Vol. 40, No. 3 (2018) 392-400, DOI: 10.24874/ti.2018.40.03.05

Tribology in Industry

www.tribology.rs

RESEARCH

Experimental Study of Frictional Vibrations Under Dry Friction Conditions

G.M. Ismailov[a], A.E. Tyurin[b]

[a]Tomsk State Pedagogical University, Kievskaya ave., 60, Tomsk, 634061, Russia,
[b]St. Petersburg National Research University of Information Technologies, Mechanics and Optics, Kronverksky pr., 49, St. Petersburg, 197101, Russia.

Keywords:

Wear
Vibration-based diagnostics
Dynamic range
Dry friction

Corresponding author:

Gafurzhan Mamatkulovich Ismailov
Tomsk State Pedagogical University,
Kievskaya ave., 60, Tomsk, 634061,
Russia.
E-mail: gmismailov@rambler.ru

A B S T R A C T

The paper discusses issues related to dynamic characteristics of friction. Vibrations are analyzed on “indenter on disk” system using brass and steel samples as an example. “Indenter on disk” system is changed by addition of supplementary degree of freedom, which allows the tangential component of friction to be analyzed. Vibration recording, processing and interpretation technique, which takes into account interaction speed, is specified. The obtained results can be used in control systems of modern mechanisms with allowances made for vibration and alternating impacts. Emerging vibrations were found to occupy a significant spectral range and have visible borders across the entire duration of implementation. The spectrographic presentation method was applied for visualization.

1. INTRODUCTION

Creation of effective means of protection against vibrations and shocks is one of the most important problems of modern technology. When operating machinery and mechanisms, impact of variable cyclic loads causes mechanical vibrations of parts and mechanisms as a whole. Particular emphasis is placed on the study of mechanisms where vibrations do not conform to normal operational conditions, which leads to further fatigue failures. Permanent dynamic impact on friction assemblies results in deformations in a contact zone, which lead to destruction of the surface layer. Tangential vibrations contribute to changing the roughness of rubbing parts, thereby intensifying wear processes [1,2]. Under such conditions, the dry friction mode is characterized by high friction coefficient and the worst wear. Similar phenomena are characteristic for mechanisms operating under alternating loads with various accelerations, such as linear plain slideways, feed nut assemblies, ball and screw units etc. [2].

Friction assemblies are affected by exciting forces of periodic and impulse nature. The operating mechanism has an extensive range of vibrations, and the most dangerous harmonics are singled out using spectral and wavelet analysis [2]. Vibrations are accompanied by different levels of speed and acceleration of micromixings, the most dangerous of which are resonance ones, which affect microgeometry of surfaces. High frequencies are generally not accompanied by large offsets, since significant accelerations, which emerge in this case, would lead to destruction of the mechanism.

Mathematical description of vibration processes is based on solving of equations of motion, the theory of stochastic processes and harmonic analysis [2]. Most studies apply a simplified frictional contact model described with linear oscillator equation with varying number of dampers and springs [3].

This paper presents an experimental technique of frictional contact analysis using vibration analysis methods. Classical "indenter on disk" friction system is studied. Wear of contacting surfaces under dry friction conditions is analyzed.

2. EXPERIMENTAL TECHNIQUE

2.1 Occurrence of Vibration in Tribocontact

Macro- and microgeometry of surface layers are the determining factors of occurrence of vibration during friction. There are technological and operational surface geometries, which emerge after run-in of certain duration. Hertz formulae for spheres or cylinders described in detail in papers [3,4] are used for simulation of contact interaction of two surfaces. However, this approach does not provide analysis capabilities in dynamics and is extremely inaccurate. Empirical methods, which take into account surface microgeometry, are often used in calculations [5,6].

The nature of microgeometry of surfaces during interaction is determined by waviness and roughness of surface. These two parameters must be taken into account to determine the actual contact area during relative sliding of solid bodies. Emerging frictional force depends not only on the actual area of touch and normal pressure in contacts, but also contributes significantly to vibration of tribological couplings.

