Applied and Computational Mechanics 8 (2014) 91–100

Dry friction damping couple at high frequencies

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Received 25 February 2014; received in revised form 27 June 2014

Abstract

The contribution deals with the application of dry friction couples for noise and vibration damping at high frequency of several kHz what brings new problems connected with the small amplitudes of relative slipping motion of contact surfaces. The most important information from the experimental results is knowledge that the value of evaluated friction coefficient can have different physical sense according to the magnitude of excitation force and to the frequency of applied vibrations. If amplitudes of motion are very small, then the external harmonic force produces only elastic micro-deformations of contacting bodies, where no slip occurs and then the traction contact force is proportional only to elastic deformation of the sample.

Keywords: dry friction, damping, high frequencies, experimental data

1. Introduction

Undesirable vibrations and noise of machines and means of transport have very often high frequency, which must be quenched by means of introducing some kind of structural damping, very often based on dry friction connection between vibrating elements. Characteristics of dry friction have been both experimentally and analytically investigated for more than two centuries, but mainly for comparatively low frequencies and also at sufficiently large amplitudes. Let us mention general friction problems in [1, 3, 8, 9], application to turbine blade dampers [2, 7] etc.

The application of dry friction couples for noise and vibration damping at high frequency of several kHz brings new problems connected with the small amplitudes of relative slipping motion of contact surfaces [4–6]. The tangential forces in these surfaces produce tangential micro-deformations that are of the same level as slip motions, and in some cases these elastic micro-deformations are the only response on the external harmonic excitation. Such kinds of contact couples do not work as energy damage, but as an elastic spring without any loss of energy, i.e., without any damping properties.

Topic of this contribution is an experimental analysis of these friction contacts.

2. Experimental sets for dry friction characteristic measurements

The tribologic literature oriented on the description of experimental investigation of friction properties at vibrations contains information usually only up to 50 Hz, exceptionally up to 200 Hz. We have found no information about properties of experimental research of contact friction behavior in the range of several kHz. Therefore, we developed a simple experimental set, which would be suitable for ascertaining with sufficient exactness in measurements of

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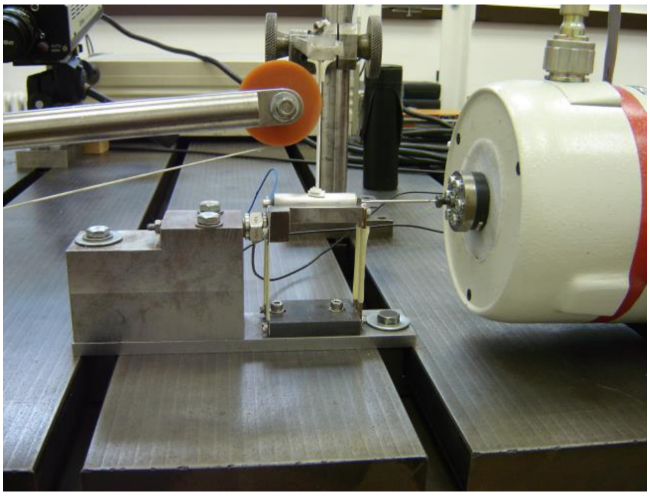

Fig. 1. Experimental set for dry friction measurements

friction forces F_t, normal trust forces F_N and relative tangential motion and velocity in friction surface, Fig. 1.

The request of measurements of friction properties up to 3 kHz we tried to fulfil by reinforcement of some parts of experimental set and also by theirs lightness, but in spite of these reconstructions, several eigenfrequencies of experimental rig are under the upper frequency boundary 3 kHz. If they are under the lower boundary frequency 1 kHz, these frequencies did not disturb fortunately the measured signals. However, there appears another problem.

