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FRICTION-INDUCED OSCILLATIONS OF A NON-ASBESTOS ORGANIC PIN SLIDING ON A STEEL DISC

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Abstract: Friction-induced oscillations result in deterioration of performance of disc brakes and are generally undesired. We conduct experimental study of friction-induced oscillations in a non-asbestos organic material / steel pair used in disc brakes of motor vehicles. The tests are done by use of a pin-on-disc machine in which the pin sample is supported on a deformable beam. The adjustable friction parameters are the disc velocity, contact pressure and temperature. The tests show that the friction coefficient decreases with the sliding velocity and increases with the temperature. The friction-induced tangential oscillation of the pin sample occurs with a frequency equal to the first natural frequency of the beam. The effects of the disc velocity and temperature on the oscillation characteristics are investigated. The oscillation amplitude increases with the disc velocity on the interval of velocities below 2 m/s. Temperature changes of several tens of degrees Celsius lead to the oscillation occurrence / decay. The obtained results can be useful for prognostication of friction-induced oscillations in disc brakes with non-asbestos organic pads.

Key words: Friction-Induced Oscillation, Pin-On-Disc Machine, Non-Asbestos Organic Material, Sliding Velocity, Temperature

1. INTRODUCTION

Friction-induced oscillation is a common phenomenon observed in various tribosystems. It is usually accompanied by uncontrollable changes in the sliding velocity, contact pressure, displacements or stress-and-strain states of the sliding components and generally results in deterioration of performance characteristics (Sheng, 2008).

Disc brakes are tribosystems widely utilized in automobiles, motorcycles, lift-and-transport machines, rail vehicles and aircrafts. The occurrence of friction-induced oscillations essentially reduces the reliability of disc brakes and quality of braking. In addition, these oscillations are the source of undesired noise. Therefore, prognostication and prevention of friction-induced oscillations at the design stage is one of the most challenging problems in the disc brake industry (Kinkaid et al., 2003; Sergienko et al., 2008).

A number of experimental and theoretical studies have been reported on the oscillatory dynamics in disc brake systems. One can distinguish several central theories describing the occurrence conditions and features of friction-induced oscillations. It is known that if the friction coefficient decreases with the sliding velocity, this results in the negative damping and associated oscillations (Kajdanowsky and Haykin, 1933; Mills, 1938). The difference between the kinetic friction force and the maximum tangential force in static contact is the reason for the excitation of stick−slip oscillations. This difference is explained by welding together of the sliding metallic materials at the local points of contact (Bowden and Leben, 1939) or strengthening of the interfacial bonds between the materials with the static contact duration (Ishlinsky and Kragelsky, 1944). The sliding instability in the form of oscillations is also possible under constant friction coefficient. It can occur due to the sprag–slip mechanism when geometrically or kinematically constrained sliding component becomes locked and then returns to the sliding state again through the pliability of the system (Spurr, 1961), thermoelastic distortion of the sliding components (Barber, 1969), self-excited elastic waves at the contact surfaces (Adams, 1995), etc.

The diversity of observations of tribosystem dynamics suggests that there is no simple and unique cause of friction-induced oscillations. The occurrence of oscillation and its features depend on the friction pair materials, friction conditions as well as characteristics of the whole tribosystem. One of the methods of experimental study of friction-induced oscillations is using a pin-on-disc machine with the pin sample mounted on a deformable support. This method allows to substitute the complicated multicomponent tribosystem under study with a simpler tribosystem with adjustable stiffness coefficients, natural frequencies and other parameters. Thereby, one can concentrate more deeply on friction-related phenomena.

Earles and Lee (1976) investigated oscillations in a steel / steel sliding contact with the aid of a pin-on-disc machine in which the pin was supported on a deformable cantilever. The construction of the cantilever allowed for the tangential and normal motions of the pin with respect to the sliding interface and its rotation related to the cantilever torsion. Another pin-on-disc machine was used by Aronov et al. (1983) for studying oscillations in a steel / steel sliding pair in the presence of water lubricant. The pin was supported on a deformable arm. The motions of the pin in the tangential and normal directions were measured by an accelerometer. Dweib and D'Souza (1990) modified the pin-on-disc machine of Aronov et al. so that the angle of the arm torsion could be measured. Tworzydlo et al. (1999) developed a pin-on-disc machine with the pin connected by a deformable arm to a slider block which, in its turn, was supported on another deformable arm. The 3 translations and 3 rotations of the slider block were measured by 6 accelerometers.