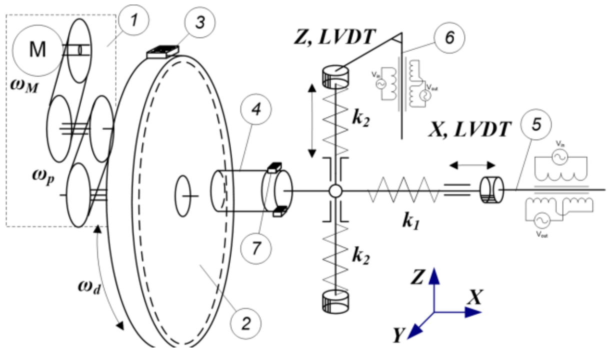
Vibration-based diagnostics are used for analysis of the vibration components in operating mechanisms. Simple tools, as well as multi-level data collection systems are used for this purpose. Devices of such type consist of primary transducer – accelerometer, data digitization and collection systems – analog-to-digital converters, software processing of mass data – formation of spectrum, determination of signs, interpretation and analysis of data. Vibration diagnostic systems are useful for critical and heavy-loaded assemblies, stationary and hard-to-reach units. Interpretation of obtained data and separation of vibration from random noise are the issues to be solved during introduction of such systems. Currently, smart mechanisms, where such tasks are partially solved: rolling element bearings, shaft beats, rotor balancing etc. – are designed and introduced. The main difficulty in diagnosing of such mechanisms lies in installation of vibration sensor near the studied object, for example, on the outer cartridge of the bearing.

2.2 Enhancing the Functionality of the "Indenter on Disk" Installation

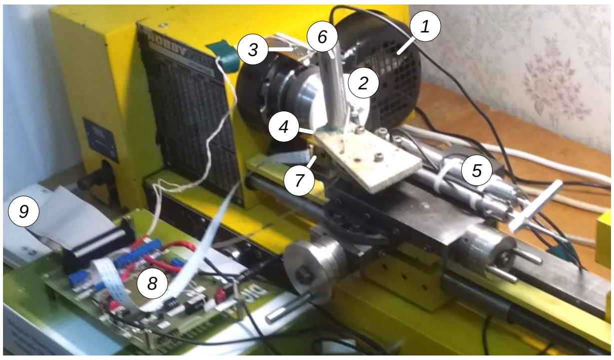
The drive *1* of an experimental unit (Fig. 1) consists of induction motor ω_M, which gears a disk *2* by means of serial belt drive ω_P. The rotation speed was controlled discretely using disks of different diameters at speeds of 250, 500, 1,000, 2,000 rpm. Rotation speed was measured by a speed sensor with a 20 bps incremental encoder *3*. The indenter *4* was mounted on a special holder so that it could travel along two independent axes. The contact is ensured by spring adjusting screws: in x direction – by k_1 stiffness spring *5*, in z direction – by k_2 stiffness spring *6*. The springs were pre-tensioned with the required force. The force was calibrated by a digital dynamometer.

Movement of the indenter *4* along the x axis is recorded by LDT 5 (linear differential transformer). The sensor operates on a physical principle of magnetic field changes during movement of ferrimagnetic core between coils. A differential amplifier installed at the outlet is designed to obtain data in a dynamic range of up to 250 Hz, and to record micro-movements of rod with an accuracy of up to 10 μm and sensor sampling frequency of 4 kHz. The linear movement transducer jointly with variable stiffness k_1 spring converts the force into movement. The system does not require correction of output signal by non-linearity and signal-noise ratio.

Sample vibrations are recorded by accelerometers *7* installed on the indenter *4*. The indenter *4* can move along two axes – z and x. The most intense vibrations occur when the sample touches the disk. Data are captured for each of the axes with different dynamic ranges of accelerometers *7* from 0 to 2 mm/s² along the x axis and from 0 to 16 mm/s² along the z axis, respectively. Different ranges make it possible to work with samples of a wide range of materials and properties.



a)



b)

Fig. 1. "Indenter on Disk" experimental unit: *a*) layout (diagram); *b*) layout (photo): *1* – drive; *2* – disk; *3* – speed sensor with an incremental encoder; *4* – indenter; *5* – LDT and spring block along the *x* axis; *6* – LDT and spring block along the *z* axis; *7* – accelerometer block; *8* – analog signal processing unit; *9* – 12-bit analog-to-digital converter.

Movement of the indenter *4* along the *x* axis is similar to a single-degree-of-freedom system and can be described by a linear second-order differential equation:

$$m\ddot{x} + n_1\dot{x} + k_1 x = F_1(t), \qquad (1)$$

where x is the movement of the indenter with mass m; n_1 is the viscous resistance coefficient; k_1 is the spring stiffness; $F_1(t)$ is the force associated with the presence of microroughness along the trajectory of the indenter on the disk circumference. The viscous resistance n_1 is non-linear in nature, it depends on microgeometry, temperature, and, most importantly, on the speed of contact interaction even on the best surfaces. The force $F_1(t)$ is determined by the formula:

$$F_1(t) = k_1 \cdot \Delta x(t),$$

where $\Delta x(t)$ is the change in the surface roughness.

The mathematical model along the z axis is described by the following equation:

$$m\ddot{z} + n_2\dot{z} + k_2 z = F_2(x, k_1, t), \qquad (2)$$

where n_2 is the damping coefficient; k_2 is the spring stiffness; $F_2(x, k_1, t)$ is the disturbing force in the direction z.