Dynamical behavior of dry friction at vibrations is much complicated than of friction with constant relative velocity between contacting surfaces. Friction velocity changes its sign twice in a period from the positive value to the negative one and vice versa and the friction force changes its sign jump-wise as well. Harmonic decomposition of this force time history contains infinite set of higher harmonic components, some of which can resonantly coincide with some of experimental set eigenfrequencies and can essentially disturb records of force and motion. The low pass filter for cut off these higher disturbing frequencies cannot be applied because it cut of not only disturbing frequencies but also the higher harmonic components of the basic jump-wise force signal. One way is to increase essentially the frequency spectrum of the whole experimental rig by decreasing its dimensions at holding all physical similarity laws. The second way is the developing of a new method for evaluation of records, which enable to gain the needed values with the good technical accuracy. This problem has been solved in paper [7] and we use it also for evaluation of the following presented results.

Measurement and excitation apparatuses completed the experimental set in Fig. 1. The accelerometer B&K 4374 measures relative motion in the friction surface between contacting bodies. Signal from this accelerometer was after double integration as a voltage proportional to the displacement $x(t)$ led on one input of digital oscilloscope YOKOGAWA. Friction force F_t was picked up by the force transducer B&K 8200 and its signal was led into Conditioning Amplifier B&K 2626 and then on the second input of the digital oscilloscope.

The moving coil exciter LDS V400 fed by digital HP 332A Synthesized generator through PA100E power amplifier was applied for vibration excitations. Ampere meter measured the feeding current. Digital generator enables measurements in linear sweep regime prescribed in given frequency range (e.g., 1–3 kHz) and in prescribed time interval (e.g., 5 s).

Time histories of friction force $F_t(t)$ and of oscillating relative motion $x(t)$ were during measurements recorded in the memory and on the screen of digital oscilloscope. At the end of measurements, these records were saved on Card Reader and off-line evaluated by means of system Xviewer.

A record of one measurement length 5 s at interval 500 Hz contains more than 10 000 periods of friction process, prepared in the memory for evaluation. However, for our purposes, it suffices to elaborate only 10 selected events approx. at 50 Hz.

In the presented examples, the sweep measurements were repeated always at two normal loads $F_N = 11.56, 23.12$ N, which act on the length of 5 cm of the line contact surface. Contact pressures are $p = 231.22$ and 462.44 N/m. The entire frequency interval 1–3 Hz was divided for simple evaluation into four subintervals 1–1.5, 1.5–2, 2–2.5, 2.5–3 kHz. Example of a record at the lowest frequency boundary 2 050 Hz and amplitude $6\ \mu$m is in Fig. 2.

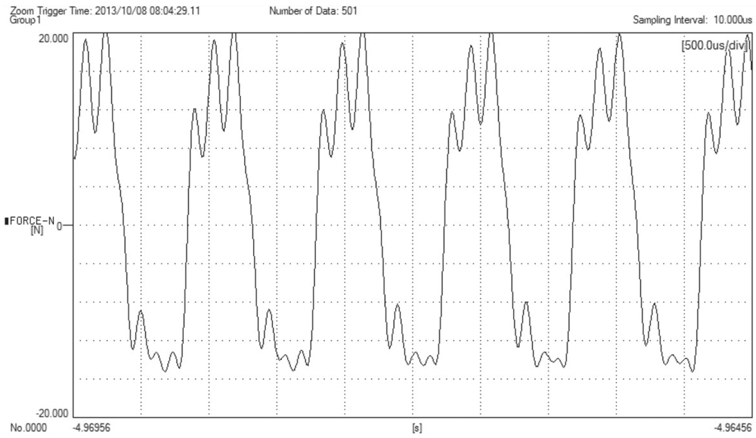

Fig. 2. Distortion of friction force record

Jumps of friction force in the extreme positions are recorded as nearly vertical lines; the friction forces between these jumps are distorted by the higher resonance oscillations of the subsystem connected the friction surface with force meter B&K 8200. These friction forces can be ascertained only as an average value of the waved upper and lower parts of records. The smaller are relative vibrations amplitudes, the more pronounced is the influence of tangential elastic micro-deformations and the slope of jump lines are smaller.

