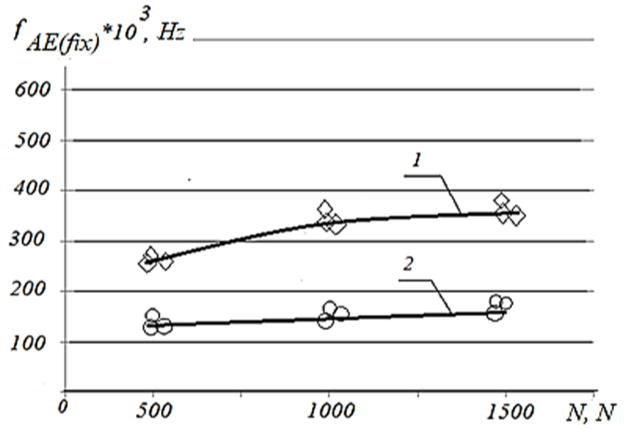

Fig. 5. Theoretical and experimental values of the change in the information frequency of the AE $f_{AE(fix)}$ fixed triboelement when changing the average pitch of irregularities *Sm* friction surfaces at various loads*:* *1 – Sm*=0.4 mm; *2 – Sm*=0.5 mm.

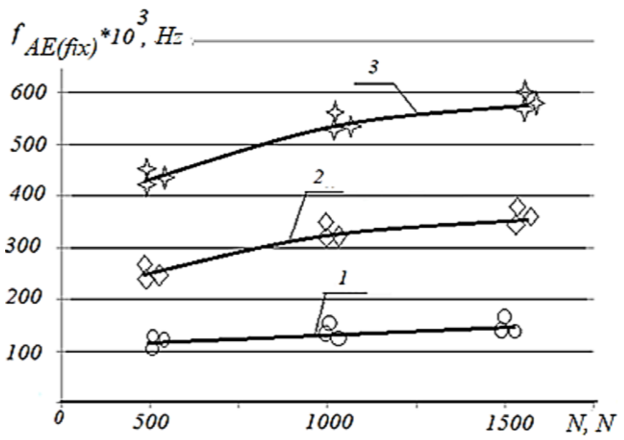

Fig. 6. Theoretical and experimental values of the change in the information frequency of the AE $f_{AE(fix)}$ a fixed triboelement when changing the sliding speed v_{sl} at various loads: 1- v_{sl} =0.2 m/s; 2- v_{sl} =0.5 m/s; 3- v_{sl} =0.8 m/s.

As follows from the dependences shown in fig. 4, an increase in the friction area of a fixed triboelement significantly increases the information frequency AE, which is generated by the tribosystem. An increase in the area of friction by 4 times leads to an increase in the information frequency from 150 kHz to 550 kHz.

The strongest influence on the value of the information frequency is exerted by the value of the surface roughness *Ra*, fig. 4 and sliding speed, fig. 6. With an increase in the roughness of the friction surfaces from 0.1 μm to 0.4 μm, the value of the information frequency increases from 150 to 620 kHz. A similar result is obtained by changing the sliding speed, fig. 6. This effect can be explained by the appearance of slippage at the actual contact spots, the stick-slip [4], and an increase in the rate of deformation of the material on the indicated contact spots, the formula (8).

Changes in the average pitch of irregularities *Sm* friction surfaces, fig. 5, to a lesser extent affects the value of the information frequency. A similar result in terms of the degree of influence on the information frequency was obtained by changing the materials of the fixed triboelement.

The obtained experimental values of information frequencies were tested for reproducibility from experiment to experiment according to the Cochran criterion. The results obtained allow us to assert that the experimental data are reproducible within a confidence level of 0.95. The adequacy of the theoretical curves to the experimental data was verified by the Fisher criterion. The obtained values of the Fisher criterion allow us to assert that the theoretical curves are adequate to the experimental data with a confidence level of 0.95.

When solving the second task of the study, the goal was set - to confirm the correlation relationship of the rate of volumetric wear of the tribosystem *I*, m^3/hour and coefficient of friction f_{fr} with the values of the peak factors of various clusters, which are calculated by the formulas (10) – (12).

Experimental studies were carried out under the following conditions: movable triboelement steel 40H (45 - 47 HRC), fixed triboelement: Br.AZh 9-4 (90 - 110 HB). Tribosystem load N = 500 - 2000 N; sliding speed 0.5 m/s; lubricating medium - engine oil SAE 20W30. During the experiments, the volumetric wear of the movable and stationary triboelements (by the method of artificial bases) and the friction moment were recorded, which were recalculated into the volumetric wear rate and the coefficient of friction.