In this equation, the damping coefficient is a function of movement of the indenter x and the time t. The disturbing force F_2 depends on pre-tension of the springs, the deviation $\Delta x(t)$ and the time t. This force is the friction force between rubbing surfaces.

The equations (1), (2) for the mounting system of the indenter (Fig. 1*a*) are presented in the form of two unrelated systems, separately for z and x coordinates. These systems appear as spring and damper pendulum systems, which are well described with classic mechanics equations [5]. Rod with k_2 springs is a spring pendulum with two springs. Frequency of vibrations for such system obtained on the basis of solution to the second-order Lagrange equation along the z axis equals to:

$$T_z = 2\pi\sqrt{\frac{m}{k_2}}. \qquad (3)$$

Along the x axis, this system is a simple spring pendulum with k_1 spring stiffness, whose period of vibrations equal to:

$$T_x = 2\pi\sqrt{\frac{m}{k_1}}.$$

This approach enables simulation for each coordinate by finding their own frequencies of vibrations and resonance. The resulting model depends on the speed (process frequency) and indenter mass. The found parameters include viscous resistance coefficient and spring stiffness, which determine the impact of microgeometry on the system. This technique allows the system's stability to be defined by catastrophe theory criteria. Full details of this approach are specified in works [3–5].

Experimental validation of this approach requires study of vibrations and vibration speed in contact using vibration acceleration measurements. The frequency spectrum related only to interaction of indenter and disk should be separated from the total vibration acceleration spectrum. This can be done in two stages. The first stage lies in filtration of signal from low and high frequencies. The second stage includes calculation of the primary signal spectrum for operation of the entire mechanism at a target speed, but without interaction between the indenter and the disk. The primary spectrum is subtracted from the operational spectrum (obtained at interaction) at a similar speed of mechanism operation. Implementation of this approach is described below.

2.3 Vibrations Recorder

Analog Devices MEMS accelerometers with the following characteristics were used as acceleration sensors.

Table 1. Accelerometers (vibration sensors).

Main parameters	ADXL 326	ADXL 327	ADXL001-70
Acceleration (max), ± (g)	16	2	70
Axes	XYZ	XYZ	X
Nonlinearity, %	0.3	0.3	0.2
Sensitivity, mV/g	57	420	16
Cutoff frequency, Hz	X, Y – 1600, Z – 500	X, Y – 1600, Z – 500	22,000
AT, °C	From –40 to 85	From –40 to 85	From –40 to 125
Case	LFCSP-16	LFCSP-16	LCC-8

Analog circuit technology, which enables primary amplification of the signal in the correct dynamic range and exclusion of external losses and noise, forms an obligatory element of the precision measuring system. Impulse actions on drive power and frequencies multiple of the network frequency pose the greatest threat. Stabilized measuring circuits power voltage sources adjusted by power stabilizers (MIC 2950) are applied. Useful signal amplification, interference compensations, impedance reduction are implemented on precision repeaters (AD8554).

2.4 Experimental Set Up

Dry friction of machine parts is a jump-type process. Such jumps result in undesirable effects of mechanism jamming, accelerated wear and tear [7,8]. Transition to dry friction is characterized by vibration in the sound range, which occurs when clean surfaces come in contact. Friction force and temperature rise are observed, which results in jamming of tribocouple. Such processes are also typical in the course of tribological interaction of elements of cable structures and emergence of vibrations during cyclic interaction of external loads [9,10]. It should be noted that such approach can be applied to devices, where couples interact during reciprocating motion [11,12].

Study of properties of materials based on this layout makes it possible to perform accelerated wear tests and to study distinct vibration phenomena in contact. The experiment was conducted for six different samples under different modes of friction. Modifiable parameters include load force, speed, and duration of the test. Measured parameters include vibrations, force in joint, speed, temperature of the motionless “pin” sample and ambient temperature. This paper pays special attention to evaluation of vibration, interpretation and processing of data.

2.5 The Nature and Types of Vibrations under Dry Friction

Normally vibrations are distinguished by occurrence type as external and internal. The first type occurs due to the impact of external sources of the mechanism shaft beat, mass unbalance, while the second type occurs due to imperfect contact. Tribological joints friction and wear processes are greatly affected by external effects, in particular, butt and radial beats, vibrations of the mechanical part.

For example, vibrations did not occur during analysis of such materials as fluoroplastic with metal. There was no energy dissipation, polymer surface became the mark of a metal sample, and self-lubrication ensured low friction coefficient at the level of 0.03–0.05. By using the fluoroplastic disk, it is possible to study the vibrations of the operating mechanism when the conjugate parts contact each other, in order to isolate the natural frequencies of the unit and the drive. For this reason, the spectra of steel and fluoroplastic were studied only for testing the system. When the fluoroplastic is in contact with steel, vibrations are possible only at the very beginning of the interaction, during the adaptation of the fluoroplastic to the indenter shape. With further interaction of these friction pairs, no vibration arises. This is in good agreement with equations (1) and (3), since viscous friction of the fluoroplastic disk with the steel indenter is observed further. Therefore, vibrations do not occur.