In the present study we investigate experimentally the sliding instability in a non-asbestos organic material / steel pair used in disc brakes of motor vehicles. The tests are conducted by use of a pin-on-disc machine with the pin sample supported on a deformable beam. A special attention is paid to the effects of the disc velocity and temperature.

2. EXPERIMENTAL EQUIPMENT

Fig. 1 shows a schematic of a pin-on-disc machine developed (Nosko, 2013). The pin sample has a cross-section area S =10×10 mm^2. It is installed into a holder which is attached to a lever by use of a beam. The holder and beam are carefully levelled. The lever can rotate about a vertical axis. The friction disc is machined with high precision to eliminate waviness and distortion of the sliding surface. It is mounted on a horizontally installed shaft together with an inertia disc. A motor drives the shaft and, accordingly, the friction disc with an angular velocity ω. The pin sample is pressed against the friction disc with a normal force N. The average friction radius is $r = 35$ mm.

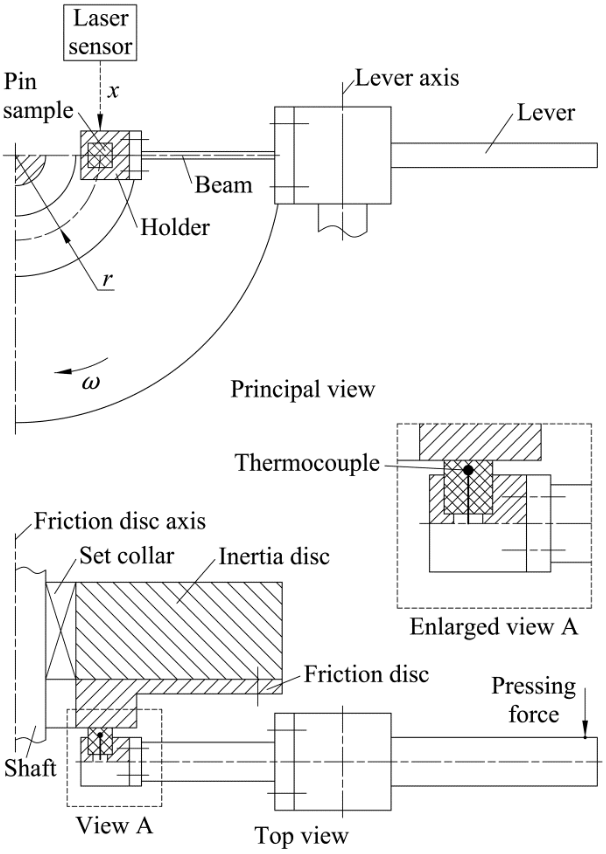

Fig. 1. Schematic of the pin-on-disc machine

The beam has a cross section of 16×2 mm^2 or 16×2.5 mm^2. It has a horizontal orientation. Under the action of the friction force on the pin sample, the beam is deformed and the pin sample moves in the direction tangential to the sliding interface. The tangential displacement x of the pin sample is measured by a laser sensor with a resolution of 0.2 μm. The laser spot, 70 μm in diameter, is focused on the polished upper face of the holder and corresponds to the radius r. The signal from the laser sensor is processed by a data logger with a sampling rate of 1 kHz.

For investigation of the temperature effect, the heating / cooling of the friction pair is provided. A gas burner with controllable gas flow rate is used for heating the inertia disc. The heat of the inertia disc is transferred to the friction disc and then to the pin sample through the sliding interface. The temperature T is measured in the pin sample by a chromel–alumel thermocouple installed at a distance of 2 mm from the sliding surface. The cooling is accomplished by natural convection from the exposed surfaces of the friction pair.

Thus, the adjustable parameters of friction are the contact pressure $p = N/S$, linear disc velocity $v = \omega r$ at the radius r and temperature T.

The pin sample is a non-asbestos organic material code-named SFP04 and used as brake pads in motor vehicles. It comprises barite, zirconium oxide, mica, phenolic resin, carbon, copper fiber, rock wool, brass fiber, etc. The friction disc is steel S275.

3. RESULTS AND DISCUSSION

3.1. Friction Coefficient

The tests are conducted to determine the friction coefficient μ at various values of the sliding velocity v_s and T. To prevent possible oscillation of the pin sample, a resin damper is attached to the beam in these tests. The friction coefficient is calculated as the ratio

$$\mu = kx/N$$

where k is the stiffness coefficient of the beam−holder couple determined experimentally. The 16×2 mm^2 and 16×2.5 mm^2 cross-section beams have k =19 N/mm and k =35 N/mm, respectively.

Fig.2 illustrates the obtained values of μ. As follows from the presented data, μ decreases with v_s, i.e., the friction–velocity slope is negative, and increases with T.

