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Acoustic Properties of Contact in Dry Friction

M. P. Kozochkin
Stankin Moscow State Technical University, Moscow
e-mail: astra-mp@yandex.ru

Abstract—Expanded application of vibroacoustic diagnostic systems in metal cutting and friction is considered. A model is proposed for the behavior of vibroacoustic signals in friction. Its diagnostic application in grinding is described.

Keywords: vibroacoustic diagnostics, friction, metal cutting, grinding
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Acoustic phenomena (sound, vibration) associated with friction are of interest as a means of assessing the state of frictional surfaces and the characteristics of the contact process by analysis of the vibroacoustic signal and, on that basis, predicting the remaining life of functional mechanisms.

In addition, vibroacoustic signals are generated directly in the contact zone and convey primary information regarding the processes there. Analogously, vibroacoustic signals are also produced in surface formation and may again provide useful information [1, 2].

Research into acoustic phenomena in friction has a relatively long history, with rapid development in the second half of the last century [1]. Three main areas may be identified: frictional self-oscillation, which affects the precision and smoothness of tool motion; acoustic-emission waves, which may be used to assess the interaction of contacting surfaces; and surface waves produced by the interaction of irregularities in the tangential direction.

Research on frictional self-oscillation has abated, but interest in acoustic emission continues [3]. However, there are stubborn obstacles to contact diagnostics in friction and cutting by means of acoustic emission.

In fact, high-frequency wave processes lose considerable intensity within short distances of their source. The damping is particularly pronounced when the acoustic emission passes through the joints of machine parts, especially when they are loose; in the presence of mobility, acoustic emission is of no value.

Experience shows that it is not always possible to place an acoustic-emission sensor in the immediate vicinity of the frictional contact. By contrast to acoustic emission, vibroacoustic signals in the range up to 50 kHz propagate through the elastic system of machinery to larger distances. The accelerometers used to record such signals are simple to operate; the information provided by the vibroacoustic signals is often similar to what may be extracted from acoustic-emission signals.

Thus, both acoustic-emission signals and vibroacoustic signals are produced in the contact interaction of the frictional surfaces, but vibroacoustic signals are more promising for broad industrial adoption (for example, in monitoring the wear of mobile joints, including the wear of cutting tools). Vibroacoustic diagnostics is used for many machines [4]. In some cases, no distinction is made between signals at different frequencies [5]. (All the elastic vibrations are described as acoustic emission.)

At the same time, the generation of vibroacoustic signals in friction has not been exhaustively studied. Accordingly, observations of vibrational processes in friction and cutting are often difficult to interpret, which hinders the application of vibroacoustic diagnostics in manufacturing.

However, the steady introduction of completely automatic equipment, with no operator involvement, demands effective monitoring of mobile joints.

In dynamic friction, a nonsteady process results from the interaction of microprojections on the contacting surfaces [1, 6]. When the microprojections come into contact, microimpacts occur, creating pulses that trigger wave processes in the elastic medium. The spectrum of these wave processes is determined by the shape of the pulses and also by any crack formation and destruction processes that may occur. Analogous process may occur when the microprojections break contact.

Since the frictional force is formed by additive interactions of individual microprojections, a similar assumption is made for vibroacoustic signals in most studies of vibroacoustic phenomena in friction [5, 7]. Thus, the power of acoustic radiation from frictional contact is assumed equal to the sum of the power created in the interaction of individual microprojections in unit time. This is a very convenient model of the acoustic properties of frictional contact, since it calls for relatively simple monitoring of the wear at the frictional contact, on the assumption that increase in wear areas leads to increase in the number of interacting microprojections.

Experiments in which the number of interacting microprojections is increased by increasing the contact pressure indicate that the power of the vibroacoustic signal increases in the first stage of loading, but then saturation sets in: further increase in load does not produce further increase in power [1, 8, 9]. In these experiments, however, the additive model was not questioned, since the explanation offered for saturation was that the number of microprojections over the thickness of each surface is limited and hence the number of interacting microprojections cannot increase beyond a certain level.

Doubts regarding the linear model appeared when the number of interacting microprojections was increased by increasing the contact area. With constant contact pressure, increase in contact area leads to proportional increase in the number of interacting microprojections but at some point saturation is observed, and further increase in contact area has no effect [2, 8, 9].

