ON STUDY OF PHENOMENA IN THE WHEEL - BRAKE SHOE CONTACT AREA[1]

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Abstract

The paper comprises the results of experimental investigation and of numerical simulation on the phenomenon of the wheel corrugation generated during braking with a brake shoe.

Keywords: dry friction, brake-shoe.

1. Introduction

Motional resistance of adjoined surfaces of interacting elements depends on many parameters. Universal theory of friction which would enclose friction resistances of free joined elements would have to consider assumptions from physics, chemistry, knowledge of commercial materials, heat treatment and mechanical continuity. There has not been such a formulation so far.

In this work are shown the selected results from author's works in the case of simultaneous acting of wheel and brake shoe, which include the experimental research and numerical simulation.

2. Hypotheses of Dry Friction of Solid Bodies

In the process of dry friction, one can mark off a sphere of relative static (static friction) and a sphere of macroscopic motion (sliding friction).

AMONTOS (1699) postulated proportion of friction force and normal force

$$F_T = \mu F_N \,. \tag{1}$$

COULOMB (1795) showed the difference between static and kinetic friction. Principle of static friction in Coulomb's opinion presents itself in the following formula:

$$|F_T| \le \mu_0 F_N \,, \tag{2}$$

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where:
F_T – friction force,
μ_0 – coefficient of static friction or coefficient of adhesion,
F_N – normal force.

The experimental investigation shows that the coefficient of static friction depends on two parameters:

- time of contact t_U, STEPANEK (1957),
- speed with which tangent force F_T acts,

$$\dot{\Theta} = \frac{\dot{F}_T}{F_N},$$

JOHANES (1973). Experimentally marked dependence, which defines the friction force in equation

$$|F_R| \leq \mu_0 \left(t_U, \Theta\right) F_N$$

does not appear in literature.

Division of the friction into adhesion and sliding is based on the principle of mutual attachment of rigid bodies. The mutual principle for rigid bodies allows the division between the state of rest and slide, while in the case of really elastic bodies certain micro-motions can be observed in the area of quiescence at the instant of tangential force action. The measurements of static friction are in a way similar to measurements of sliding friction at low speed. For this reason, many authors do not consider static friction, SIMKINS (1967), SARGENT (1974). The division into areas of tenacity and slide is an ideal consideration approximating the real peculiarities. Decision whether the friction line is considered as constant or mutable should be accepted not dogmatically but according to the formulated point. Such a procedure will be realized in this work. Non-linear segments of friction will be replaced by linear segments. Differences which are results from replacing the non-linear diagrams by linear ones can be regarded as unimportant. The sliding friction is the result of the relative motion of two elements top layer being in contact. According to Coulomb elementary theory, coefficient of sliding friction μ is independent from the value of relative speed. The affecting direction of vector $\mathbf{F}_T$ of friction force depends on the affecting direction of relative speed $\mathbf{v}_r$

$$\mathbf{F}_T = -\mu F_N \frac{\mathbf{v}_r}{|\mathbf{v}_r|}, \tag{3}$$

whose numerical value is calculated according to formula (4)

$$F_T = -\mu F_N \operatorname{sgn}\left(v_r\right). \tag{4}$$

The sliding friction is defined, first of all, by basic processes of adhesion and by elastic and plastic deformations. During relative motions, the following phenomena take place: elastic and plastic deformations in the top layers of irregularity, tear of bridges being welded in cold and also cutting off the materials heights. All inherent actions rising at the point junction cause the formation of resistance forces. As a result of dissipating energy at the point of junction, the temperature rises and it influences the friction force. The dependence of the friction force on the relative speed and the normal force for quasi-stationary conditions is described by *Eq.* (3). With rising relative speed, the time of contact of the adjoined top-layer areas will decrease, which causes decline of friction force. This dependence is included in equation which shows the coefficient of friction as a function of speed, $\mu = \mu(v_r)$ — KRAGIELSKI (1968) formula (5)

$$\mu = 0.6 \cdot \frac{16k + 100}{80k + 100} \cdot \frac{100}{30v + 100}, \tag{5}$$

where:
k – compressive force of cast-iron block on the wheel measured in [Mp]
v – speed in [km/h].

In the BOWDEN and LEBEN's (1939) and BOWDEN and TABOR's (1939) papers, attention is paid to the fact that slide of rigid body on the ground will not occur smoothly but as a step function. If friction force is increasing with the decline of relative speed, then self-excited vibrations will arise, which are called stick-slip vibrations.