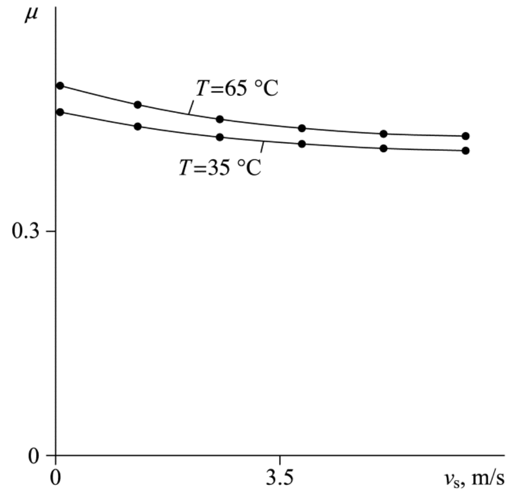

Fig. 2. Friction coefficient μ decreasing with the sliding velocity v_s at p =0.2 MPa

3.2. Oscillation Frequency

When the pin sample slides on the friction disc, one can observe its tangential oscillation, as presented in Fig. 3. The motion of the pin sample has a trajectory close to harmonic. Fig. 4 shows its frequency spectrum obtained by use of the discrete Fourier transform. The spectrum includes two noticeable peaks at f and $\omega/(2\pi)$. The peak at f is dominating. The small peak at $\omega/(2\pi)$ is evidently associated with the oscillation of the disc sliding surface. The tests show that f is 126 Hz for the 16×2 mm^2 cross-section beam and 163 Hz for the 16×2.5 mm^2 cross-section beam.

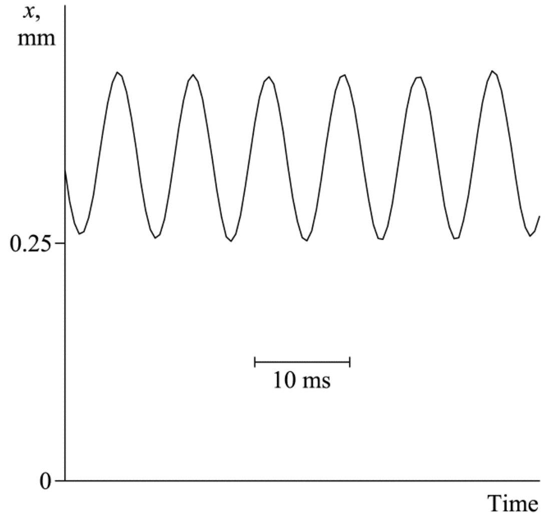

Fig. 3. Harmonic oscillation: 16×2 mm^2 beam, f =126 Hz, p =0.1 MPa, v =1.7 m/s, T =20 ºC

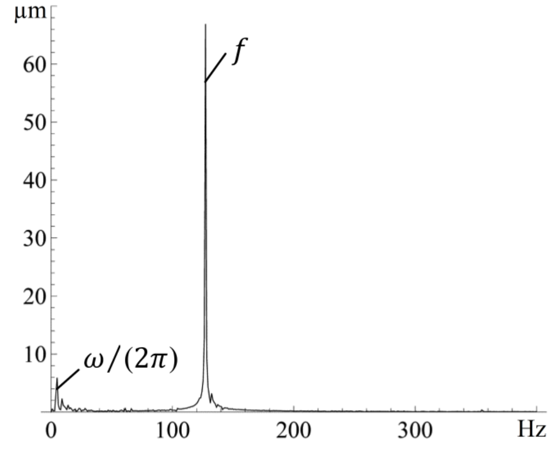

Fig. 4. Frequency spectrum

The evolution of x under the free oscillation of the beam-holder-sample system uninvolved in friction is analyzed. It is found that the frequencies f =126 Hz and f =163 Hz correspond to the first natural frequencies of the systems with the 16×2 mm^2 and 16×2.5 mm^2 cross-section beams, respectively.

Consequently, the observed tangential oscillation of the pin sample is a friction-induced oscillation which is most probably caused by the negative friction–velocity slope and occurs at the first natural frequency of the beam−holder−sample system. The oscillations of such type have been comprehensively studied earlier (see, for instance, Sheng, 2008).

According to the experimental data, if the oscillation occurs, its frequency f is insensitive to the friction conditions. However, the friction conditions influence considerably the oscillation amplitude A. Further, we consider the effects of v and T.

3.3. Disc Velocity Effect

The tests are done at v increasing from zero to some maximum value with a fixed increment each 30 seconds, as shown in Fig.5. One can notice that A increases at each increment of v.