3. Examples of friction characteristics

3.1. Records of low frequency events

Let us see first of all on the records of friction forces at very small frequency, e.g., at 12 Hz, when the inertia forces and dynamic compliances of contacting bodies are negligible. The time history shown in Fig. 3 presents the harmonic course of relative slip motion in contact surface and

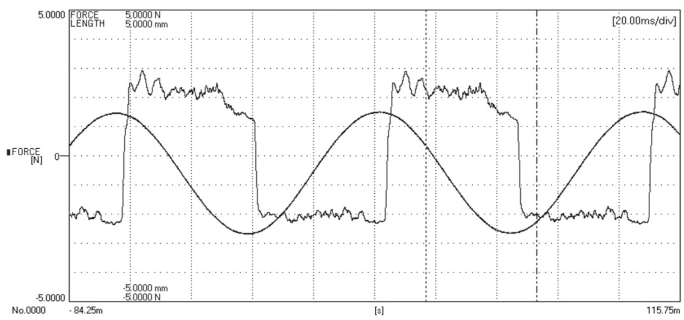

Fig. 3. Harmonic motion and friction force at 12 Hz

roughly rectangular form of friction force. The jumps between positive and negative values of friction force in the return points are nearly vertical, but the sliding parts of the force history are recorded by very noisy horizontal curves. This is caused by the micro-unevenness of contacting surfaces and theirs abrasive wear.

The mapping of the same friction process in the force-displacement coordinates is shown in Fig. 4. The closed rectangular form proves stationary properties of friction process. The very small elastic tangential micro-deformations in reverse points are very small in comparison to the displacement amplitude (approx. 2 mm) and cause only very gentles inclinations of vertical jump lines. The area of this hysteretic loop is proportional to the friction energy loss during one period of vibration.

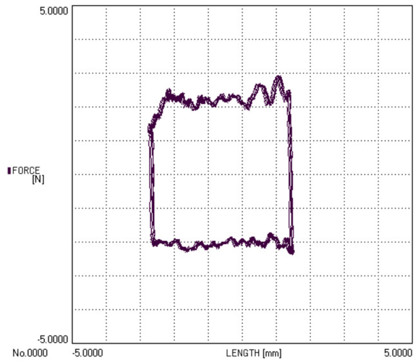

Fig. 4. Hysteretic loop at 12 Hz

3.2. Records of high frequency events

The random disturbances caused by the micro-unevenness of contacting surfaces are contained also in the friction processes realized at much higher frequency vibrations, in the range of one or more kHz, but the more important record's distortion is usually the influence of eigenfrequencies of the experimental rig, excited by the higher harmonic components of the jumps in the rectangular course of friction force, as has been mentioned in the previous chapter. However by means of special evaluations procedure and careful readings it is possible to ascertain the friction coefficient also in such cases, but the accuracy of these values is worse, sometimes with error up to 10 % or more.

Let us see on the results measured in the frequency range 1 kHz up to 3 kHz. Measured friction couple consists of a steel cylinder ⌀ 14 mm (stainless steel, CSN 17240), length 25 mm contacting on the surface straight line of steel cylindrical groove (ER7 – cat. 2), Fig. 5. Surface finish of both elements was Ra 3.2. Specific pressure on 1 m length of contact line was $p = 231.24$ N/m.

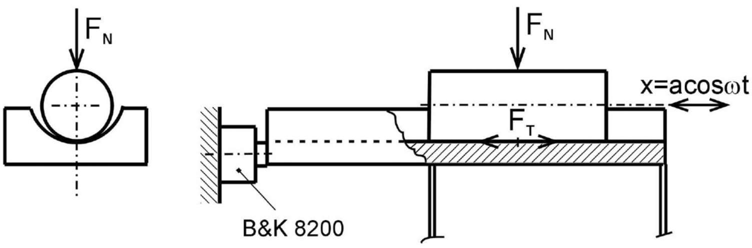

Fig. 5. Friction couple for high frequency measurements

Dry friction coefficient f at vibrations in the lowest range 1–1.5 kHz is shown in Fig. 6, where values at three groups of amplitudes are plotted. Vibrating motion of cylinder was realized by an electro-dynamic vibrator feed by alternating currents $I = 2, 4, 6$ A (in Fig. 6 labeled by □, △, ◇, respectively). Corresponding amplitudes in the given frequency range are plotted in Fig. 7.