3. Stick-Slip Friction

The fundamental phenomena in the adhesion-slide process can be explained by the body motion, which is stimulated to vibrations by the contact with the moving band, *Fig. 1*. The friction between the body mass and moving band is described by *Eq.* (4). The coefficient of friction μ depends on the relative speed (6)

$$\mu(v_r) = \begin{cases} \mu_0 & \text{for} \quad V_r = 0 \\ \overline{\mu} & \text{for} \quad V_r \neq 0 \end{cases}, \quad \mu_0 \geq \overline{\mu}. \tag{6}$$

To describe the mass motion (*Fig. 1*), the differential equation of the second order is used:

$$mX'' + dX' + cX = \mu F_N \operatorname{sgn}\left(X' - V\right), \tag{7}$$

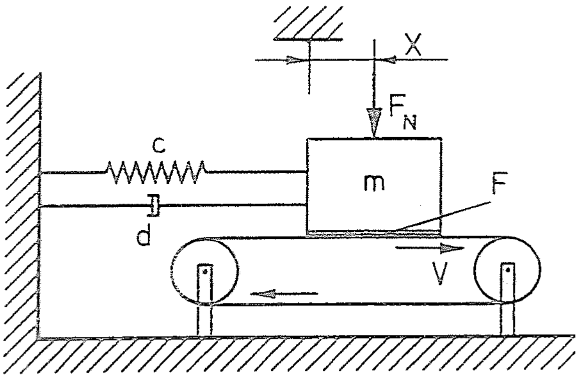


Fig. 1. Typical mechanical system representative for a friction measuring system

where m is the mass, d the damping coefficient, c the stiffness coefficient and F_N the normal force. The speed of band V is contained in this equation in the statement of friction coefficient.

It's easy to present analysis by taking advantage of dimensionless coordinates. It enables decreasing a number of system parameters. For this purpose, we choose time unit $\tau_0 = \sqrt{m/c}$ and force unit F_0. It can be, for example, weight of the body or normal force. The choice of the unit enables the normalization of friction models.

Let us introduce the following dimensionless values:

$$\tau = \tau_0 t \,, \qquad x = \frac{cX}{F_0} \,,$$

$$\gamma = \sqrt{\frac{d[\mathrm{cm}]}{2}} \,, \qquad v = \sqrt{\frac{V[\mathrm{cm}]}{F_0}} \,,$$

$$\delta = \frac{F_0 \omega_0}{c} \Longleftrightarrow v = \frac{V}{\delta} \,, \qquad \mu \left\{ \delta \left(x' - v \right) \right\} = \frac{\mu F_N \left(X' - V \right)}{F_0} \,.$$

After introducing these values into *Eq.* (8), the following is obtained:

$$x'' + 2\gamma x' + x = \mu \left(\delta \left(x' - v \right) \right) \operatorname{sgn} \left(x' - v \right) \,. \tag{8}$$

The parameters of *Eq.* (8) are:

$\mu(V)$ – friction model

γ – dimensionless damping

v – dimensionless speed of the band

Function $\mu(V)$ describes the model of friction. We will consider functions $\mu(V)$ corresponding to characteristics investigated experimentally by the author. It is assumed that function $\mu(V)$ is antisymmetric, continuous and linear in some segments. During numerical simulation, it is turned out that the non-linear model could be described by a linear one of big slope for $v_r = 0$. Such a model is simpler for mathematical analysis and programming.

4. Results of Experimental Investigation

The experiments of braking with two types of brake-shoes has been made on the stand (*Fig. 2*), where the investigated elements have standard dimensions. Experiments consider: one type of wheel and brake-shoes made from two different materials was used; traditional cast-iron P6 (W_1) and pressed from metal powders on the base of copper (Ws). On the base of experimental investigation, curves of friction coefficient function of speed were plotted — *Fig. 3*.

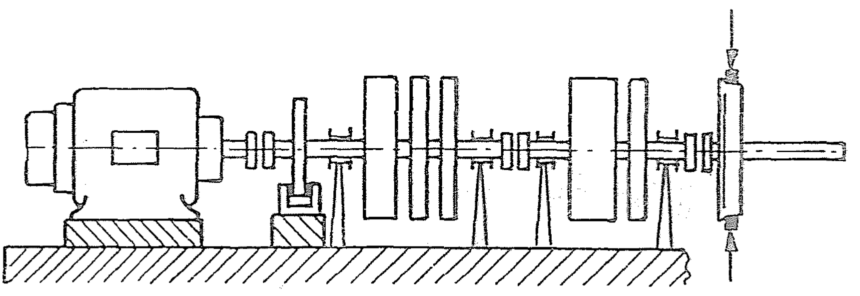


Fig. 2. Experimental stand

Macro-picture of wheel surface (after braking trial with shoe W_1 with initial speed 100 km/h — to stop, and shoe pressure on wheel 4 kPa, after 10 seconds of braking) showed clear mark of influence of friction stick-slip, *Fig. 4*. After braking trial with shoe Ws (with the same pressure and speed during braking), no stick-slip was observed.