Curves *1* and *2* in Fig. 1a show typical transient changes in the effective amplitude of vibroacoustic signals with increase in contact area. Curve *1* is close to exponential, while curve *3* passes through a maximum before saturation sets in. Investigation of saturation (or acoustic equilibrium [2]) up to 50 kHz shows that it covers a wide frequency range in the friction of very diverse materials (including metals and polymers) and may therefore be regarded as an objective feature of the frictional interaction [10, 11].

Since quantitative changes in the number of actual contact points qualitatively changes the acoustic properties of frictional contact, it seems natural to assume that the acoustic energy emitted in the collision of individual microprojections will depend on the number of adhesive bridges surrounding the point of collision [2].

The elementary processes arising in the formation and rupture of microcontacts between two surfaces are illustrated in Fig. 1b, where microcontacts between pairs of microprojections are denoted by *a*, *b*, *c*, and *d*. At microcontact *b*, two individual microprojections collide, producing an acoustic signal.

At nearby microcontacts *a* and *c,* adhesive bonds *b* appear. At microcontact *d*, the adhesive bridges are broken, and elastic deformation is restored. Thus, some microcontact points are associated with the impact of individual microprojections, generating elastic waves of broad spectral composition, while others (at the tips of microprojections that are already in contact) are associated with the formation of adhesive bridges.

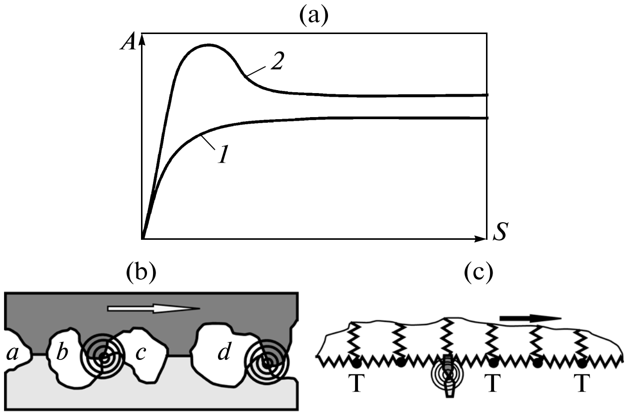

Fig. 1. Variation in amplitude *A* of the vibroacoustic signal with increase in contact area *S* (a); elementary processes in frictional contact (b); and interacting microprojections (c).

The influence of adhesive bonds on the power of the emitted vibroacoustic signal is confirmed by an experiment in which the interaction of individual microprojections is simulated by the impacts of sand. Dry quartz sand is spilled from a slotted vessel onto an inclined metallic plate, where an accelerometer is positioned. The mean kinetic energy of the sand is constant. The number of impacts of the sand per unit time is proportional to the area of the projection of the slot onto the metallic plate. The number of collisions is regulated by horizontal motion of the slot relative to the plate.

Inclining the plate ensures that the impact of individual sand particles will be independent, since the particles are removed after impact. Analysis of the vibroacoustic signals recorded with linear increase in the number of collisions per second shows that the power of the vibroacoustic signal increases linearly up to frequencies beyond 4 kHz. In other words, when the interactions are independent, additive behavior is retained.

The vibroacoustic energy excited at frictional contact propagates through the elastic system and produces vibration in all the system components, including the accelerometer (or other vibration sensor). Thus, the elastic system is an acoustic channel in which information regarding the frictional or cutting zone is sent to the primary converter [12].

A set of harmonic oscillators whose eigenfrequencies match those of the mechanism may be adopted as a phenomenological model of the acoustic channel. Their combined vibration under the action of individual impacts determines the form of the vibroacoustic signal. We may consider the change in the motion of an individual oscillator when adhesive bridges appear.