When such materials as brass are used, the friction coefficient in the course of dry friction of steel is at the level of 0.4 during aging and 0.2–0.25 in the normal mode. The above data were obtained from experiment "brass disk and indenter made of soft steel" (Fig. 2, carbon 0.22 %, manganese 0.30 % etc.). The experiment was conducted for 30 minutes; however, the most interesting signals were obtained within first 10 seconds from the beginning of the experiment (Fig. 2). Since this period determines aging of the surface, signals of vibration acceleration of the primary mode should be considered. For dry friction, the movement of the indenter can be described by the following equation:

$$m\ddot{z} + F(\dot{z}, z) + k_2 z = N(\Delta x, \varphi_2, \dot{\varphi}_2) \cdot f, \quad (4)$$

where N is the normal load; f is the coefficient of friction; $F(\dot{z}, z)$ is the function of dry friction.

All forces arise and close in contact. Some of these forces are excited by rotation of the disk and depend on the angular coordinate φ_2, linear speed of the disk at a given contact radius ($\dot{\varphi}_2 \cdot R$), normal load (pressing force) N and coefficient of friction f. Another part of the forces arises from jumping of the sample along the x axis due to the surface roughness Δx of friction pairs. In the right-hand side of the equation (4), one of the components of the force, coefficient of friction f, is shown explicitly to demonstrate that it is variable. It is caused by change in the frictional force. These components of the frictional force cannot be singled out. In this case, the system is excited by friction, while friction contributes to stabilizing the motion of the sample. Since the sample has a certain mass and spring, it also has its self-motion in addition to the vibration imposed by friction. Therefore, the sample is in steady motion in case of viscous friction and jumps in case of dry friction. This equation (4) emphasizes that dry friction occurs at a variable coefficient of friction f.

The second term on the left-hand side of the equation (4) is the resistance to the motion (function of dry friction) caused by the motion of the indenter, taking into account the speed and the influence of the z coordinate. This function can be represented as:

$$F(\dot{z}, z) = n_2(z)\dot{z}, \quad (5)$$

since the damping coefficient $n_2(z)$ also changes with the z coordinate of the steel indenter on disk at a given time. By substituting the equation (5) into the equation (4), we obtain a conventional vibration equation.

The vibration signal was obtained in the form of diagram of dependence of the reduced amplitude of vibration acceleration (m/s^2) at any specific time recorded in certain points of the mechanism, with sampling frequency of 3 kHz. This frequency makes it possible to record the signal from acceleration sensors with up to 1.4 kHz cutoff frequency, which is conditional upon the dynamic range of accelerometers.

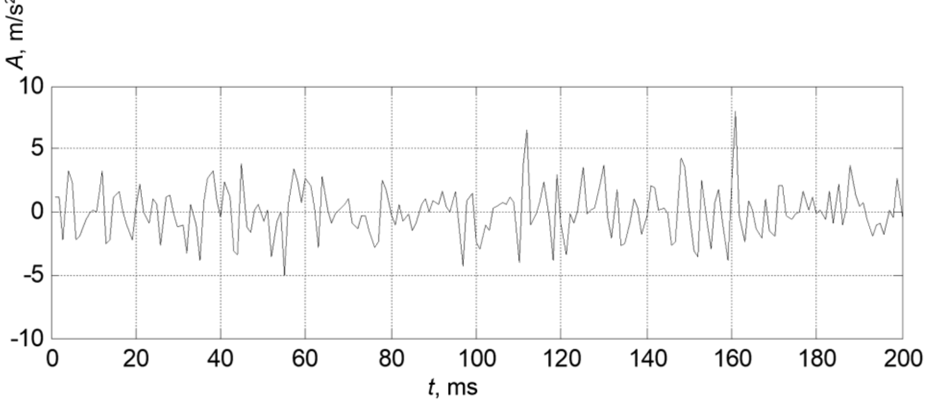


Fig. 2. Signal from the vibration sensor prior to filtration for the brass disc and the steel indenter.

2.6 Data Filtration

The study revealed the need for multi-stage filtration of undesired interference. Primary filtration was carried out directly by analog part – RC-chain of low-frequency filter with parameters (R = 33 kOhm, C = 0.1 μF) and cutoff frequency f_c = 5 Hz (−3 dB). This treatment was primarily aimed at exclusion of the most significant highly-modularized bursts, and then the signal was digitized at sampling frequency of 3 kHz. The data with the highest frequency are within the range of up to 1.5 Hz.