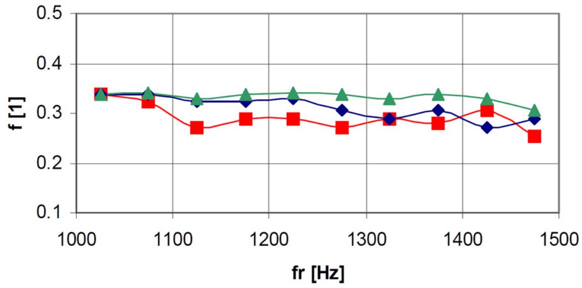

Fig. 6. Dry friction coefficient f in frequency range 1–1.5 kHz, contact pressure $p = 231.24$ N/m

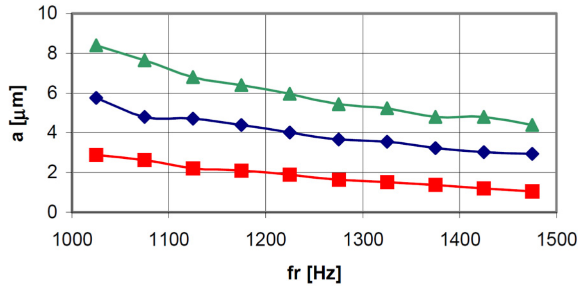

Fig. 7. Amplitudes of relative vibrations, $I = 2, 4, 6$ A, (□, △, ◇)

From the last two figures it is evident that the dry friction coefficient in the whole range of amplitudes up to 9 μm is constant and equals $f = 0.3$. The measured coefficients of dry friction at the twice higher pressure $p = 462.48$ N/m and at the same feeding currents $I = 2, 4, 6$ A are plotted in Fig. 8. It is seen that also at these higher normal forces, friction coefficients stay roughly constant $f \approx 0.3$ in the entire range of frequencies 1–1.5 kHz, with the exception of the smallest forcing motion $I = 2$ A (□) near 1 500 Hz, where $f \approx 0.2$.

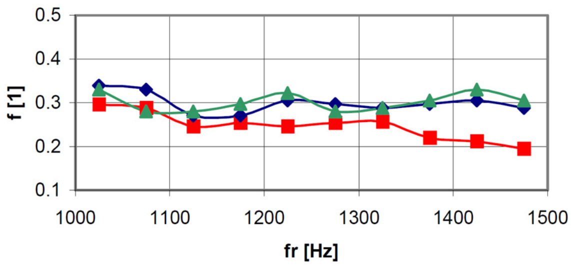

Fig. 8. Dry friction coefficient f in frequency range 1–1.5 kHz, contact pressure 462.48 N/m

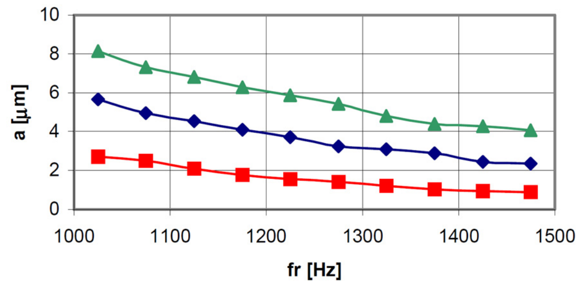

Fig. 9. Amplitudes of relative vibrations, contact pressure $p = 462.48$ N/m

Courses of amplitudes vibrations do not change essentially with the increase of normal thrust on double, as seen from the comparison of curves in Figs. 7 and 9.

The distortion of force records in this range of frequency is shown in Fig. 10 picked up at 1 249 Hz. Repeated jumps excite at this high frequency unexpected oscillations of the signal trace between origin of the friction force and the force transducer BaK 8200 so that the upper and lower parts of records have the forms of wave curve, instead of horizontal lines corresponding to the constant friction forces.

Hysteretic curve of force-displacement record at the same frequency 1 249 Hz is plotted in Fig. 11. The high eigenfrequency oscillations of the trace between source of the friction force and the force transducer cause also the wavelike distortion of the upper and lower parts of hysteretic curve, where the straight lines could be expected, if the friction force should be measured direct in the contact surfaces.

