

The physical mechanisms have been investigated that form and transform the corpuscular-vortex-wave thermal complexes of disturbances in contact tribosystems based on the quantum-mechanical exchange interaction. The presence of a contact gap determines the generation of pairs of quasi-particles-disturbances stabilized by wavelength and frequency. Internal instability and collapse processes in such a system of disturbances lead to the formation of defects in a tribo-pair's material and underlie the emergency friction regimes. This paper gives specific technical examples of the generation of thermal complexes at fretting, during the friction of sliding and rolling, and at cutting. It has been established that the destructive nature of the process of fretting at low values of reverse sliding speeds is caused by the generation and collapse of the corpuscular-vortex-wave thermal complexes. An example of acoustic friction emission in the ultrasonic region of the spectrum has been used to show the quantum nature of the disturbances generated by friction. The high-frequency spectrum of acoustic emission corresponds to the unbalanced composition of the disturbances and leads to the formation of wear particles. The exchange interaction in a tribosystem involving rolling on the plane has been considered. The results of statistical analysis of such rolling showed the existence of the effect of negative friction caused by the quantum generation of long-wave disturbances. It has been demonstrated that the collapsed component of the generation of disturbances is significantly increased under the modes of materials destruction, including when cutting the materials. The corpuscular-vortex-wave mechanism of selective transfer and hydrogen wear in tribosystems has been described. It is shown that the properties of a serovite film under the mode of selective transfer are provided by the collapse processes in the system of disturbances. Similar processes at the vortex-wave transfer of hydrogen atoms in metals lead to the wear and destruction of the surface layer of friction

Keywords: contact tribodynamics, corpuscular-vortex-wave thermal complex, exchange interaction, collapse, acoustic emission

EXCHANGE INTERACTION AND MODELS OF CONTACT GENERATION OF DISTURBANCES IN TRIBOSYSTEMS

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Received date 20.07.2020

Accepted date 03.08.2020

Published date 31.08.2020

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1. Introduction

Classical tribology considers external friction as a dissipative, locally-determined form of interaction of rubbing bodies during the accidental realization of the actual contact areas. Methods from physical mechanics have recently been widely used to study friction processes and adhere to the same concept, even though experimental results indicate the presence of wave processes in a tribosystem. The wave movement forms are not considered in the theory of dissipative self-organization of friction processes based on the so-called unbalanced thermodynamics. Entropy as a function of the system state is almost

insensitive to the directional movement of the system or any wave movement of its elements. A thermodynamic flow considers only a form of chaotic movement that fully corresponds to the general provisions on dissipative friction. Wave vibrational processes are based on the interaction between the elasticity of contact and material inertia and are common to the wave and vibrational motion. A well-known concept of external friction is based on the slip of the indenter over an elastic-plastic deformable half-plane, it is limited to only one degree of freedom and eliminates all wave elastic bonds. Modern friction models are multifactorial, and triboacoustics has a wide range of research tools for the wave movements that accompany friction.

Thus, it is a relevant scientific task to study the physical and mechanical features of the tribotechnical contact from the positions of quantum-mechanical processes.

2. Literature review and problem statement

The study of the physics of friction processes from the positions of quantum-wave aspects has been receiving increased attention in recent times.

Based on the theory of macroscopic quantum electrodynamics for unstable systems, paper [1] calculated statistical parameters of the friction force at zero temperature. The quantum force of friction was determined at a time point corresponding to the generation of the first excitation for each pair of unstable oscillators. At the same time, the estimated ratios obtained did not address the actual friction processes of the technical systems.

It is shown in [2] that in a dissipative dynamic system driven by an oscillating force, the force of friction can create a quasi-stationary resistance that is always directed in the opposite way to the force caused by the spatial heterogeneity of vibrations. At the same time, the physical nature of the forces was not taken into consideration.

The friction of the slip between a rigid hemispheric indenter and the deformable textured surface, which represents irregularities that change their shapes, was investigated in [3]. Friction fluctuations were observed when sliding in the direction perpendicular to the motion using optical images and friction profiles.

Works [4, 5] report the experimental results of a triboacoustic control over the integrity of the nominally-immobile frictional connection under the conditions of fretting. Two opposite-directed wave energy cascades were observed under fretting modes. However, there is no theoretical analysis of the study results.

The non-stable processes in the operation of friction nodes in automotive equipment in the presence of motor lubricants were considered in papers [6-9]. The experimental studies have established the effect of various additives to oils on the stabilization of friction forces and reducing the wear of rubbing surfaces. Modern tribodiagnosing methods for assessing the technical condition of friction pairs are given, including based on the criterion of vibrational resistance.

A problem of the vibrational frictional contact under conditions of adhesion wear is analyzed in [10]. It is shown that if the tangential amplitude is preserved in the wear range, energy dissipation can be controlled by the amplitude of normal vibrations. At the same time, the hypothesis put forward requires experimental confirmation.

A model of the effect exerted by the system dynamics on the sliding friction is reported in [11]. The model shows that micro-vibrations play an important role in the dynamic effect on the system friction resistance. Determining the range of critical parameters makes it possible to systematically control friction resistance by adjusting the geometry and rigidity of the system.

The estimation-experimental models of predicting the durability of cylindrical sliding tribo-systems, taking into consideration the dissipation of friction characteristics, are proposed in works [12, 13]. At the same time, the physical prerequisites of the dissipative processes are not fully disclosed.