Further signal processing was carried out only with digital algorithms in several stages. The first stage included repeated filtering of the low-frequency component with skipping frequency 5 Hz and delay frequency 2 Hz. The second stage included high-frequency filtration with skipping frequency 470 Hz and delay frequency 490 Hz. During the last stage, band elimination filter was applied at frequencies multiple of 50 Hz with ±2 Hz bandwidth. This stage includes removal of impulse noise of the supply line frequency. It was noted that any reasons for non-sinusoidality of the magnetic field should be considered as the reasons for increase in the intensity of the vibration noise, especially, on the double frequency of induction motor power.

The same filter algorithm with sixth-order Butterworth finite impulse response was used for all filters. Data on the vibration phase were not considered in this paper, the range was calculated on the basis of comprehensively conjugate algorithm of multiplication of spectrum amplitudes.

It is difficult to study a signal form as a large amount of data (11 channels with sampling of 1.5 kHz/s), so spectral representation should be used for evaluation of harmonics. Discrete Fourier transform (bandwidth 4,096 pcs.) was applied for retrieving the spectral composition. Filtration result is shown in Fig. 3.

2.7 Impact of the Test Speed and Unit Operation on Vibration Measurements

Let us consider the spectrum of vibration acceleration (Fig. 3). It varies significantly for all three cases, and each part of installation drive affects the signal under consideration differently. When all assemblies are in operation, this spectrum was used as a basis for determination of their own noises from the drive and the mechanical part at a speed of 500 rpm. Fluoroplastic disk and steel polished indenter were used as test samples. The spectrum was recorded after aging of surfaces resulting from four minutes of testing. Different installation drive rotation speeds affect vibration pattern of the experiment. Significant changes of the vibration pattern for vibration acceleration were detected with increasing spindle rotation speed (Fig. 4).

Own frequency pattern appears differently, relation between the speed of rotation of the "disk" drive output arm and the vibration frequency has no clear functional dependency. Shift of the spectral component towards high frequency at speeds of 1,000 rpm or higher occurs.

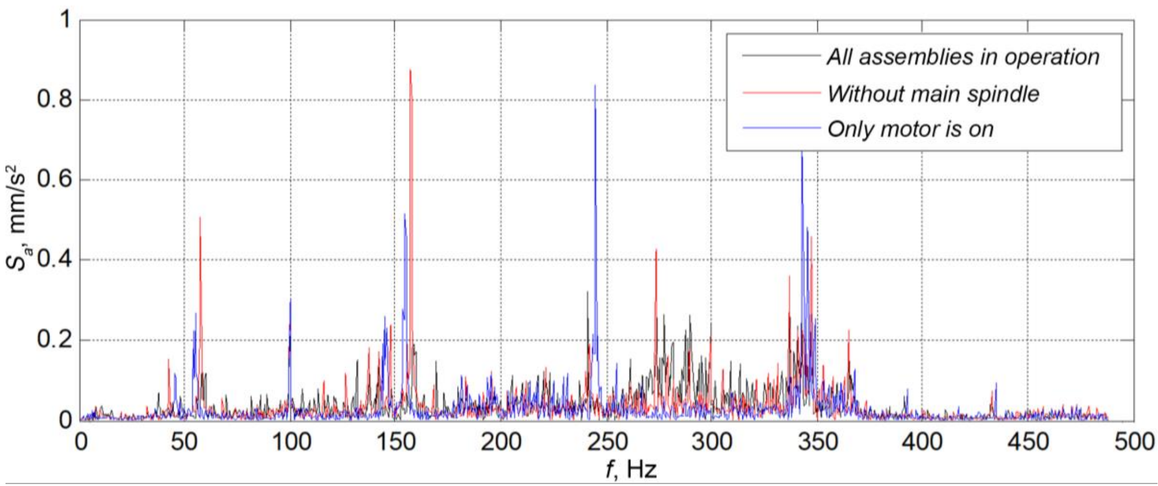


Fig. 3. Spectrum of vibration acceleration of the operating drive "Indenter on Disk" units, all groups of filters are applied. Studied materials: fluoroplastic disk and steel indenter.