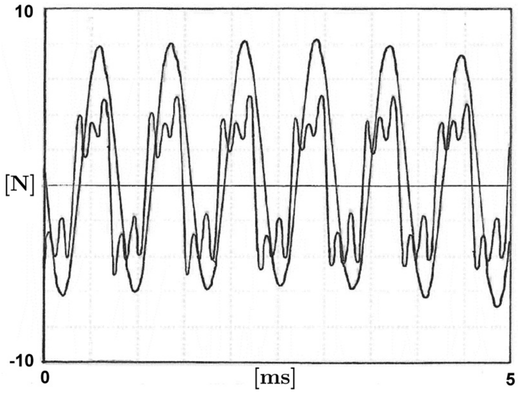

Fig. 10. Motion and friction force at 1 249 Hz

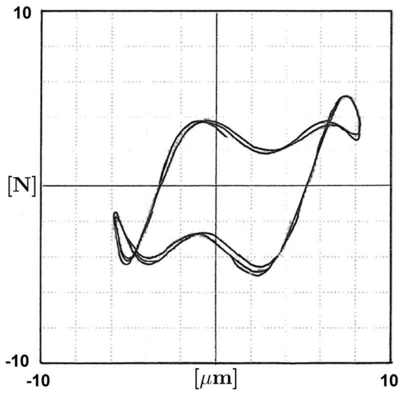

Fig. 11. Hysteretic loop at 1 249 Hz

The area of this hysteretic curve is again proportional to the energy lost during one cycle, but it must be taken into account, that two small marginal loops have opposite circulation and therefore determine not lost but gained energy.

Increase of frequency range on 1.5–2 kHz at the same contact pressure $p = 462.48$ N/m acting on contact line of length 5 cm and at the same feeding currents $I = 2, 4, 6$ A causes the small decrease of dry friction coefficient as seen in Fig. 12. The lowest coefficient values $f \approx 0.2$ are again at the smallest forcing motion created by feeding current $I = 2$ A (□).

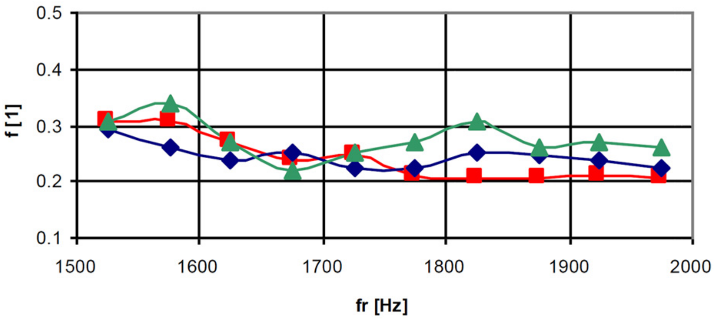

Fig. 12. Friction coefficient f in frequency range 1.5–2 kHz, contact pressure 462.48 N/m

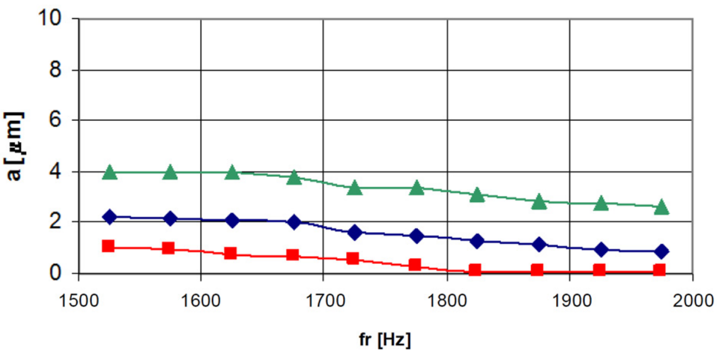

Fig. 13. Amplitudes of relative vibrations in frequency range 1.5–2 kHz

Courses of amplitudes vibrations decrease in this higher frequency range very essentially as seen from comparison of Figs. 9 and 13. This decrease is strongest evident at the smallest feeding current $I = 2$ A (□), where amplitudes in the frequency range 1.8–2 kHz are near to zero. This behavior can be explained by the insufficient excitation force, which does not reach the boundary dry friction force and can produce only elastic tangential (stick) micro-deformations in the contact line surface. These elastic micro-deformations influence also motions at higher excitation-moving-coil forces (feeding currents $I = 4$ A $\triangle$, 6 A $\diamondsuit$), where the slip motions are only parts of measured amplitudes, which results in the lower corresponding amplitude-frequency records in Fig. 13.