The studies of friction surfaces with regular geometric microelements [14–16] investigated the processes of exciting

internal magnetic fields at the edges of discrete regions. It is shown that the combination of studies of friction and wear processes in areas such as mathematical statistics, contact mechanics, surface physics, provides a deeper explanation of non-stationary processes on discrete surfaces of contact elements.

A model of the body wear at high friction speeds in a probabilistic statement is proposed in [17, 18]. The model is based on the thermokinetic theory of material destruction. The wear model patterns were identified considering the random nature of the factors involved. The model is represented in a discrete form and is not sufficiently adapted for numerical modeling.

The physical basis of the frictional contact interaction of surfaces is analyzed in works [19, 20]. A physical pendulum was adopted as a tool for researching energy losses in tribo-systems.

The results of our analysis of the scientific literature reveal the need for deeper systemic research of quantum-mechanical processes in the contact interaction of technical tribosystems. Such studies could discover new features in the mechanics of a tribological contact and are promising for analyzing the durability of machine friction nodes.

3. The aim and objectives of the study

The aim of this work is to form and implement the physical model of contact disturbance generation in tribosystems, taking into consideration the exchange interaction and collapse of corpuscular-vortex-wave thermal complexes.

To accomplish the aim, the following tasks have been set:

- to derive the basic estimation ratios for the pseudo-equilibrium and collapsed model of disturbance generation in the contact interaction of tribosystems;
- to analyze the formation processes of the corpuscular-vortex-wave thermal complexes under the modes of fretting, the friction of sliding and rolling;
- to establish the impact of the collapsed component of the generation of disturbances under the modes of materials destruction, including when cutting;
- to analyze the mechanisms of selective transfer in friction and hydrogen wear from the positions of the corpuscular wave tribodynamics.

4. The pseudo-equilibrium and collapse models of contact disturbance generation in tribosystems

The physical model under consideration is based on the interaction of thermal radiation with the vortex-wave forms of substance movement. It is known that the equilibrium thermal radiation is compatible with only two simple forms of macroscopic movements of matter – moving as a whole at a constant speed and a solid-body rotation at a constant angular velocity. The tribocontact interaction of deformable solids significantly expands the types of mesoscopic and macroscopic movements of matter by various vortex-wave forms. It is natural to assume a certain transformation of thermal radiation in the interaction with such forms. To describe this transformation, a method of quasi-particles as elementary thermal excitations, adequate to the vortex-wave movements of matter, is used in this paper. These quasi-particles are the excited forms of the thermal radiation itself in

comparison with its main form – the equilibrium thermal radiation.

An important feature of the model is the consideration of the dimensional factor. Characteristic gradients of contact stresses, velocities, and temperatures have a micron and sub-micron scale. At the same scale, there are the wavelengths corresponding to an extremum in the spectrum of equilibrium thermal radiation at room and elevated temperatures. This spatial resonance distinguishes the systems of dynamic contact interaction as the generators of the combined corpuscular-vortex-wave complexes of disturbances of the velocity field of the material environment and the field of thermal radiation.

Consider an ensemble of quasi-particles disturbances with the following characteristics:

$$E = \pm \bar{p}\bar{v}; \quad \bar{p} = \hbar\bar{k}, \quad (1)$$

where E , \bar{p} , \bar{v} , \bar{k} are, respectively, the energy, pulse, speed, and wave vector of disturbances; \hbar is the Planck constant. After mutual substitutions, we obtain:

$$E = \pm \hbar\bar{k}\bar{v} = \hbar\omega, \quad \omega = \pm\bar{k}\bar{v}, \quad (2)$$

where ω is the cyclical frequency of disturbances. In this case, the group speed of the latter is determined in the following way:

$$\bar{v}_{gr} = \frac{\partial E}{\partial \bar{p}} = \frac{\partial \omega}{\partial \bar{k}} = \pm\bar{v}. \quad (3)$$

Introduce the corpuscular-wave mass m of disturbance quants in a regular way:

$$\bar{p} = m\bar{v} = \hbar\bar{k}. \quad (4)$$

As a result, the equivalent energy ratios follow from (1) to (4):

$$E = \hbar\omega = \pm m(\bar{v})^2 = \pm \frac{\hbar^2}{m}(\bar{k})^2. \quad (5)$$

The \pm signs in expressions (1) to (5) correspond to two possible directions of time. Between these two possibilities, the first one (a plus sign) is usually selected, corresponding to the positiveness of the absolute temperature T and the non-negative increase in entropy ΔS :

$$T > 0; \quad \Delta S \geq 0. \quad (6)$$

Here, take into consideration a second possibility (a minus sign in (1) to (5)):

$$T < 0; \quad \Delta S \leq 0. \quad (7)$$

In this context, introduce a pair of disturbances with the total energy ΔE (considering the signs in (1)):

$$\Delta E = \bar{p}\bar{v} - \bar{p}'\bar{v}', \quad (8)$$

where strokes indicate disturbances that develop over time opposite to those without strokes. The total pairs' energy module is limited from below by the basic principle of quantum mechanics – the principle of uncertainty:

$$|\Delta E| \geq \hbar/|\Delta t|, \quad (9)$$

where Δt is the finite lifecycle of disturbances that form a pair. On the other hand, by virtue of the same principle of uncertainty, the energy ΔE can be regarded as the energy of self-disturbance, ratio (8) – as the condition of the energy balance in the triad of disturbances. It should be supplemented with the momentum conservation law in the following form:

$$\Delta \bar{p} = \bar{p} - \bar{p}'; \quad \Delta \bar{k} = \bar{k} - \bar{k}'. \quad (10)$$