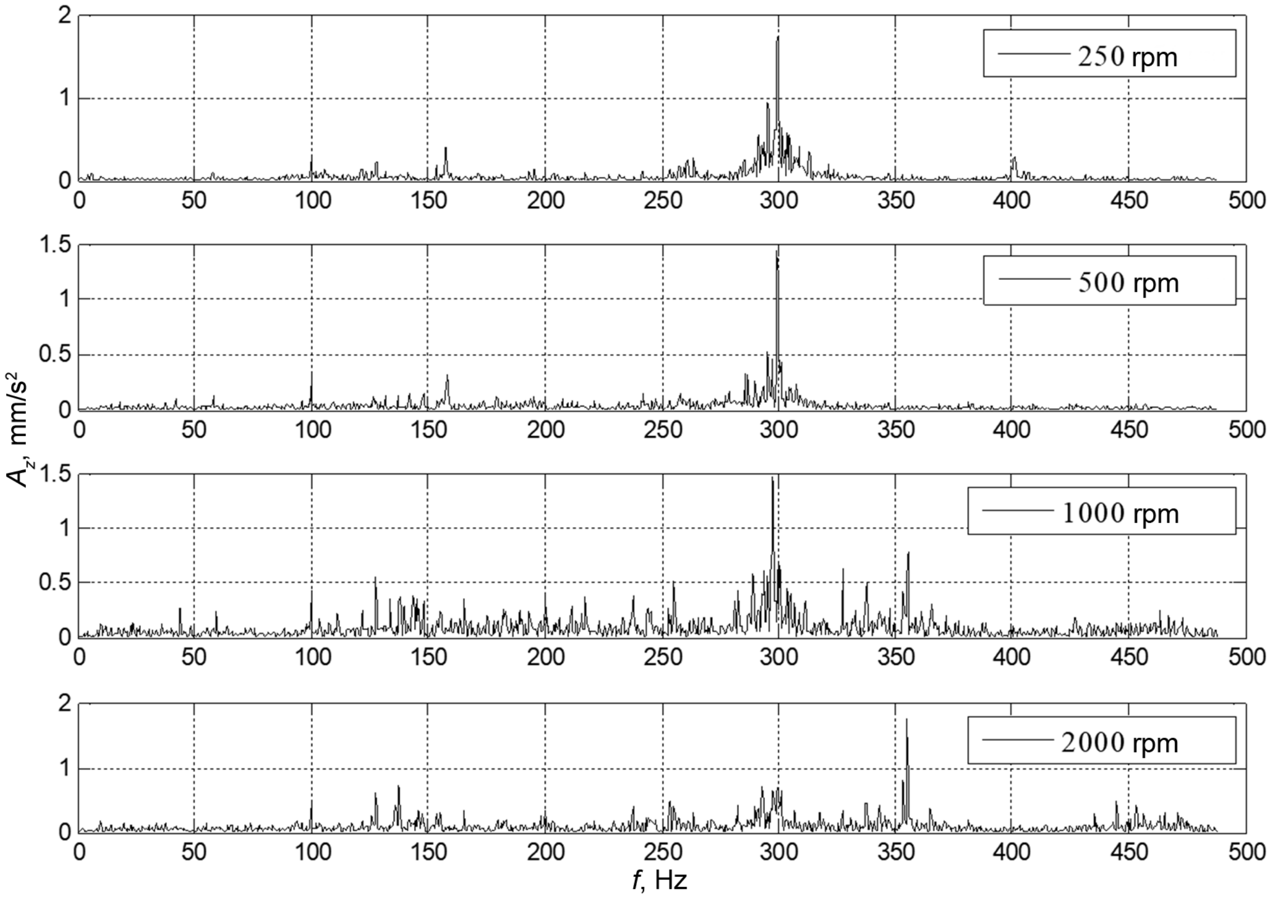


Fig. 4. Vibration acceleration signal spectrum at different rotation speeds for the fluoroplastic and steel pair.