The details of force and motion records at frequency 1 790 Hz is shown in Fig. 14. Similar as in the previous case, the signal of friction force picked up by force transducer BaK 8200 contains distortion due to higher eigenfrequency (approx. 5 800 Hz) of the signal trace between origin of the friction force and the force transducer. These distorted vibrations have three periods in one period of relative motion as distinct from the record in Fig. 10, where are five periods of distorted vibrations per one period of relative motion. Hysteretic curve at frequency 1 790 Hz is plotted in Fig. 15. Its horizontal width is smaller than in Fig. 11 and corresponds to the amplitude $a = 3.6$ μm (see Fig. 13 curve 6 A).

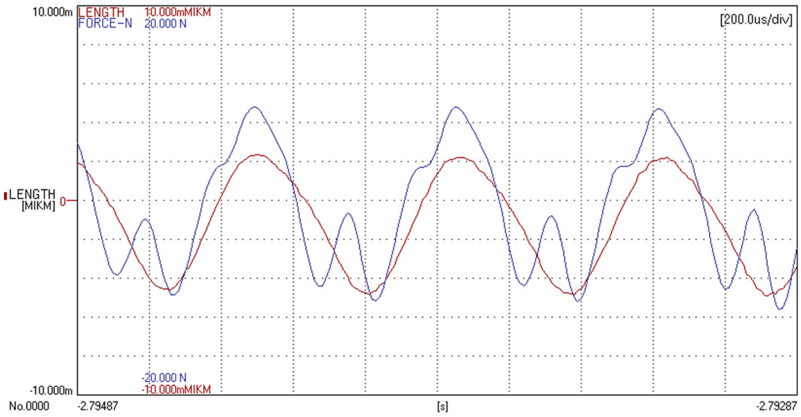

Fig. 14. Motion and friction force at 1 790 Hz

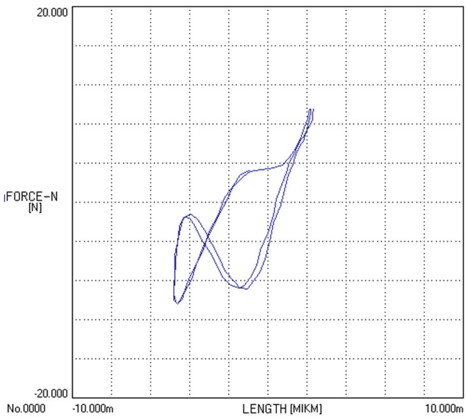

Fig. 15. Hysteretic loop at 1 790 Hz

The higher are the excitation frequencies at the limited vibration excitation force, the smallest are amplitudes of relative tangential motions in contact surface and the strongest is influence of elastic tangential stick micro-deformations. This case occurred, e.g., in the highest frequency range 2.5–3 kHz. Measured dependences of friction coefficient — frequency and amplitude — frequency for the same linear contact pressure $p = 462.48$ N/m and the same currents $I = 2, 4, 6$ A feeding moving-coil vibrator, as in the previous examples, are plotted in Figs. 16 and 17.

Curves in Fig. 16 demonstrate nearly constant, with frequency moderately decreasing values of coefficient f, but they are different ones for various excitation forces ($I = 2$ A $\square$, 4 A $\triangle$, 6 A $\diamondsuit$) and roughly proportional to these forces in the ratios $2:4:6$.