It is necessary to note the widespread use of expressions in the form (10) in the calculations of non-linear transmission of energy and pulse by the triads of wave disturbances in the theories of quasi-two-dimensional turbulence [21], as well as spiral three-dimensional turbulence. The most well-known result of these calculations is the reverse energy cascade (in the direction of large spatial scales), opposite to the direct cascade of conventional three-dimensional turbulence [21]. Turbulence in the system of quasi-particles under consideration is represented by continual clusters on the spectra of disturbances. Here, the focus is on the narrow-band highlighted peaks on these spectra, due to the exchange interaction of quasi-particles. Unlike the vast turbulent clusters, which are quantum fluid, such highlighted components of spectra can be considered within the concept of the quasi-ideal quantum gas. The statistics of such gas are determined by the spin of quasi-particles, equal, in this case, to $s=1/2$ (in the units of the Planck constant). The possibility of coherent amplification of disturbances is predetermined by the pairing of quasi-particles with opposite spins. The effect of attraction, required for such pairing, is provided by the exchange of phonons. Depending on the sign of the spirals of disturbances in pairs, it is possible to form thermal complexes both on running waves and on standing waves. By considering these pairs of disturbances to be bosons, we use the statistics by Bose-Einstein, taking into consideration the possibility of exchange interaction in the ensemble of disturbances:

$$\langle n_E \rangle = \frac{1}{e^{\frac{E}{kT}} - 1}, \quad (11)$$

where $\langle n_E \rangle$ is the average number of quasi-particles in a quantum state with the energy E ; k is the Boltzmann's constant.

Given the variable number of disturbances, the chemical potential in (11) is accepted to equal zero. In the case of tribodynamics, we note that the disturbance energy E lies in the acoustic range while the average thermal energy kT is many orders of magnitude higher. By decomposing exponent (11) into a series and discarding small terms, we obtain a simpler ratio for the average filling numbers:

$$\langle n_E \rangle \approx \frac{kT}{E}; \quad \langle E \rangle = E \cdot \langle n_E \rangle \approx kT. \quad (12)$$

Here $\langle E \rangle$ is the average energy of the entire ensemble of identical quasi-particles in a certain quantum state. The approximate equality of this energy to the average thermal energy determines the possibility of effective energy exchange between the ensemble of disturbances and the thermostat. This exchange is carried out with the help of photons of forced thermal radiation. Given the aforemen-

tioned observation, the conditions $E \ll kT, \langle n_E \rangle \gg 1$. are met. This determines the high effectiveness of exchange interaction in a given system of disturbances. For bosons, it has the character of attraction, which, as will be shown using real examples, can significantly exceed the repulsive contact forces of electromagnetic origin.

The potential for exchange interaction can only be revealed in a coherence environment. The functioning of tribosystems under the mode of a coherent acoustic radiation generator was generally considered in work [22]. Significant clarifications should be made to the physical mechanisms of these types of disturbance processes. First of all, regarding the unbalanced environment itself, as well as the structure of the composite resonator.

Statistics (11) describe the equilibrium states of the ensemble of quantum objects. The peculiarity, in this case, is that the forced disintegration of unstable quasi-particles with the radiation of acoustic and electromagnetic waves at the high efficiency of heat pumping is possible in the case of the equilibrium distribution of these quasi-particles by energies. Unlike stable particles, whose system requires the inversion of the populations of energy levels.

The simultaneous stabilization both for wavelength and frequency predetermines the multi-level structure of the resonator of the contact generator of disturbances. The main role here is given to the mesoscopic spherical resonator, formed as part of the corpuscular-vortex-wave thermal complexes. The radius r of such a resonator is determined from the following ratio:

$$\lambda = 2\pi r = \frac{2\pi}{\tilde{k}} = \frac{h}{mv} = \frac{b}{T} = \frac{ch}{4.965kT}. \tag{13}$$

Here, λ , \tilde{k} , v are, respectively, the wavelength, wave-number, and the module of quasi-particles velocity, b is the Win's constant; c is the speed of light in a vacuum; $h = 2\pi\hbar$ is the Planck constant; 4.965 is the root of the transcendent equation for finding a Win's constant.

Ratio (13) reflects the stabilization of the wavelength of the thermal complex (the radius of the resonator r) based on an extremum in the spectrum of equilibrium thermal radiation corresponding to the temperature T . Combining the above expressions, we obtain additional ratios for the cyclical frequency and velocity of the corpuscular-vortex-wave thermal complexes:

$$\omega = \pm \frac{(4.965kT)^2}{\hbar mc^2}, \tag{14}$$

$$\frac{v}{c} = \frac{4.965kT}{mc^2}. \tag{15}$$

Expressions (14), (15) describe the right-hand (high-frequency) side of the threesomes of disturbances (8). The low-frequency part of these threesomes with the energy ΔE competes with two high-frequency components in view of the sharp increase in the role of forced thermal radiation relative to the spontaneous one with an increase in the wavelength. This causes the formation of low-frequency clusters of the contact-induced disturbances in the infrasound part of the acoustic spectrum. The macroscopic resonator of the disturbance contact generator is formed by the whole set of feedbacks in a tribosystem [22]. Here, there is the possibility of both the high-frequency stabilization at their natural

shapes of oscillations of the elements of a tribosystem and the low-frequency one – at the angular shapes of rotating parts and the slacked shapes of the drive's oscillations.