In Fig. 1c, an individual microprojection is shown in the form of a reduced mass elastically coupled to one body of the frictional pair. The other body of the pair is a single microprojection. The dark circles

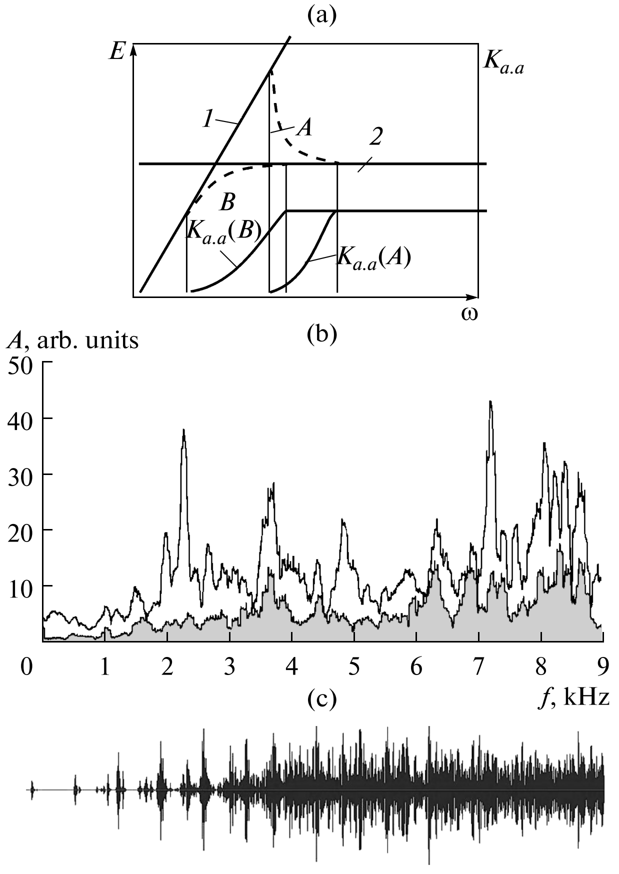

Fig. 2. Dependence of the power E of the vibroacoustic signal and the adhesive activity $K_{a.a}$ of frictional contact on the interaction frequency ω of the microprojections (a); spectra of the vibroacoustic signals in grinding without (upper curve) and with (lower curve) grinding fluid, when the grinding depth is 0.04 mm and the grinding width is 1 mm (b); and vibroacoustic signal in the 8-kHz octave as a grinding wheel and a diamond dressing tool approach (c).

denote points where adhesive bridges may appear (denoted by T in Fig. 1c), with corresponding increase in the rigidity of attachment of the microprojection.

In this case, the equation describing the motion of a mass under the action of the tangential force associated with the collision of individual microprojections may be regarded, in the first approximation, as a dynamic equation describing the simplest oscillator with mass m, a viscous frictional coefficient, and rigidity k_Σ: $k_\Sigma = k + k_a$. Here k is the initial rigidity of the dynamic system, and k_a is the additional rigidity due to the formation of adhesive bridges. The modulus of the amplitude–frequency characteristic $|H(f)|$ of this system at eigenfrequency f_n may be written in the form

$$|H(f_n)| = \frac{\sqrt{m}}{c\sqrt{k}}.$$

If we imagine that a flux of pulses with random period and amplitude is sent to the input of this dynamic system, the power of the acoustic emission from the frictional contact will be the sum of the power of the vibroacoustic signals from each of the interacting contacts. The mean number of interacting microprojections per unit time may be expressed as the frequency ω, and the mean number of adhesive bridges at the contact area by the frequency ω_a.

To estimate the mean power E of the vibroacoustic signal emitted by the frictional contact, we must make some assumptions. The power of the vibroacoustic signal is proportional to the mean power created in the interaction of individual microprojections; the rigidity, determined by the adhesive bonds, is proportional to ω_a and the mean rigidity k_a^1 of a single adhesive bond. In this case, the power of the vibroacoustic emission at the frictional contact takes the form [10]

$$E \approx C\omega(k + k_a^1\omega_a)^{-1}, \qquad (1)$$

where the constant C takes account of all the other components.

Note that the adhesive bridges only arise after interaction of the individual microprojections. Therefore, we may assume that $\omega_a = K_{a.a}\omega$, where $K_{a.a}$ is the adhesive activity of contact in the given conditions. Values of $K_{a.a}$ in the range 0–1 are possible: when $K_{a.a} = 0$, no adhesive bonds are formed; when $K_{a.a} = 1$, all the interacting microprojections form adhesive bonds. We now write Eq. (1) in the form

$$E \approx C\omega(k + k_a^1 K_{a.a}\omega)^{-1}. \qquad (2)$$

We may consider Eq. (1) in two extreme cases: (1) when the actual contact area is very small and the adhesive bonds do not appear or may be ignored because their total rigidity is small relative to the initial rigidity k; (2) when the actual contact area is large and the initial rigidity k of the system may be disregarded in comparison with the adhesive rigidity.