Spectral analysis made by author shows that when applying the shoe W_1, self-excited vibrations of the elements in frictional contact are about 100 times greater in comparison with the self-excited vibrations of the elements with the shoe Ws, *Fig. 5*.

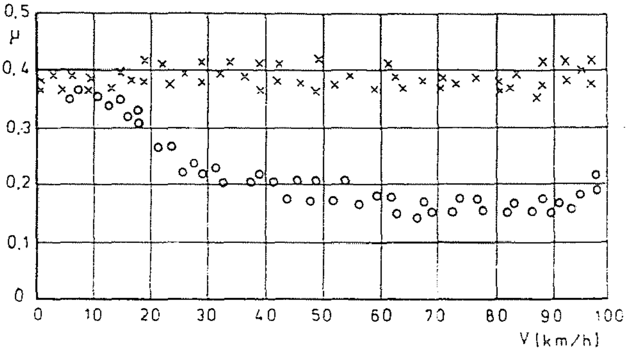


Fig. 3. Friction coefficient (experimental)
o – material of shoe W_1
× – material of shoe Ws

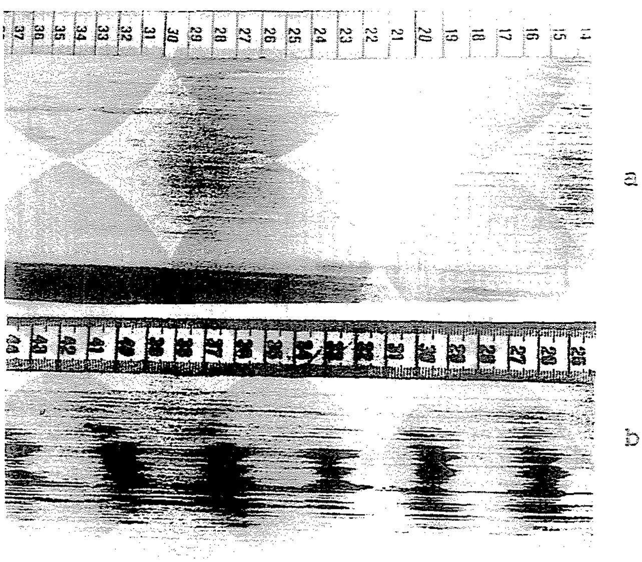


Fig. 4. General view of frictional surface of wheel sector; *a*) before braking with the shoe W_1 and *b*) after braking with visible influence of stick-slip friction

In the material of shoe Ws braking the self-excited vibrations is not reckoned with. There is no change in the wheel frictional surface.

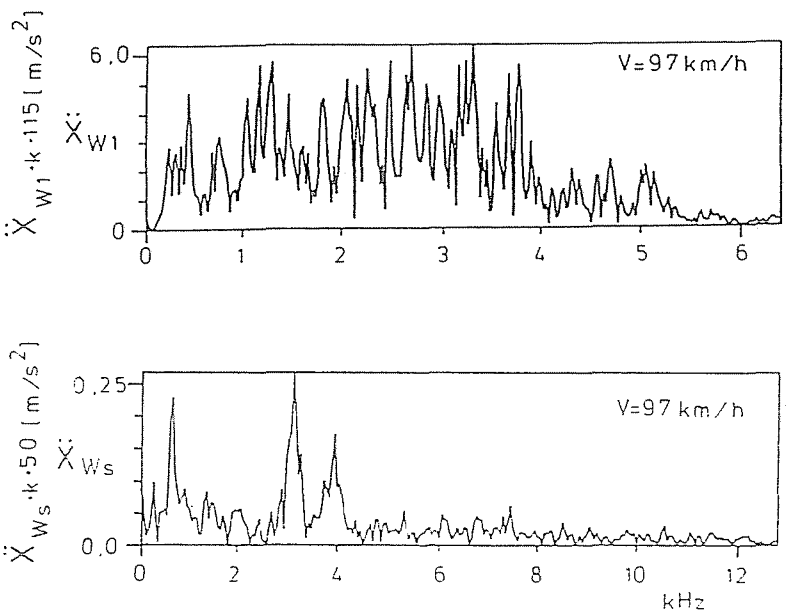


Fig. 5. Spectrum of tangential accelerations of the brake shoe W_1 and Ws during braking from velocity 100 km/h to stopping, in case the pressure of the shoe is equal to 4 kPa