In addition to the pseudo-equilibrium scheme of disturbance generation, another scheme is also possible – with a collapsed energy pumping. It is at the heart of emergency and catastrophic regimes. Spreading in the material of contact and sub-contact layers, the corpuscular-vortex-wave thermal complexes can attach to themselves the material mass M , enclosed in the volume of the spherical resonator and determined from the following ratio:

$$\frac{Mv^2}{2} = kT. \tag{16}$$

In this case, the above expressions yield a limit on the density of the attached substance (for the high-frequency component of disturbances):

$$\rho = \frac{59.58}{ch^3} (\pi mkT)^2. \tag{17}$$

Due to the contact break, the effective density of the attached substance can dynamically vary and auto-adjust to condition (17). It also follows from (17):

$$\frac{Mc^2}{mc^2} = \frac{2}{(4.965)^2} \frac{mc^2}{kT} = \frac{2}{4.965} \frac{c}{v}. \tag{18}$$

If the entire energy $Mc^2 \gg E$ (or its large part eMc^2) is added to (11), the average filling numbers are zeroed and a thermal complex collapses. The correlated destruction of many thermal complexes leads to a colossal release of energy in tribological standards. For example, a single micron-scale spherical resonator with an attached condensed substance of conventional densities contains the energy of $Mc^2 > 10^2$ J, while, as it is estimated in [23], the plastic deformation of the volume of matter with a side of 0.1 mm requires $\sim 10^{-4}$ J only. Even the small magnitude of the attachment ratio $e \ll 1$ can provide the effects of negative friction (at local time stages) at the most common functioning of tribosystems, which has no explanation in conventional approaches [22].

Consider specific experimental confirmations of the considered mechanism of contact disturbance generation in tribosystems.

5. Generating disturbances under the modes of fretting, sliding and rolling friction

The destructive nature of the fretting process at low speeds of reverse slip (slippage) is caused by the generation and collapse of the corpuscular-vortex-wave thermal complexes. The characteristic speeds of fretting of the order of $10^{-5} \dots 10^{-3}$ m/s at normal temperatures and the values of m , equal to the masses of atoms and molecules of matter, correspond to expression (15). As an example, Fig. 1 shows the contact stress oscillograms in the polymeric substrate of the tribopair steel–plate made from polymethylmethacrylate (PMMA) depending on the average speeds of reverse friction. The acoustic range of the tribopair sound is shown in Fig. 2. The dominant frequency here is $\nu \approx 4.3$ kHz; it corresponds to expression (14) at $T \approx 300$ K, $m = 1$ u (hydrogen). The long-wave packet of disturbances in Fig. 1 is stabilized

at a frequency of 43 Hz, corresponding to (14) at $T \approx 300$ K, $m = 100$ u (the $C_5O_2H_8$ PMMA molecule). The optimal sliding speed, $V = 400$ micrometer/s (Fig. 1, c) is exactly the same as expression (13) at these parameters.

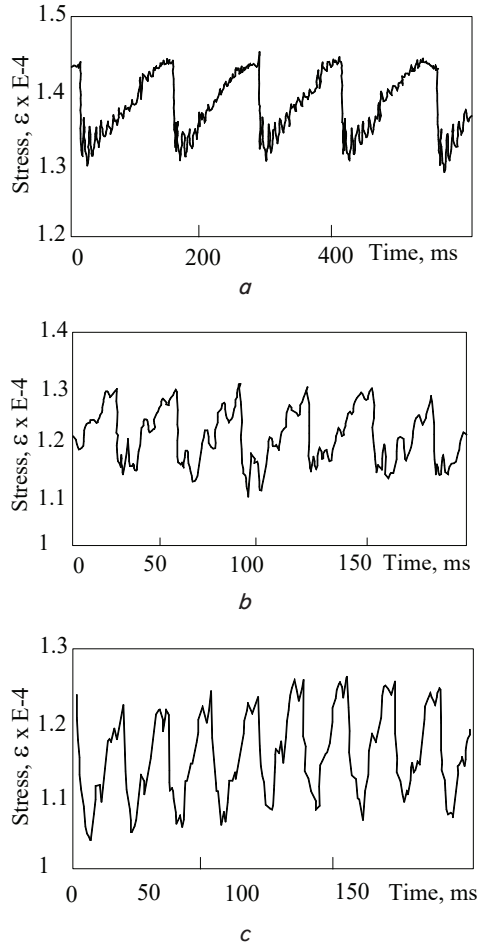


Fig. 1. Oscillograms of sub-contact stresses in the polymeric substrate of the steel–PMMA tribopair at the following average reverse friction speeds [24]: $a - 40 \mu\text{m/s}$; $b - 200 \mu\text{m/s}$; $c - 400 \mu\text{m/s}$

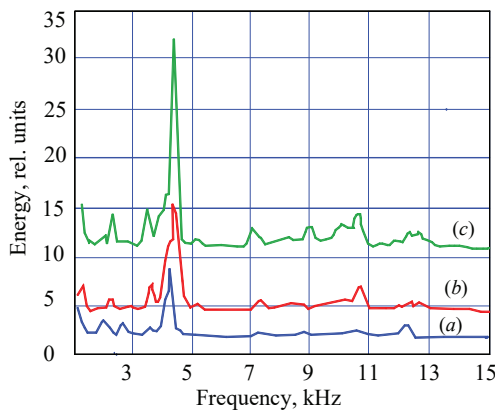


Fig. 2. The spectra of acoustic emission of the steel–PMMA tribopair at the following reverse friction speeds [24]: $a - 40 \mu\text{m/s}$; $b - 200 \mu\text{m/s}$; $c - 400 \mu\text{m/s}$

Fig. 3 shows the transfer functions of the rod-disk tribopair and the spectrum of the acoustic emission of this tri-

bopair [25]. The characteristic frequency $\nu \approx 2.2$ kHz on this spectrum corresponds to expression (14) at $T \approx 300$ K, $m = 2$ u. It is necessary to pay attention to the low-frequency cluster of an acoustic emission signal (Fig. 3, d), due to the generation of long-wave packets of disturbances. The specified characteristic frequency of $\nu \approx 2.1 \dots 2.2$ kHz is also present in the spectra of acoustic friction emission reported in works [26, 27].