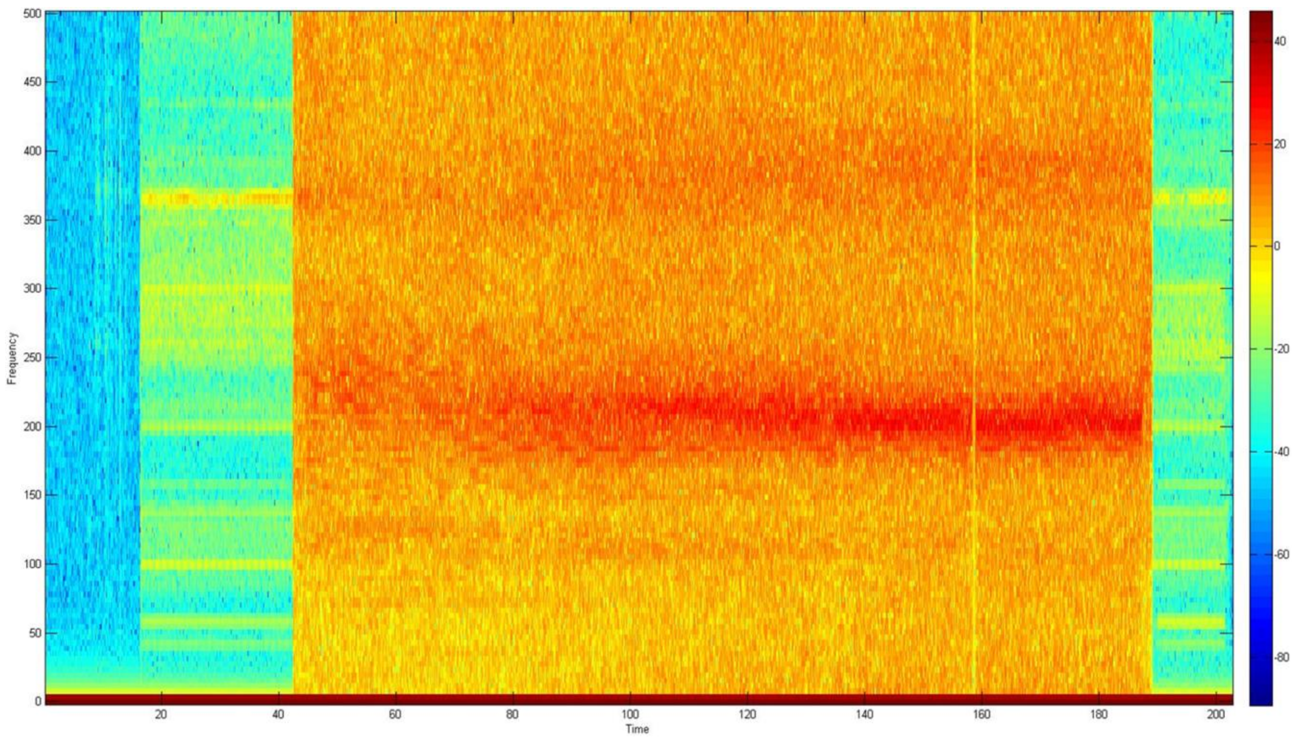


Fig. 5. Spectrogram of a signal from acceleration sensor; steel – brass specimen within the range of frequencies 0–500 Hz with 200 s duration.

In order to separate the useful signal from the effects related to operation of mechanical parts, we applied the multilevel filtration method by isolating the test signal spectrum from the analyzed signal spectrum at the preset speed. After calibration of the measuring system, test runs were carried out with fluoroplastic and steel specimens. This approach allowed the impact of permanent noise to be excluded from the mechanical part of the unit. Only one signal of vibration acceleration (Fig. 2) and one spectrogram (Fig. 5) are presented for the steel and brass pair. Other cases (Figs. 3 and 4) represent the vibration spectra of the drive and their effects at different speeds. To study the influence of the drive and speed, the "fluoroplastic disk – steel indenter" pair was used.

2.8 Spectrogram of the Surface Aging Period

Evaluation of the spectrogram of the vibration process is one of the options of visual examination of processes, which take place across the entire frequency range. Spectrogram (Fig. 5) is a three-dimensional representation of the frequency domain of the process where along the abscissa axis *x* is record time, along the ordinates axis *y* is frequency (which is equal to half the signal sampling rate), along the *z* axis there is a color scale on the right that shows the level of intensity of process amplitude in decibels [5]. The spectrogram is based on windowed Fourier transform with window length of 512 samples per each individual point in time throughout the implementation [5,6]. Modern processing systems are able to calculate the spectrogram directly in the course of the experiment; however, such information is redundant for decision-making systems, and the signal spectrum and its variations are sufficient.

Blue bands on the left (0–15 s) correspond to the period when the device was off. To the right and on the right bands with yellow bands of less intensity correspond to open-loop system, but the drive operates at 500 rpm frequency. Harmonics of 50 Hz signal and harmonics, which are multiples of them, correspond to the supply frequency. Low frequencies are shown with the maximum intensity, but they are not within this dynamic range. Low sensitivity of selected accelerometers (see Table 1) does not allow analyzing 0–15 Hz range.

The above Fig. 5 shows increase in intensity towards 200 Hz frequency and low background change towards 400 Hz frequencies. The graph clearly shows increase in energy in 200 Hz frequencies after the initial aging period. Relation between aging processes and intensification of frequencies emerges due to transition to equilibrium roughness, gradual wear of surface layers towards dry interaction of inner layers of materials occurs. Increase in the actual contact area between the indenter and the disk is one of emerging factors.

3. CONCLUSION

A study of vibration properties of dry friction for steel-brass materials under normal conditions was carried out. Special attention was given to the processes of the initial stage of contact of friction couplings. It was revealed that aging processes are of critical importance at the start of the mechanism. "Indenter on Disk" experiment scheme capabilities were extended; extra degree of freedom, which allows analyzing vibrations in the tangential direction during friction, was added.