The results of experimental studies are shown in fig. 7, which display the average values of the volumetric wear rate and the coefficient of friction at the steady-state operation of the tribosystem (after the completion of the running-in) at various loads, as well as the calculated values of the peak factors for three clusters of AE signals from the friction zone.

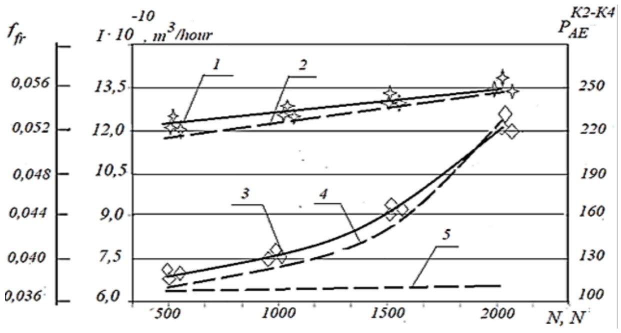

Fig. 7. Dependences of changes in the volumetric wear rate *I*, coefficient of friction f_{fr} and the calculated values of the peak factor AE P_{AE} different clusters when load changes *N* on tribosystem: 1 – friction coefficient; 2 – cluster peak factor *K2*; 3 – volumetric wear rate; 4 – cluster peak factor *K3*; 5 – cluster peak factor *K4.*

Analysis of the obtained dependences allows us to assert the presence of a correlation between the coefficient of friction f_{fr} and the values of the peak factor of the cluster К2, correlation coefficient r = 0.99. Speed volumetric wear I, m3/hour and the values of the peak factor of the cluster К3, correlation coefficient r = 0.99.

The values of the peak-factor cluster К4 do not correlate with the above tribological characteristics.

To establish a correlation between the tribological characteristics and the values of the peak factor of the cluster К4, AE signals were recorded during tribosystem operation during running-in [32], which is shown in fig.7.

Analysis of the dependences obtained allows us to assert the presence of a correlation between the rate of volumetric wear *I*, m^3/hour during running-in and the values of the peak factor of the cluster К4, correlation coefficient r = 0.98.

Evaluation of the reproducibility of the results of measuring the AE signals at various loads, followed by the calculation of the Cochran criterion, showed that the parameters of the AE signals during the operation of the tribosystem at various loads are homogeneous and reproducible.

6. DISCUSSION OF RESEARCH RESULTS

Analyzing the presented dependences in fig. 7 and fig. 8 it is possible to make a platoon that the cluster analysis of acoustic emission signals from the friction zone of the tribosystem at informative frequencies makes it possible to identify surface processes during wear, thereby increasing the robustness of the AE method. This analysis can be the basis for the development of a technique for diagnosing tribosystems during their operation, which will make it possible to measure the wear rate at any time and calculate the tribosystem resource.

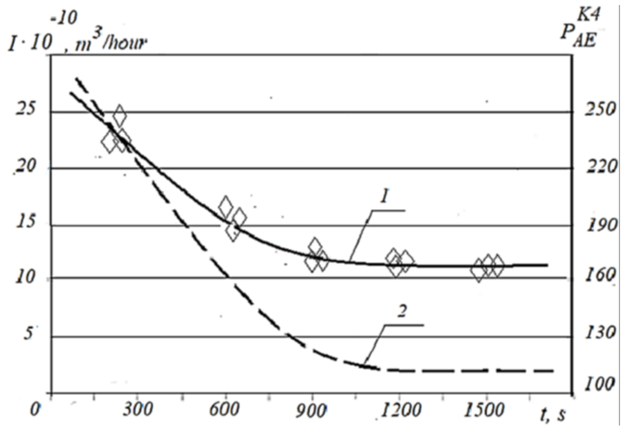

Fig. 8. Dependences of changes in the volumetric wear rate *I* and the calculated values of the peak factor of the AE cluster *K4* during running-in under load *N* = 1500 N: 1 - volumetric wear rate *I*, m^3/hour; 2 – peak factor of cluster *K4.*

Based on the results of the experimental values using the least squares method, regression equations in natural values were obtained, which have the following form.

For the coefficient of friction:

$$f_{fr} = a_2 \cdot \frac{W_{TP}}{W_i} \cdot \exp(\frac{P_{AE}^{K2}}{b_2}). \qquad (13)$$

where a_2 and b_2 – dimensionless coefficients, take into account the design of the tribosystem and operating conditions, are determined experimentally, increase the adequacy of equation (13) to the experimental data; W_{FR} – the rate of work of dissipation in the tribosystem is determined by the formulas given in the work [30], dimension J/s.

The power supplied to the tribosystem is determined by the expression:

$$W_i = N \cdot v_{sl}, J/s,, \quad (14)$$

where N – load on tribosystem, N; v_{sl} – sliding speed, m/s.