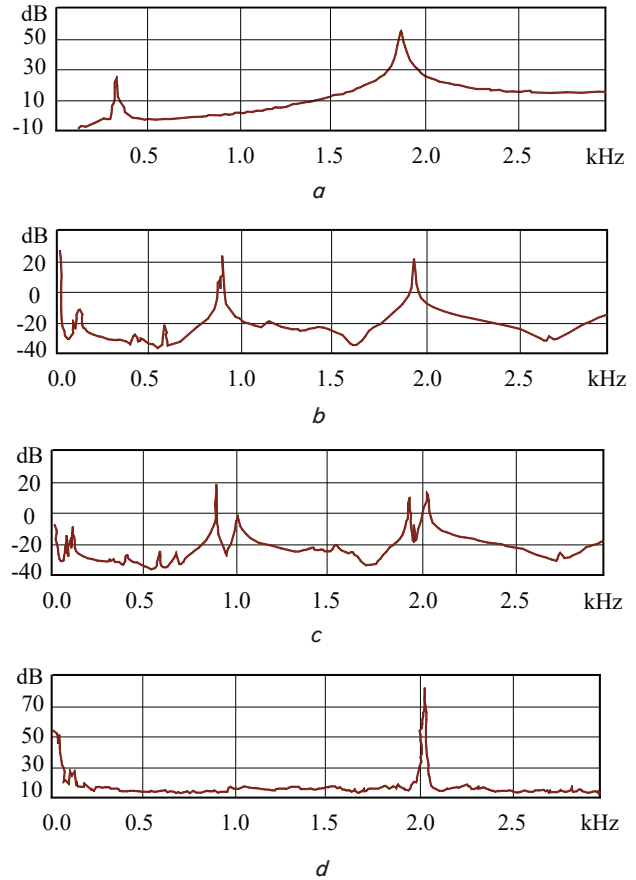


Fig. 3. Transfer functions: $a -$ disk; $b -$ rod; $c -$ the disk-rod system under static contact conditions; $d -$ the spectrum of sound generated at the friction of a tribopair

An example of the acoustic friction emission in the ultrasonic region of the spectrum is shown in Fig. 4 [27].

That clearly reflects the quantum nature of the disturbances generated by friction. There is also a division of the acoustic emission signal into two clusters: a narrow-band low-frequency and high-frequency broadband. In this interpretation, this division corresponds to the equilibrium (in each of the two thermostats separately) and the unbalanced composition of the disturbances. In the latter case, jet forms of a vortex field of velocities are generated, thereby forming the wear particles. Suppressing such forms by increasing a contact load (Fig. 4, b) reduces wear [27]. The role of adhesion in the formation of wear particles is also well-emphasized. In this regard, we note that the exchange interaction considered here is the same as the adhesion. Therefore, the cumulative effect can significantly exceed the controversial action of the forces of elasticity in the sub-contact layers, which leads to jamming.

The frequency of an acoustic friction emission $\nu \approx 100$ kHz is very typical for triboprocesses in the ultrasonic region of the spectrum of disturbances generated [27, 28]. From our point of view, this frequency corresponds to the generation of dis-

turbances near the melting point of steel: $T \approx 1,500$ K, $m = 1 u$ (hydrogen), according to (14). For an unbalanced high-frequency cluster in Fig. 4, *a* with a maximum at $\nu \approx 270$ kHz, an effective hydrogen temperature can be introduced:

$$T_H = \frac{(h\nu \cdot m_H c^2)^{1/2}}{4.965k} \tag{19}$$

This expression follows from (14) when taking into consideration the ratio $\omega = 2\pi\nu$, assuming $m = m_H = 1 u$. In this case, the temperature $T_H \approx 2,400$ K significantly exceeds the melting point of steel, which determines the local imbalance of the friction process under the modes corresponding to the high-frequency cluster in Fig. 4. The division of the spectrum of acoustic friction emission into narrowband and broadband clusters is noted in the literature on tribospectroscopy [28].

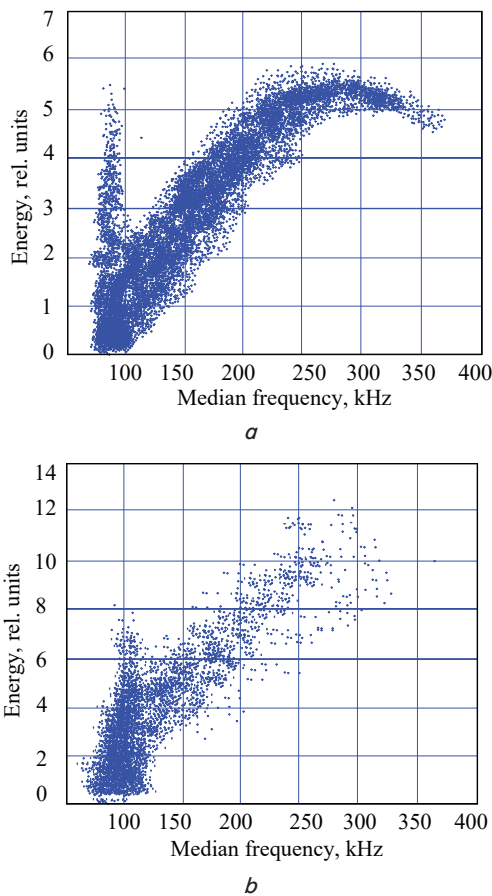


Fig. 4. Dependence of the energy of an acoustic signal on the median frequency at friction in the system ball-disk with a load on the ball: *a* – 2N; *b* – 3N [27]

Exchange interaction is manifested under the normal modes of tribosystem operation. As an example, Fig. 5 shows the spectrum of the acoustic emission, accompanying the rolling of a ball in the bearing with a diameter of 6 mm over the polished glass plane of a mirror.