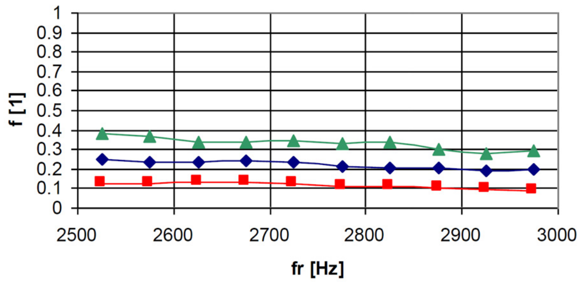

Fig. 16. Coefficient f in frequency range 2.5–3 kHz, contact pressure 462.48 N/m

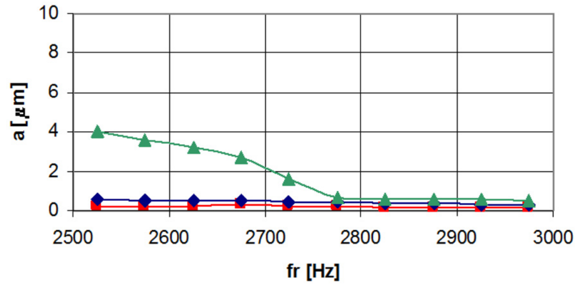

Fig. 17. Amplitudes of relative vibrations in frequency range 2.5–3 kHz

Corresponding amplitudes, plotted in Fig. 17, have approximately zero values (under 1 μm) with the exception of the highest forcing force ($I = 6$ A, $\diamondsuit$) in range 2 500–2 750 Hz, where the force of vibrator reaches over the friction force and evokes greater vibrations. No slip in the contact surface occurs in the other cases, but only elastic tangential micro-deformations with amplitudes in the ratios of excitation forces.

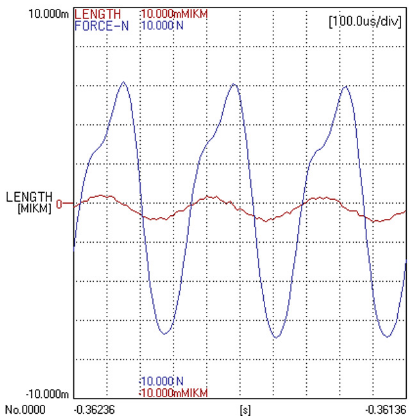

Fig. 18. Motion and friction force at 2 850 Hz

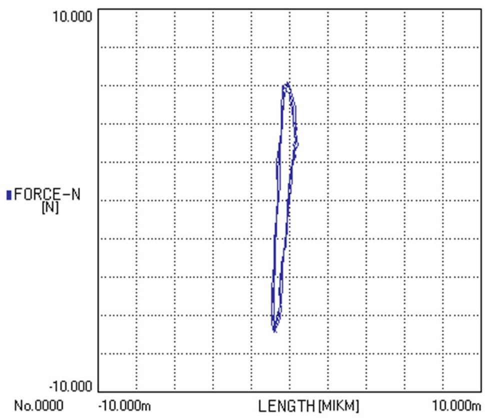

Fig. 19. Hysteretic loop at 2 850 Hz

The example of force and motion records in this range of frequency are picked up at excitation frequency 2 850 Hz and at feeding current $I = 6$ A. Three periods of this record are shown in Fig. 18. The smallest sinusoidal curve indicates recorded motion $x(t)$ of upper cylindrical body (see Fig. 5) with amplitudes $a \approx 0.5$ μm, a little distributed by the noise of applied apparatus. The quasi-sinusoidal curve with higher amplitude (approx. 6 N) describes the friction force. It is evident that this measured tangential force causes only elastic deformation and therefore it has quasi-harmonic form without any slips and it equals to the acting force of electro-dynamic vibrator. A small distortion of form is due to the resonance effect caused by the nearby eigenfrequency of experimental rig.

Fig. 19 presents hysteretic loop (force – displacement). Its small area indicates that in some parts of contact surfaces, marginally and low pressed, friction micro-slips can occur. Moderate inclination of this loop is caused by the elastic compliance properties of the force transfer trace between friction surface and position of force measurement.