In the first case, it follows from Eq. (2) that $E \sim \omega$. In the second case, the numerator and denominator in Eq. (2) are both proportional to ω, and hence $E =$ const. In Fig. 2a, we show the results of analysis of Eq. (2). In curve *1*, the power E of the vibroacoustic signal increases in proportion to the contact area in the initial stages. Curve *2* corresponds to the behavior at large contact area and high contact frequency.

The dashed curves correspond to possible transient processes of two types (A and B) relating the extreme cases expressed by curves *1* and *2*. Different transient processes arise because the size of the actual microprojections at contact is determined by the roughness of the contacting surfaces.

With increase in size of the microprojections, their interaction frequency declines, but the interaction energy is greater. More powerful impact pulses facilitate rupture of the few adhesive bridges formed in the initial stage of formation of the actual contact area. In this case, the adhesive bridges are retained with greater contact area than at surfaces with smaller microprojections.

In Fig. 2a, we plot $K_{a.a}$ for transient processes of type A and B. We see that, for type A, $K_{a.a}$ remains zero for a longer time with increase in the contact area. Once the number of adhesive bridges is sufficient to resist the impact pulses, $K_{a.a}$ rises to some stable level, which need not be one.

The model considered here corresponds qualitatively to the experimental data in Fig. 1. The model assumes that the making and breaking of contact between pairs of microprojections are not cooperative processes; that the microprojections are distributed uniformly over the contact area; and that increase in the interaction frequency does not produce additional deformation of the elastic system, affecting the steady recombination of microprojections. In practice, these assumptions are not universally satisfied. The deviations from these assumptions seen in the parameters of the vibroacoustic signal may provide information useful in diagnostics of the frictional interaction.

Cooperative interaction of the microprojections may be due to the presence of regular relief at the frictional surface, associated with already existing machining tracks or else with the presence of forced vibration or self- vibration characterized by relative motion normal to the contact surface [12, 13].

Experiments regarding the influence of relative vibrations on the behavior of the vibroacoustic signals show that tangential vibration with velocity considerably less than the slip velocity have relatively little influence on the amplitude modulation of the vibroacoustic signals. This is because the frequency ω changes only slightly in such vibrations.

The relative vibration normal to the contact surface has little influence on the depth of modulation of the vibroacoustic signal, unless it briefly opens the frictional contact. In the latter case, cooperative rupture of the adhesive bonds will occur ($K_{a.a} = 0$), with synchronization of the contacts between the interacting microprojections. That results in deep modulation of the vibroacoustic signal and sharp increase in its peak values.

With forced vibration of variable frequency at the frictional contact, the peak amplitude of the vibroacoustic signal changes by an order of magnitude when the frequency of the forced vibration approaches the eigenfrequency of the elastic system (a frequency shift of several Hz). A similar effect appears outside the resonant frequency with gradual increase in amplitude of the relative vibration normal to the contact surface. Beyond a certain amplitude, further increase (by fractions of a percent) greatly increases the peak values of the vibroacoustic signal.

There may be sharply unstable zones of frictional contact, where the smallest change in the contact conditions will sharply change the output characteristics of the vibroacoustic signals. These regions correspond to cooperative rupture of the frictional contact, when $K_{a.a}$ returns to zero, with impact normal to the contact surface.

The formation of adhesive bridges depends on sufficient time for the surfaces to move close together and for structural rearrangement of the atoms [6]. As a result, at the beginning of contact and at rupture, with relative vibrations, there is no stabilizing influence of the adhesive bridges and the amplitude of the vibroacoustic pulses is a maximum.

When contact is broken, especially large vibroacoustic surges are noted, on account of relaxation of the potential energy stored in the elastic system in overcoming the frictional force. This effect is seen, for example, in tool fracture. On that basis, the fracture of even a small cutting tool may be detected in massive equipment [14–16].

In cutting, it is difficult to monitor the cutting edges of different tools. Since cutting and frictional processes have many common features, the properties of frictional contact may be used for tool diagnostics [17–19].

For example, to understand the physics of grinding, its analogy with the friction process has been emphasized [18]. In grinding, 85–90% of the grains are not involved in cutting but only in elastic and plastic deformation of the machined surface. Thus, all the basic processes associated with friction are present. That permits more extensive use of the acoustic properties of frictional contact.