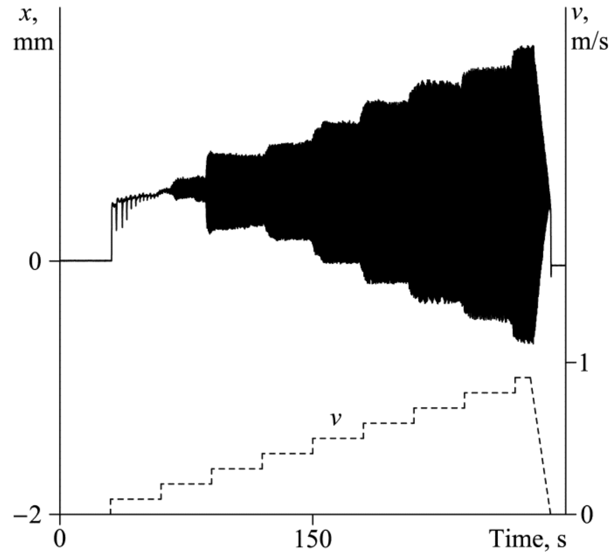

Fig. 5. Oscillation amplitude A increasing with the disc velocity v: 16×2.5 mm^2 beam, f =163 Hz, p =0.1 MPa, T =26–27 ºC

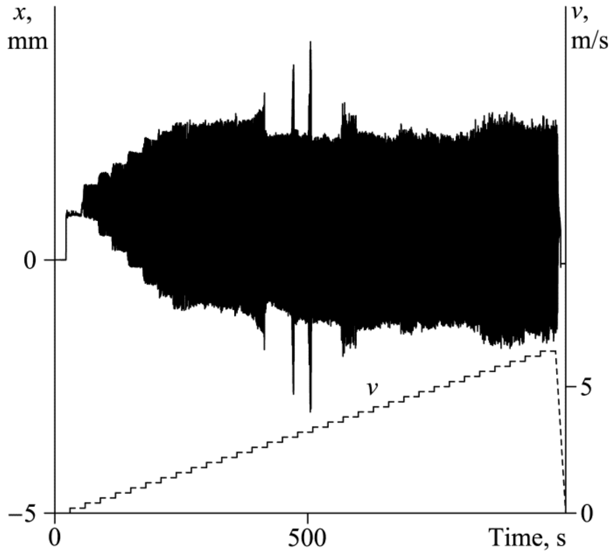

Fig. 6. Unpredictable change in the oscillation amplitude A at v >2 m/s: 16×2 mm^2 beam, f =126 Hz, p =0.2 MPa, T =29–37 ºC

The increase of A with increasing v is observed on the interval of small velocities. When v exceeds a value of about 2 m/s, there is no systematic relationship between v and A, as presented in Fig. 6. This result is testified for both 16×2 mm^2 and 16×2.5 mm^2 cross-section beams.

3.4. Temperature Effect

The influence of the temperature T on the oscillation occurrence is investigated. In the tests, v is constant, while T changes due to the heating / cooling of the friction pair.

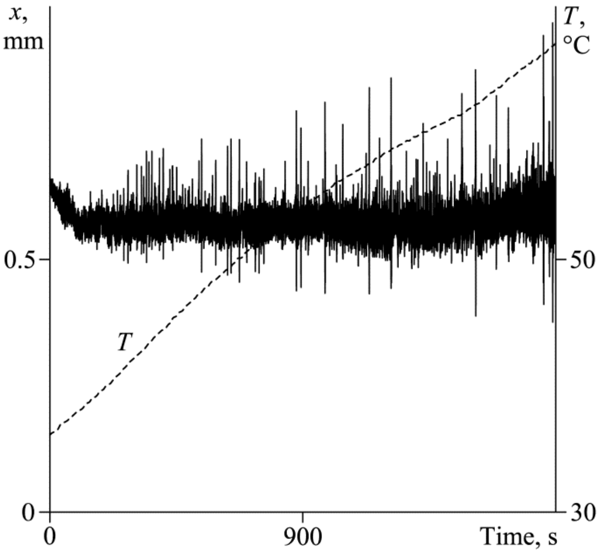

Fig. 7. Change in the sliding character with increasing temperature T: 16×2 mm^2 beam, p =0.2 MPa, v =4.4 m/s

For example, consider the experimental data depicted in Fig. 7. The test uses the 16×2 mm^2 cross-section beam. T increases from 36 to 64 °C. At the beginning of the test, the sliding is almost stable. The observable deviations of the pin sample are insignificant, as shown in Fig.8. In the course of time, T goes up and the instability of sliding in the form of oscillation is excited. At the end of the test, the oscillation occurs with A of the order of 100 µm, as shown in Fig.9.

