EXPERIMENTAL DETERMINATION OF MECHANICAL PROPERTIES OF TEXTILE AND ELASTOMER MATERIALS BY VIBROTECHNICAL METHODS

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Abstract. The use of soft and flexible materials in technology, transport, and everyday life is well known. Mechanical properties such as slip and rolling friction play an important role in the manufacture of such objects. It appears as objects slide along each other. High friction is desirable in some objects, although high wear will be expected, in others, it is desirable to reduce friction. The study considers the possibility of experimentally determining some important mechanical properties of soft materials (textiles, elastomers). For this purpose, the forces of interaction between objects made of the same or different materials during their mutual motion are analyzed. From the analysis two physical parameters have been chosen as the estimation of the mechanical properties for the materials: the coefficient of sliding friction and the coefficient of rolling friction. For the identification of each parameter, the corresponding experimental rigs were dynamically studied. First, the oscillatory motion of a physical pendulum along an inclined plane with large angle of inclination, when the motion is damped by a constant sliding friction force, is studied. It is shown that by changing the initial conditions it is possible to synthesize a wide range of damped oscillations, from one half-cycle to five and more cycles. By measuring the angle at the starting position of the pendulum and the angle at the subsequent stopping position (after one oscillation cycle), an analytical formula for determining the coefficient of sliding friction was obtained. Then, the rolling friction coefficient was determined from the motion of the object along an inclined plane with a small angle of inclination. The moving object is designed as a platform on wheels. Two parameters were used to identify the rolling friction coefficient: the angle of inclination of the plane and the angle between the direction of motion of the object and the horizon. In addition, it has been shown that the rolling friction coefficient can also be determined with the above-mentioned physical pendulum rig. The results obtained in the work can also be used to identify the mechanical properties of non-soft materials. The main goal of the study is to obtain a theoretical justification for three new prototypes of experimental rigs for identifying the friction parameters of materials.

Keywords: textile materials, elastomers, sliding friction, rolling coefficient.

Introduction

In the manufacture of textile fabrics or more complex structures, one of the estimates of the contact surface may be the coefficient of sliding friction. In some cases, it is desirable to reduce this factor, in others to increase it. Accordingly, this factor depends on the fabric material and the pattern of manufacture. This means that experimental methods are needed to determine this physical property [1-10]. It is also important to determine the coefficient of sliding friction when making objects of “soft” materials (elastomers, rubber, plastics, etc.) [11-16]. Experimental evaluations sometimes need to determine additional physical parameters that characterize rolling friction [17-19]. In existing experimental studies, the coefficient of sliding friction is mainly determined using flat objects, a dynamometer, and a horizontal plane. It is proposed to use an inclined plane. Then, one can measure the angle at which the motion begins. An inclined plane also is suggested to use for determination of the coefficient of rolling friction, but in this case a wheeled platform is used as an object. In most such techniques, the coefficient of friction at rest is determined. To determine the coefficient of sliding friction, a much more complex experimental rig is required, in which the objects move, and it is necessary to observe the velocity of motion. The following study proposes some very simple, inexpensive methods for determining the coefficients of friction. The methods under consideration use the approaches of vibro technique, by taking the parameters of the damped oscillations of an object on inclined plane. The main difference between the proposed methods and the existing methods [1-19] is that different initial conditions and several cycles of oscillations are used for the identification. The proposed methods allow to determine both the coefficients of sliding friction and coefficients of rolling friction.

Model for determining the coefficient of sliding friction

The model considered in this paper for determining the coefficient of sliding friction on an inclined plane is shown in Figure 1.

The experimental rig consists of a vertical plane 1, a horizontal plane 2, and an inclined plane 3. A slider 5 is attached to one end of the connecting rod 4, the other end of which is attached to the inclined plane 3 (Fig.1). The inclined plane 3 is placed at the angle α to the horizon. This angle is a variable parameter during an experiment. The rod 4 can rotate around a hinge A, its position is described by the angle φ. The motion starts from rest with the initial angle of the connecting rod is $\varphi 1$. The slider 5 starts a sliding oscillatory motion along the inclined plane 3. In one cycle, if possible, the slider stops at the position $\varphi 2$. Knowing the system parameters and angles $\varphi 1$, $\varphi 2$, it is possible to determine the coefficient of sliding friction *f* with a very simple formula. This is discussed below.