For the volumetric wear rate of the tribosystem:

$$I = a_3 \cdot \frac{W_{FR}}{Q} \cdot \exp(\frac{P_{AE}^{K3}}{b_3}), m^3/hour, \quad (15)$$

where a_3 and b_3 – dimensionless coefficients, take into account the design of the tribosystem and operating conditions, are determined experimentally, increase the adequacy of equation (15) to the experimental data; Q – the quality factor of the tribosystem is determined by the formulas given in the work [30], dimension J/m^3.

For volumetric wear rate during tribosystem running-in:

$$I_{np} = a_4 \cdot \frac{W_{TP}}{Q} \cdot \exp(-\frac{P_{AE}^{K4}}{b_4}), m^3/hour, \quad (16)$$

where a_4 and b_4 – dimensionless coefficients, take into account the design of the tribosystem and operating conditions, are determined experimentally, increasing the adequacy of equation (16) to the experimental data.

The obtained expressions (13) - (16) are common for the diagnosis of tribosystems. While changing the construction of the combination of materials, friction areas or installation location of the sensor AE, the values of the coefficients a_i and b_i will change. These coefficients allow to adapt the developed technique to specific tribosystems taking into account the location of the sensor. The disadvantage of the developed methodological approach is that these coefficients must be determined experimentally, for this purpose a test-training experiment is performed on the aggregate, which will be diagnosed in operation. However, after their determination, which can be called calibration of the measuring system, and substitutions in formulas (13) - (16), it is possible to monitor tribosystems throughout the life cycle. A necessary and sufficient condition for the accuracy and reproducibility of monitoring results is the sameness (immobility) of the installation site of the AE sensor.

The solution to the third research problem is aimed at developing a methodological approach to using the acoustic emission method for monitoring tribosystems in operation. Based on the studies carried out and the obtained dependencies, we will formulate a sequence in constructing a method for monitoring tribosystems in on-line mode.

1. From the analysis of design documentation the materials from which triboelements (modulus of elasticity and Poisson's ratio), and also parameters of roughness of surfaces of friction are made are defined (Ra, Sm) and the value of the smaller area of friction of one of the triboelements F_{min}.
2. From the analysis of operating conditions the operating mode of a tribosystem (loading and speed of sliding) is defined.
3. Formulas (5) - (6) determine the rate of deformation of the triboelement material, and formulas (7) - (8) determine the informative frequency that will be generated by the triboelement during operation. Calculations of the informative frequency must be performed for the material of the triboelement on which the piezoelectric element will be installed.
4. Taking into account the noise coming from the equipment, the cluster K1 in the frame, formula (9), as well as the sufficiency of the length of the recorded frame is determined. The sufficiency of the frame length is established using the value of the autocorrelation coefficient, the calculation method of which is presented in [25].
5. According to formulas (10) - (12) the values of the peak factors of the cluster K2 are determined; cluster K3; cluster K4.
6. According to formulas (13) - (16) the values are determined: coefficient of friction, formula (13); wear rate, formula (15) wear rate during tribosystem running-in, formula (16). To increase the adequacy of the calculation formulas (13) - (16), use empirical coefficients: a_2; a_3; a_4 and coefficients: b_2; b_3; b_4. These coefficients are determined experimentally.

The given methodical approach allows to carry out monitoring of tribosystems during their operation and to establish values of coefficient of friction, wear rate on a steady mode and wear rate at a running-in stage at any moment of time of operation in an online mode.

The methodical approach is developed for monitoring of modes of wear without damage and change of types of wear. Therefore, the friction surfaces have optimal roughness, covered with oxide films without signs of damage.

The account of various types of wear and mechanisms of damage of friction surfaces can make directions of the further researches of using of this methodical approach for monitoring of tribosystems.

7. CONCLUSION

1. On the basis of the established correlation between the calculated and experimental values of acoustic emission from the friction zone, formulas for determining the information frequencies were obtained. Information frequencies are determined depending on the design, technological and operational factors of tribosystems, as well as the place of installation of the piezoelectric element.
2. A correlation has been established between the values of the peak factors of various clusters, the wear rate, the coefficient of friction, and the processes of running-in tribosystems. Regression equations are obtained that allow calculating the values of the friction coefficient and wear rate of tribosystems based on the results of monitoring acoustic radiation during operation in the online mode.
3. A methodological approach has been developed for using the acoustic emission method for monitoring tribosystems in operation. The methodological approach has the following components: calculation of information frequency; splitting the general signal into clusters; calculation of the crest factor values for each cluster; adaptation of the calculated dependencies to the conditions of construction and operation by empirical coefficients; tribosystem monitoring based on the results of AE measurements from the friction zone.

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