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Research paper

Analysis of selected friction properties with the Froude pendulum as an example

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ABSTRACT

The paper presents the method of friction parameters identification of the shaft-sleeve kinematic pair with the Froude pendulum as an example. Experimental and numerical tests covered the range of a small relative displacement of frictional pairs at which the hysteresis friction effects appear as well as the range of significant sliding velocities when the frictional force value results from the static relation to the friction coefficient characteristics. The pendulum motion description has involved a modified LuGre model, in which the Stribeck curve was replaced by cubic b-spline curve to enable the complex course approximation of friction coefficient characteristics. The specific behaviours of the pendulum motion observed during the experimental tests have been reproduced by simulating the modified LuGre model. Moreover, the numerical tests have demonstrated that the radial pendulum clearance up to 0.1 mm causes high-frequency oscillation, not substantially affecting the pendulum trajectory and sliding velocity.

1. Introduction

Friction is a complex and nonlinear phenomenon common in all mechanical systems. In some mechanism solutions, friction is at the core of operation. The key characteristic of friction is the friction force that opposes the relative motion of the bodies in contact. The force is tangent to the contact surface of the bodies, its direction is consistent with the sliding velocity, and it shows an opposite sense relating to that velocity. This information is basic and it has been known for a long time [1,2]. However, the nature of friction force formation is not yet sufficiently understood, despite long-term and intensive work by scientists in numerous research centres around the world [3–7].

Currently the models describing the path of frictional forces can be divided into two major groups [8–14]: static and dynamic. Static models are based on the Coulomb model, e.g.: the Karnopp model [15], the Quinn model [11], the Kikuuwe model [11], the Awrejcewicz model [16], the Wojewoda model [17]. Whereas the dynamic models, e.g.: the LuGre model [18,19] the Leuven model [20,21], the GMS model [22–25], are derived from the Dahl model.

This division results from the method of friction modelling in static friction state.

In the traditional static models it is assumed that in static friction phase the sliding velocity of rubbing bodies is equal to zero, at which the friction force is discontinuous. Therefore the friction force balances all the external forces acting on the body, making the body motionless. In kinetic friction conditions, when the sliding velocity is different from zero, the friction force assumes a value resulting from a static mapping of the friction coefficient (usually dependent on the

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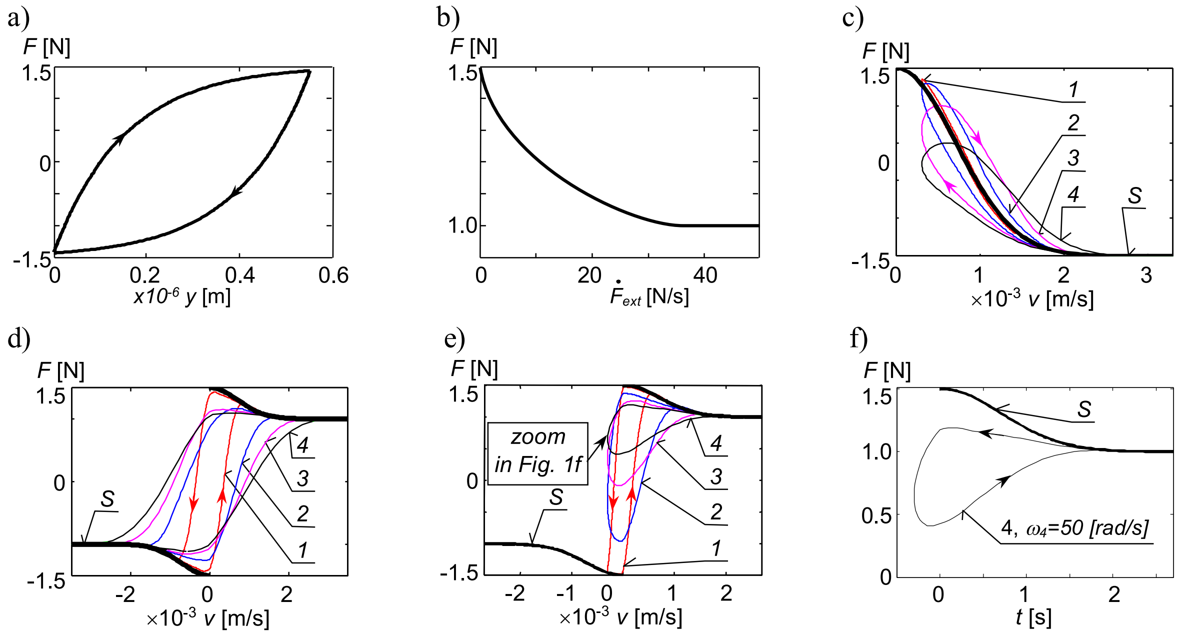