The dominant peak at the frequency $\nu \approx 250$ Hz corresponds to the formation of thermal complexes on water molecules ($m = 18 u$ at room temperature according to expression (14). Fig. 6 shows the results of a statistical analysis of the process of such rolling. The total time of the ball's movement on the plane was compared with the standard rolling time calculated using the standard ratios of solid mechanics. A dotted

line in Fig. 6 corresponds to a zero-friction movement. The formal positivity of the tangential contact reaction (negative friction) below this line is explained by the quantum generation of longwave disturbances considered here. Similar dynamic characteristics with negative friction were obtained in the tests of roll bearings (Fig. 7) and have a similar explanation.

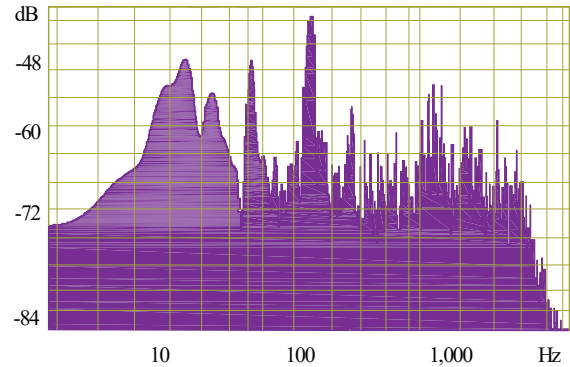


Fig. 5. Spectrum of acoustic emission when rolling a ball in the bearing with a diameter of 6 mm over the glass sloping plane of a mirror

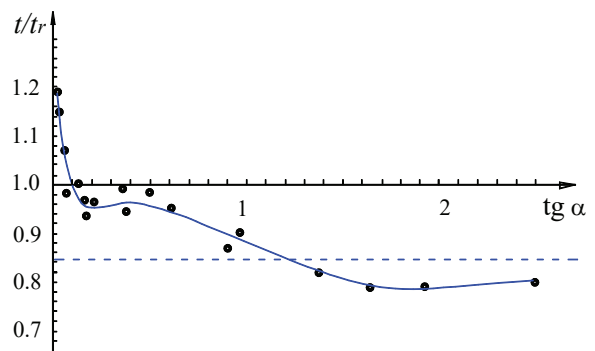


Fig. 6. Dependence of the ratio of the time of the ball's movement on a sloping plane to the calculated rolling time according to the standard scheme of solid mechanics on the tangent of the angle of the plane tilt

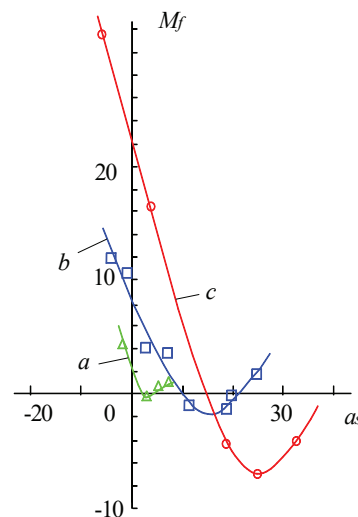


Fig. 7. Dependences of the average reduced friction force momenta in a roll bearing on the average reduced load accelerations in the Atwood's experimental machine at the average values of angular velocities of block rotation: *a* – 5.0 ± 0.5 rad/s; *b* – 9 ± 1 rad/s; *c* – 16 ± 1 rad/s

Therefore, external friction should be considered as a self-coordinated process of dynamic interaction, based on the transmission of a wave pulse with the generation of disturbances.

6. Contact-induced flutter and buffeting under the cutting modes of materials

The collapse component of the disturbance generation is significantly amplified under the modes of the destruction of materials, including when cutting. Fig. 8 shows the examples of the spectra of acoustic emission, accompanying the cutting of steel rods on a turning machine under the non-regular modes of flutter-buffeting. There is clearly a reverse energy cascade in the ensemble of quasi-two-dimensional spherical disturbances generators, carried out at the mesoscopic level. The macroscopic stabilization of these disturbances at the drive’s natural frequencies ($\nu_1 \approx 13$ Hz, $\nu_2 \approx 40$ Hz) predetermines the dominant narrowband maxima in the central part of the spectrum. At the same time, the pronounced flutter peaks in the high-frequency region correspond to (14) at the following parameter values: $m=2$ u, $T \approx 340$ K (frequency $\nu \approx 2.7$ kHz in Fig. 8, *a*), $m=1$ u, $T \approx 350$ K (frequency $\nu \approx 5.6$ kHz in Fig. 8, *b*).