In Fig. 2b, as an example, we show the spectra of vibroacoustic signals accompanying the grinding process with and without grinding friction. The grinding fluid forms a film between the frictional areas of noncutting grains but does not penetrate into the contact zone of the cutting grains, which may continue to interact with fresh surface elements.

When grinding fluid is introduced, the amplitude of the vibroacoustic signal drops sharply, indicating considerable increase in $K_{a.a}$. This may be the result of a greater number of adhesive bridges or a lower impact frequency ω. We may assume that the number of adhesive bridges is not increased, but there are fewer collisions of the noncutting grains separated by the grinding-fluid film.

This hypothesis is confirmed in that, in the absence of grinding fluid, the contact area of the grinding wheel with the machined surface is increased (as a result of the greater grinding width), with almost proportional increase in amplitude of the vibroacoustic signal over a broad frequency range. In the presence of grinding fluid, increase in the contact area does not significantly change the amplitude of the vibroacoustic signal. That indicates more rapid saturation in contact.

Thus, in grinding, the cutting grains take on the role of the adhesive bridges in stabilizing the process. This is inconsistent with the widely held view that acoustic-emission signals are determined by destruction processes.

Another property of frictional contact that is often employed in grinding is the zero value of $K_{a.a}$ at the initial moment of contact. This ensures rapid increase in amplitude of the vibroacoustic signal at the beginning of surface contact. In grinding, when the margin removed may be 10–20 μm, it is very important to know the moment at which the grinding wheel first makes contact with the surface of the workpiece. In practice, that moment may be uncertain on account of the spread in workpiece dimensions, thermal deformation, and indeterminacy in the diameter of the wheel. However, it may be established by monitoring the vibroacoustic signal above 4 kHz. In Fig. 2c, we show the vibroacoustic signal in the 8-kHz octave as a grinding wheel approaches a diamond dressing tool.

It is evident from Fig. 2c that, when the wheel reaches the diamond dressing tool, only the sections of the wheel that project furthest in the radial direction first make contact. In the initial stage, this produces only one pulse per turn. Then, as the surfaces move closer, the number of pulses gradually increases. We see that, in the fourth rotation after the initial contact (each rotation lasts 0.03 s), the peak amplitude of the vibroacoustic signal exceeds the peak amplitude corresponding to complete contact over the whole circumference. This may be explained in that $K_{a.a} = 0$ at initial contact, and the pulse amplitude is determined by the impact parameters when the microprojections interact.

A numerically controlled machine tool may be regarded as a measuring machine. Accordingly, when the first pulse appears at contact with the grinding wheel, the coordinate of the grinding chuck may be recorded, and hence the depth of dressing may be monitored in subsequent motion. This is important since the margin in dressing may be 10–20 μm, and the deviations associated with thermal deformation and indeterminacy of the wheel dimensions may be comparable with (or even greater than) those values.

If, besides the initial contact, the initial moment of complete contact over the whole circumference is recorded, we may determine the dressing depth required to eliminate nonuniformity of the grinding wheel. The same principle may be used to determine the moment at which the wheel makes contact with the blank.

Tool fracture due to the propagation of brittle cracks is accompanied by relaxation of the accumulated potential energy, rupture of adhesive bonds, and a surge in the amplitude of the vibroacoustic signal, over a broad frequency range. However, if the chip is small in comparison with the cutting zone, the rupture of the adhesive contacts may be local, with partial retention of the adhesive bridges. In that case, the vibroacoustic pulse is relatively uninformative. Assessment of the tool's state then requires analysis of the vibroacoustic signal observed during subsequent tool operation [10, 14].

The appearance of intense self-vibration accompanied by brief loss of contact between the cutting edge and the surface of the workpiece is reflected in the vibroacoustic signal, so that the quality of the cutting process may be monitored. Since the microshocks that appear in intense self-vibration are of different frequencies, considerable growth in amplitude of the vibrations is observed at many eigenfrequencies of the machine tool's elastic system [12, 13].

Note, in conclusion, that the vibroacoustic signal accompanying frictional contact is as informative as the acoustic-emission signal and may be used in diagnostic systems ensuring safe operation of automated technological equipment. The proposed phenomenological model largely explains the complex behavior of the vibroacoustic signal in different conditions of frictional contact and permits the design of algorithms for vibroacoustic diagnostics.

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