Fig. 1. Hysteresis effects of friction in the LuGre model: (a) pre-sliding displacement, (b) breakaway force, (c) frictional lag, (d) stick-slip, (e) stick-slip at asymmetric sinusoidal sliding velocity, (f) magnified detail of Fig. 1(e); *S*—Stribeck curve, 1–4—angular frequency in sinusoidal input function of sliding velocity, respectively: $\omega_1 = 2$ rad/s, $\omega_2 = 10$ rad/s, $\omega_3 = 25$ rad/s, $\omega_4 = 50$ rad/s; LuGre model parameters [12]: $F_s = 1.5$ N, $F_c = 1$ N, $v_s = 0.001$ m/s, $\sigma_0 = 10^5$ N/m, $\sigma_1 = (10^5)^{0.5}$ Ns/m, $\sigma_2 = 0$ Ns/m, $m = 1$ kg, $\delta_{vs} = 2$.

sliding velocity). The advantage of the static models is their simplicity and intuitiveness, and the drawback—the difficulty in numerical simulations of bodies motion at sliding velocities close or equal to zero [17].

Dynamic models assume a slight presliding displacement in static friction conditions [26]. This ensures a continuous transition between the static and kinetic friction states. In the static friction state a dominant role in friction force formation is played by adhesion forces; the friction force is more of a function of displacement than sliding velocity. This effect is due to the elastic-plastic deformations of the surface asperities of adjacent bodies, behaving like nonlinear springs. The greater the deformations, the more connections between asperities break, causing slippage. In the sliding friction regime, all the connections between asperities are broken and the friction force becomes a function of sliding velocity, as in typical static friction models.

Dynamic models (as opposed to static models) allow for recreating the processes known from experiments [12] which occur in the static friction regime and at very low sliding velocities. Exemplary hysteresis effects of friction phenomenon determined based on the LuGre model (Eq. (1)) are shown in Fig. 1.

$$\begin{cases} F = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 v \\ \dot{z} = v - \frac{\sigma_0 |v|}{s(v)} z \\ s(v) = F_c + (F_s - F_c) \exp\left(-(v/v_s)^{\delta_{vs}}\right) \end{cases} \tag{1}$$

where:

$s(v)$—Stribeck's curve in the function of sliding velocity v,
σ_0—asperity stiffness,
σ_1, σ_2—damping coefficients relating to the presliding and kinetic friction states, respectively,
z—state variable interpreted as elastic deformation of surface asperities of adjacent bodies,
v_s—Stribeck's velocity,
F_s, F_c—static friction force and Coulomb friction force, respectively,
δ_{vs}—Stribeck curve shape factor

Fig. 1(a) shows a hysteresis loop of the friction force produced in the presliding displacement range of the rubbing bodies. Fig. 1(b) illustrates a graph representing the break-away force, i.e. the relationship between the maximum static friction force and the increase rate of external forces causing the slip. According to the graph, the higher the increase rate of external forces, the lower the required force causing the static friction "breaking". Thus, in order to register force F_s used in the Stribeck curve (Eq. (1)), the increase rate of the external force $\dot{F}_{ext}$ should be very low. As for low sliding velocities of constant sense, frictional lag is revealed (Fig. 1(c)), and as for low sliding velocities of alternating sense, it is the stick-slip which is identified (Fig. 1(d)). An interesting stick-slip course occurs in the case of asymmetric sinusoidal sliding velocity