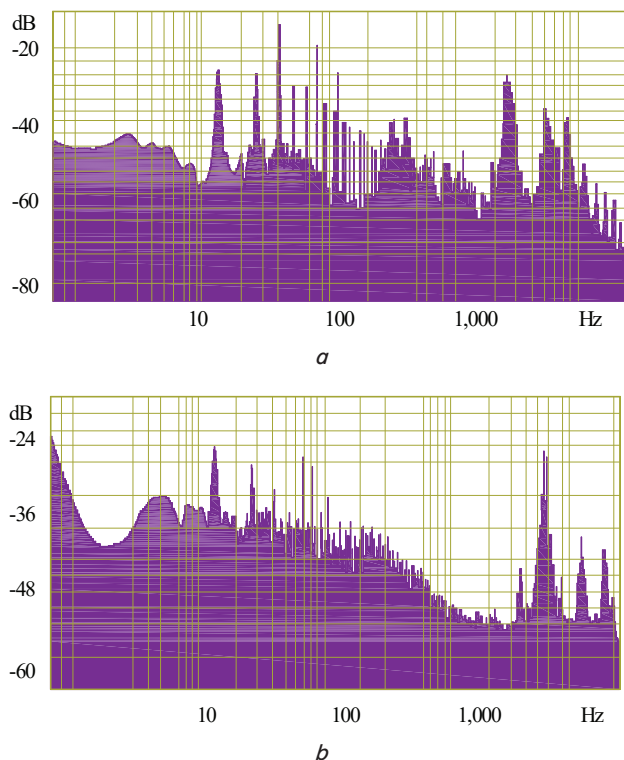


Fig. 8. Spectra of acoustic cutting emission under the dynamically loaded flutter-buffeting modes: *a* – non-hardened steel 40 Kh13; *b* – hardened steel

Dividing an acoustic emission signal at cutting into two clusters associated with the short-wave and long-wave packets of disturbances forms in a series of cases a characteristic drop in the central part of the spectrum (Fig. 9, *a*). The absence of dominant discrete lines here indicates the imbalance of the process of generating disturbances. In this case, the effective temperature (by hydrogen) is $T_H \gg 430$ K. A similar

drop in the spectrum of disturbances also occurs during the impact interaction between the teeth of transmission gears in electromechanical machines (Fig. 9, *b*). The effective temperature here is $T_H \gg 380$ K. It should be noted that the introduction of such temperatures is quite conditional because in the friction zone there is a hierarchy of disturbances with different temperature values. Its high-temperature components produce the ultrasonic signals of acoustic emission (Fig. 4).

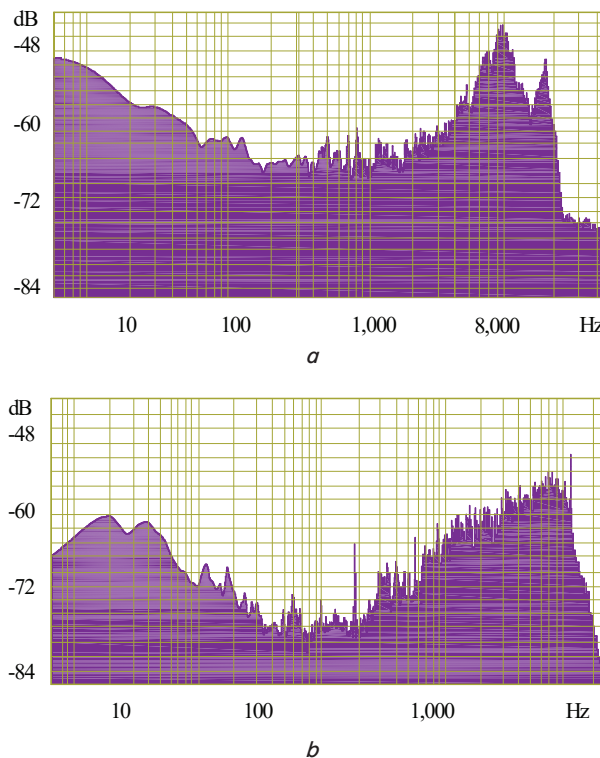


Fig. 9. Acoustic emission spectra: *a* – when sharpening a steel strip with an abrasive circle; *b* – when the electromechanical surface grinder is idle

At the same time, the ultrasonic signals under the cutting modes at frequencies $n \gg 3 \dots 30$ MHz, observed in [28], correspond, according to expression (16), to the thermal complexes on electrons ($m=m_e$) at very moderate temperature values.

7. Corpuscular-vortex-wave mechanism of selective transfer and hydrogen wear

Processes as different in their tribological significance as the selective transfer (a wearless effect) and hydrogen wear have similar mechanisms of their origin. The known criticality of the selective transfer of copper atoms (and other metals) to the temperature regime and the composition of a lubricant (29, 30) is explained by condition (25), which imposes certain restrictions on the parameters of the formation of corpuscular-vortex-wave thermal complexes in the friction zone. Specifically, at $m \approx 63$ u (copper) and $T \approx 300$ K, it follows from (19) that the value of $\rho \approx 1.26$ g/cm³ is almost equal to the density of glycerin, or the density of the oil freon mixture in the compressor systems of refrigeration installations.

On the contrary, replacing glycerin, for example, with Vaseline oil ($\rho \approx 0.8 \dots 0.9 \text{ g/cm}^3$) does not meet condition (19), which explains the known lack of the selective copper transfer in this case [29, 30]. The special properties of the servovite film under a selective transfer mode (porosity, defectiveness, low shear resistance) are directly provided by the collapsed processes in the disturbance system considered here. The same processes in the vortex-wave transfer of hydrogen atoms into metals produce the exact opposite result – gradual (wear dispersion) or instant destruction of the surface layer of friction.