The further example of force and motion records in this range of frequency, picked up at 2 950 Hz, is shown in Fig. 20. The feeding current was $I = 6$ A and pressure $p = 452.48$ N/m.

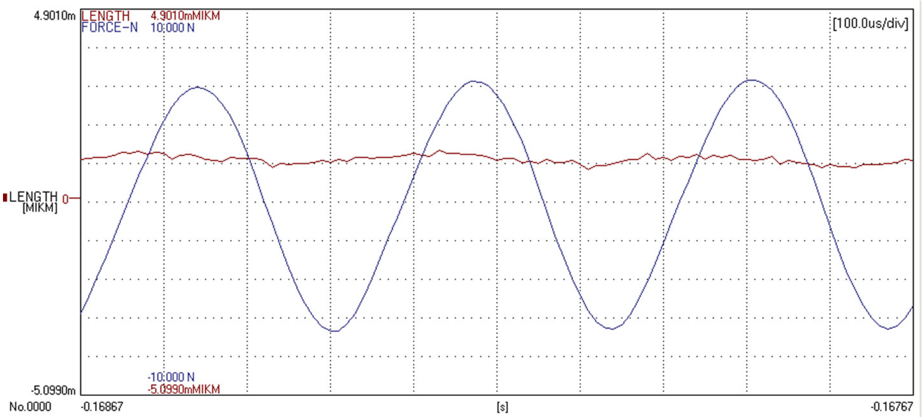

Fig. 20. Motion and friction force at 2 950 Hz

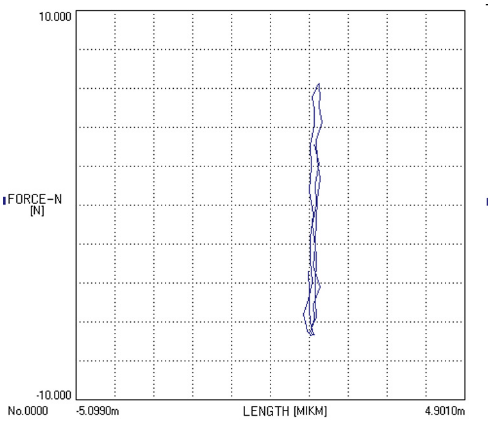

Fig. 21. Hysteretic loop at 2 950 Hz

The measured tangential force causes again only elastic deformation and therefore it has a pure harmonic form corresponding to the force of electro-dynamic vibrator.

The record of relative motion $x(t)$ is much smaller than in previous case. Corresponding hysteretic loop force-displacement degrades to a straight, moderately leaned line (Fig. 21) with no area and also with no damping properties.

4. Conclusion

The dry friction properties at high frequency vibration of contacting bodies are strongly influenced both by the elastic tangential compliances of these bodies near the contacting surface and also by the dynamic frequency spectrum of the entire measuring set, particularly of its part lying between friction contact (force-signal source) and the force meter position. In spite of these distorting influences, the dry friction coefficient $f = 0.3$ at 1 kHz with a moderate decrease to higher frequencies has been ascertained.

One of the important information gained from the presented results of measurements is knowledge that the value f ascertained as ratio of measured tangential force F_T to the perpendicular force F_N can have different physical sense according to the magnitude of excitation force and to the frequency of applied vibrations. At sufficiently large amplitudes a of motions, F_T gives the friction force and ratio $F_T/F_N = f$ ascertains dry friction coefficient.

If amplitude a of motion is very small, then the external harmonic force produces only elastic micro-deformations of contacting bodies, where no slip occurs and the value $f = F_T/F_N$ is usually smaller than dry friction coefficient. The tangential friction force F_T is then proportional to the amplitude of excitation motion (or of current) from the electro-dynamic vibrator and expresses static friction ('stiction'). The ratio F_T/a is approximately constant and proportional to the stiffness [N/m] of trace between the points of amplitude measurement and tangential force measurement, including tangential micro-deformation in contact surface.

Acknowledgements

This work was elaborated in Institute of Thermomechanics AS CR v.v.i. and it was supported by conceptual development of research organizations RVO: 61388998.

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