The integrated approach of the process on the basis of a study of a frequency representation of signals using spectral analysis methods was presented. This approach allows finding critical points of transition from one surface condition to another. This paper describes the methods of creation of the multi-channel data collection system, as well as the methods of processing and interpretation of the vibrational component of dry friction. Spectral evaluations of the process were specified for visualization of the results. It would be useful to study not only changes in the tribological characteristics of materials, but also changes in the condition of contact surfaces of friction couplings of these systems for designing biomechatronic systems and 3D print technology [13,14].

In this paper, the vibrations along the *x* axis are measured in order to determine whether these vibrations affect the vibrations along the *z* axis, which are associated with the roughness of the disc and the sample. If they are related, resonance phenomena may arise. Excitation frequencies along the *z* axis are determined by the change along the *x* axis and by the roughness of the surfaces of the rubbing parts.

The technique of separation of the unit mechanism noise from the recording of the experiment was suggested. It is implemented by way of subtraction of spectra during idle operation of the unit under load when specimens are in contact. Intermittent pattern of contact of dry surfaces appears at all frequencies. The first phase of aging is the most important. In the initial period, the energy level is small. With ageing, the spectrum at some frequencies narrows, and the intensity of amplitudes changes. In the course of this process, as the operating time increases, the intensity of the spectral components changes. These signs allow detecting a problem of mechanism start and to take measures to avoid damage to the mechanism.

REFERENCES

[1] K.V. Frolov, *Modern Tribology: Results and Prospects*, Moscow: Izdatelstvo LKI, 2008 (in Russian).

[2] Y.G. Panovko, *Introduction to the Theory of Mechanical Vibrations*, Moscow: Nauka, 1991 (in Russian).

[3] G.A. Verkovich, E.N. Golovenkin, V.A. Golubkov, *Reference Book for Precision Instruments Designer*, Leningrad: Mashinostroenie, 1989 (in Russian).

[4] J.S. Bendat, A.G. Piersol, *Engineering Application of Correlation and Spectral Analysis*, New York: Wiley, 1980.

[5] B.A. Wernitz, N.P. Hoffmann, *Non-Linear Signal Analysis of Friction Induced Vibrations*, in 28th Annual SAE 2010 Brake Colloquium and Exhibition, 10–13 October, 2010, Phoenix, Arizona, USA.

[6] J.J. Sinou, O. Dereure, G.B. Mazet, F. Thouverez and L. Jezequel, *Friction-induced vibration for an aircraft brake system – Part 1: Experimental approach and stability analysis*, International Journal of Mechanical Sciences, vol. 48, iss. 5, pp. 536-554, 2006, doi: 10.1016/j.ijmecsci.2005.12.002

[7] F.P. Bowden, D. Tabor, *The Friction and Lubrication of Solids*, Oxford, 2001.

[8] V. L. Popov, *Contact Interaction Mechanics and Physics of Friction*, *From Nanotribology to Earthquake Dynamics*, Springer, 2013.

[9] G.M. Ismailov, A.E. Tyurin, K.V. Ikonnikova, Yu.S. Sarkisov, M.S. Pavlov, V.E. Mineev, *Force Interaction of Flexible Cable Elements Under Operation Conditions*, in IOP Conference Series: Earth and Environmental Science, vol. 87, pp. 1–7, 2017, doi: 10.1088/1755-1315/87/8/082023

[10] G.M. Ismailov, *Study of Cyclic Wear of Cable Structures Elements*, PhD thesis, Tomsk Polytechnic Institute, Tomsk, 1993 (in Russian).

[11] G.M. Ismailov, A.E. Tyurin, V.M. Musalimov, Y.A. Vlasov, V.A. Metelitsa, *Device for Study of Tribotechnical Characteristics of Materials*, Pat. RF, no. 158916, 2016 (in Russian).

[12] G.M. Ismailov, A.E. Tyurin, Y.A. Vlasov, *Device for Study of Tribotechnical Characteristics of Materials*, Pat. RF, no. 2600080, 2016 (in Russian).

[13] P. Kovalenko, S. Perepelkina, T. Korakhanov, *Investigation of Tribological Properties of Friction Pairs Duralumin – Fluoropolymer Used for Design and Manufacturing of Biomechatronic Devices*, Tribology in Industry, vol. 39, no. 2, pp. 192–197, 2017, doi: 10.24874/ti.2017.39.02.05

[14] S. Perepelkina, P. Kovalenko, R. Pechenko, K. Makhmudova, *Investigation of Friction Coefficient of Various Polymers Used in Rapid Prototyping Technologies with Different Settings of 3D-Printing*, Tribology in Industry, vol. 39, no. 4, pp. 519–526, 2017, doi: 10.24874/ti.2017.39.04.11