The difference here lies in the ratio ε of the substance attachment inside the mesoscopic perturbators. The vortex-wave transfer of these disturbances deep into the contact zone also explains the expressed plastic deformations in the depths of the friction zone in the absence of strong plastic deformations directly on the surface of friction, observed in [26, 27].

Thus, the practical examples considered have confirmed the proposed physical mechanism of the contact generation of disturbances in tribosystems.

8. Discussion of results of studying the quantum-mechanical processes in the contact interaction of tribosystems

The dynamic contact of deformable solids is a source of disturbances in a broad range, often leading to devastating consequences. The presence of contact gaps in the dry and boundary friction modes, the temporal and spatial discreteness of contact limit the possibilities of the continuum mechanics and classical field theory methods when describing such modes. In this case, we propose the ideas and methods developed in quantum field theory, as well as in the theory of turbulence. One of the most effective methods of this kind is the description of disturbances in the form of a quantum ensemble of quasi-particles involved in a specific exchange interaction, which is absent in classical mechanics. To analyze tribotechnical processes based on the quantum-mechanical approach, we have derived estimation ratios (14), (15) for the frequency and speed of wave tribodisturbances. Our analysis of experimental characteristics of friction processes at fretting, sliding and rolling friction has shown conformity to theoretical dependences. It has been established that the destructive nature of the fretting process at the low values of reverse sliding speeds is predetermined by the generation and collapse of the corpuscular-vortex-wave thermal complexes. The example of acoustic friction emission in the ultrasonic region of the spectrum has confirmed the quantum nature of the disturbances generated by friction (Fig. 4). The high-frequency spectrum of acoustic emission corresponds to the unbalanced composition of the disturbances and leads to the formation of wear particles. The exchange interaction in the tribosystem with rolling on the plane has been considered. The results of a statistical analysis of such rolling showed the presence of the effect of negative friction (Fig. 6, 7), caused by the quantum generation of longwave disturbances. The results obtained indicate that external friction should be considered as a self-agreed process of dynamic interaction, based on the transmission of a wave pulse with the generation of disturbances.

The exchange interaction arising against the background of ordinary electromagnetic processes determines, in particular, the catastrophic modes of contact-induced flutter and

buffeting, which are also characteristic of hydro (aero) dynamic systems under conditions of discontinuity of the flow. An analysis of the results (Fig. 8, 9) shows that the collapse component of the generation of disturbances is significantly enhanced under the modes of the destruction of materials during cutting.

A rare beneficial effect associated with the exchange interaction in tribo-equipment is a known wearless effect (selective transfer), whose theory needs to be significantly clarified. The controversial mode here is hydrogen wear, described so far without taking into consideration the exchange interaction and a vortex-wave transport in the tribosystems. Studies have shown that the special properties of the servovite film under a selective transfer mode are directly provided by the collapse processes in the disturbance system. Similar processes in the vortex-wave transfer of hydrogen atoms into metals produce the opposite result – the destruction of the surface layer of friction.

The specificity of contact friction is also evident in sharp temperature gradients, which causes the formation of corpuscular-vortex-wave thermal complexes involved in the exchange interaction. Co-operative processes in the system of such thermal complexes are, in fact, the main source of contact-induced disturbances.

The obtained results and their analysis allow us, based on methods of diagnosing the quantum-wave signals during the operation and study of friction nodes, to reasonably analyze and predict the progress of friction and wear processes, to prevent the occurrence of emergency operation of machines and mechanisms.

At the same time, it should be pointed out that the limitation of this study is to consider the approximated problem of quasi-ideal quantum gas. Additional consideration of the interaction of disturbances requires consideration not only of the discrete components of the spectra but also of the turbulent spectral clusters reflecting the processes of cascading energy transport in the system under consideration.

In the future, it is expedient to devise specific technical procedures and methods for suppressing contact-induced disturbances associated with emergency modes of operation of tribosystems. It is also advisable to generalize the results obtained for similar hydro(aero)dynamics problems associated with critical modes of operation.

9. Conclusions

1. We have analytically presented a method to describe disturbances in a tribosystem in the form of a quantum ensemble of quasi-particles involved in a specific exchange interaction. A physical model of the contact generation of disturbances in tribosystems has been constructed, which takes into consideration the exchange interaction and collapse of the corpuscular-vortex-wave thermal complexes.

2. It has been established that the destructive nature of the process of fretting at the low values of reverse sliding speeds is caused by the generation and collapse of the corpuscular-vortex thermal complexes. An example of acoustic friction emission in the ultrasonic region of the spectrum was used to show that the high-frequency component of the spectrum corresponds to the unbalanced composition of the disturbances and leads to the formation of wear particles. The results of a statistical analysis of the exchange interac-

tion in the tribological system with rolling showed the presence of the effect of negative friction caused by the quantum generation of longwave disturbances.

3. It has been established that the collapse component of the disturbance generation is significantly enhanced under the modes of the destruction of materials, including the cutting of materials.

4. Based on the corpuscular-vortex-wave mechanism, it is shown that the properties of the servovite film under a selective transfer mode are provided by the collapse processes in the disturbance system. Similar processes in the

vortex-wave transfer of hydrogen atoms in metals lead to the wear and destruction of the surface layer.

Acknowledgments

This study was funded by the State Budget of Ukraine as part of the scientific project No. 0120U102070 “Forecasting the durability and reliability of bearing nodes and the optimization of their parameters” commissioned by the Ministry of Education and Science of Ukraine.

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