A test similar to that above is conducted for the 16×2.5 mm^2 cross-section beam. The relation between T and the variation range of A is determined on the temperature interval of 20−56 °C. Fig.10 shows the obtained result. It is seen that at T = 20−29 °C $A = 0$, that is, the sliding is stable. When T = 29−48 °C, the oscillation may occur or decay unpredictably. Finally, if T exceeds 48 °C, the oscillation occurs continuously in time with A of the order of 20 µm. There is a clear trend of increasing A with T.

The two tests described are in agreement between each other. They reveal qualitative changes in the character of sliding caused by temperature variations. Note that these changes are reversible, i.e., at the stage of cooling, when T goes down, the oscillation amplitude A decreases and the oscillation can decay completely.

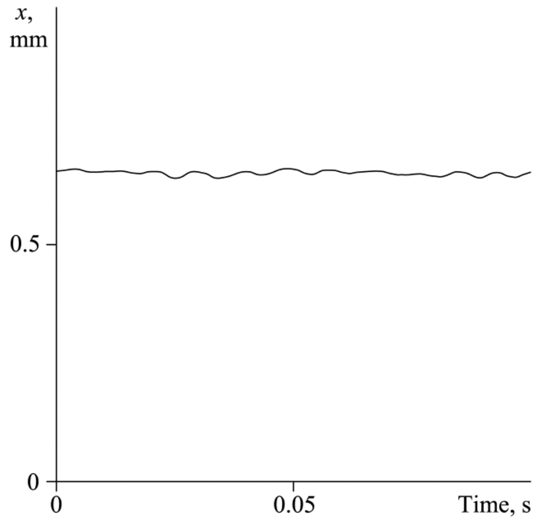

Fig. 8. Stable sliding with insignificant deviations at T =36 °C

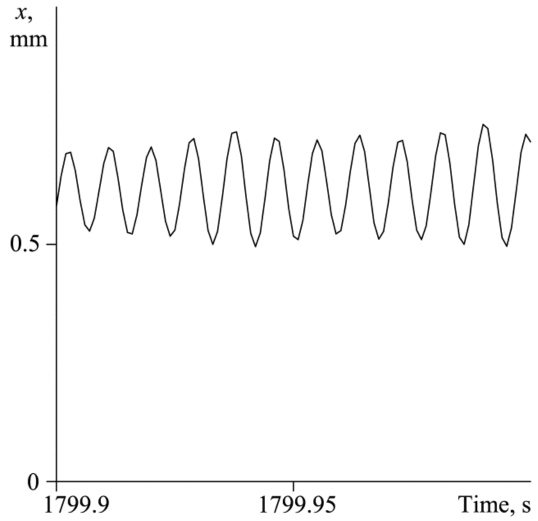

Fig. 9. Occurrence of oscillation at T =64 °C

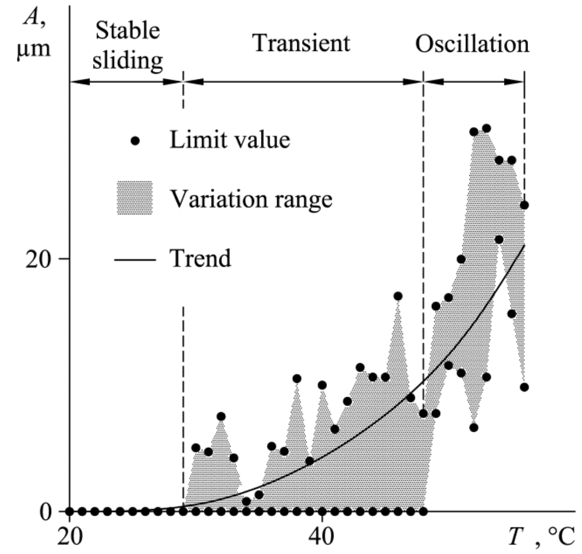

Fig. 10. Variation in the amplitude A depending on the temperature T: 16×2.5 mm^2 beam, p =0.2 MPa, v =4.4 m/s

4. CONCLUSIONS

An experimental study of friction-induced oscillations of a non-asbestos organic pin sample sliding on a steel disc has been done. The main results of the study are presented below.

1. The friction-induced tangential oscillation of the pin sample occurs at the first natural frequency of the supporting beam.
2. The oscillation amplitude increases with the disc velocity on the interval of velocities below 2 m/s. At higher velocities it changes unpredictably.
3. Temperature changes of several tens of degrees Celsius result in the oscillation occurrence / decay.

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