5. Results of Numerical Simulation

The diagrams of friction coefficient versus velocity shown in *Fig. 5* can be written by formulas (9) and (10), respectively:

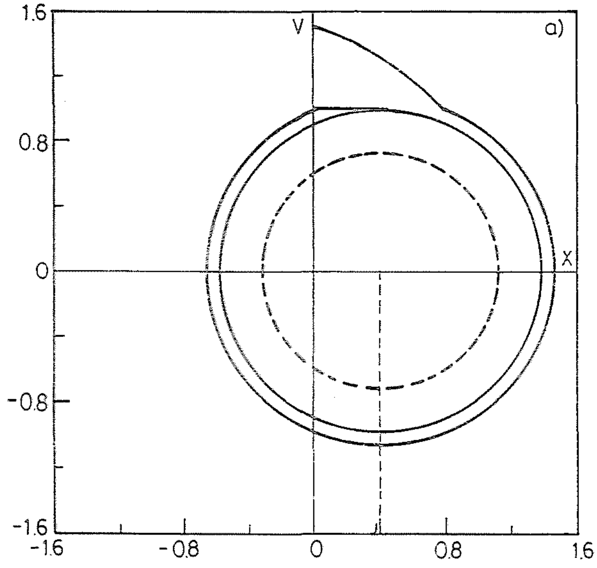
a, for material Ws

$$\mu_s(v_r) = \begin{cases} \mu_0 & \text{for } V_r = 0\,, \\ \overline{\mu} & \text{for } V_r \neq 0\,, \end{cases} \tag{9}$$

b, for material W_1

$$\mu_1(v_r) = \begin{cases} \mu_0 & \text{for } V_r = 0\,, \\ \dfrac{\mu_0 - \mu_*}{1 - \alpha|v_r|} + \mu_* + \beta v_r^2 & \text{for } V_r \neq 0\,, \end{cases} \tag{10}$$

where
$\mu_0 = 0.4$
$\overline{\mu} = 0.4$
$\mu_* = 0.1$
$\alpha = 0.2\ [\mathrm{sm}^{-1}]$
$\beta = 0.00005\ [\mathrm{s}^2\mathrm{m}^{-1}]$.



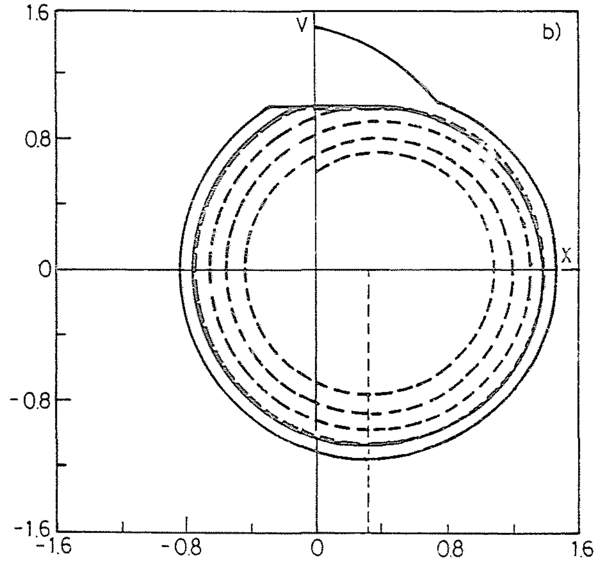


Fig. 6. Phase-plane for the processes of analyzed system (*Fig. 1*) by applying the brakes; a – Ws, b – W_1

Solution of *Eq.* (7), showing system performance (*Fig. 1*) for friction coefficient (*Fig. 3*) given by formulas (9) and (10) and for damping coefficient $d = 0$, is shown by phase-plane in *Fig. 6* for shoes Ws and W_1.

The result of phase-plane analysis shows that during braking with shoe W_1, the limiting cycle appears, in which the time of stick and slip can be distinguished.

6. Final Remarks

The experimental investigations as well as the numerical simulation show that stick-slip friction does not crucially affect the interaction of frictional elements if the value of static friction coefficient is smaller than or equal to the value of sliding friction coefficient. In our case, it is equivalent to better properties of shoe Ws material in damping the self-excited vibrations (*Fig. 5*).

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