The given mechanical system has one degree of freedom, which is described by the angle of rotation of the connecting rod φ. Irrespective of the air resistance and friction in the hinge, the differential equation of motion is as follows (Fig. 2), [1]:

$$J_A \cdot \ddot{\varphi} = -m \cdot g \cdot \sin(\alpha) \cdot d \cdot \sin(\varphi) - R \cdot L \cdot \mathrm{sign}(\dot{\varphi}), \tag{1}$$

where J_A – moment of inertia of the slider-rod system about the hinge A;
$\ddot{\varphi}$, $\dot{\varphi}$, φ – angular acceleration, angular velocity, and angle of the connecting rod;
m – total mass of the rod and slider;
g – acceleration due to gravity;
d – radial coordinate of the center of gravity of the rod-slider system;
α – angle of inclination of a plane;
R – slider dry friction force;
$\mathrm{sign}(\dot{\varphi}) = \pm 1$, where the "+" sign is used for a positive angular velocity $\dot{\varphi}$ and the "–" sign for a negative angular velocity $\dot{\varphi}$ (Fig. 2).

Since the rod and the slider rotate about a fixed axis Y1, the slider interacts with the inclined plane, the normal reaction *N* and the friction force can be determined as follows (2):

$$N \cdot L = m \cdot g \cdot \cos(\alpha) \cdot d; R = f \cdot N, \tag{2}$$

where f – sliding friction coefficient.

From the expressions (1), (2) we obtain the following differential equation of motion (3):

$$J_A \cdot \ddot{\varphi} = -m \cdot g \cdot d \cdot [\sin(\alpha) \cdot \sin(\varphi) - f \cdot \cos(\alpha) \cdot \mathrm{sign}(\dot{\varphi})]. \tag{3}$$

That nonlinear differential equation (3) can be integrated at given initial conditions numerically or analytically by harmonizing the integration steps when the angular velocity $\dot{\varphi}$ changes sign. Some phase graphs are shown in Fig. 3 and Fig. 4. Parameters are given below each image in system SI.

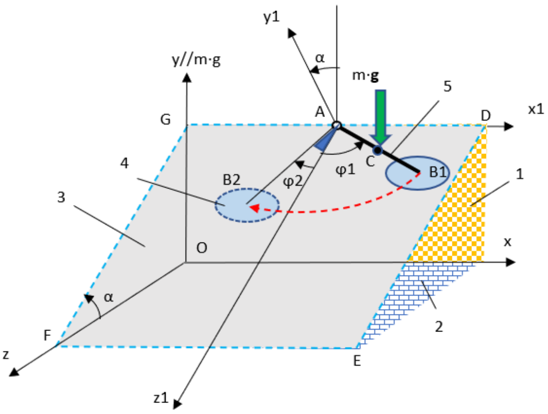

Fig. 1. **Scheme of the experimental rig:** 1 – vertical plane; 2 – horizontal plane; 3 – inclined plane; 4 – slider; 5 – connecting rod

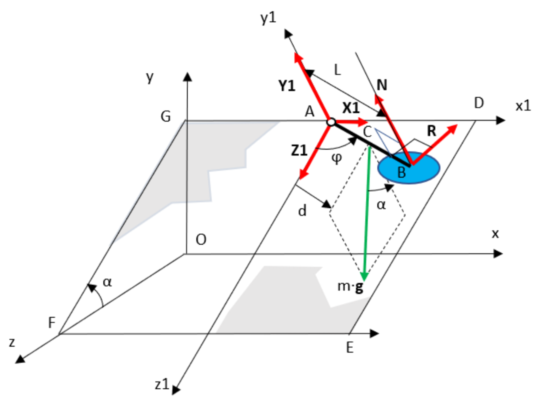

Fig. 2. **Free body diagram:** $m{\cdot}g$ – weight; R – dry friction force; N – slider normal reaction; X1, Y1, Z1 – smooth spatial hinge reaction components; O,x,y,z – fixed coordinate system; A, x1,y1,z1 – inclined plane coordinate system; d – radial coordinate of the center of gravity of the slider-rod system; L – radial coordinate of the slider

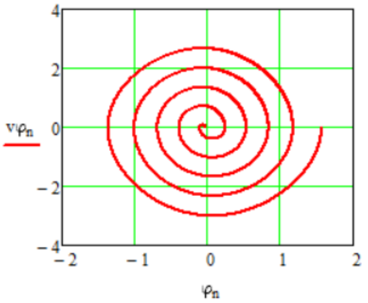

Fig. 3. **Numerical results of oscillatory motion on the phase plane in system SI (φ – angle; $v\varphi$ – angular velocity):** $m{\cdot}g{\cdot}d{\cdot}J_A^{-1}$ = 5.144; f = 0.2; α = 1.222; $\varphi 1 = \pi{\cdot}2^{-1}$

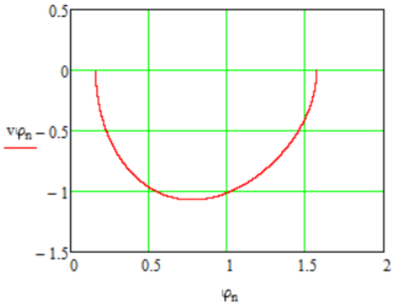

Fig. 4. **Half-cycle motion of the slider on the phase plane:** $m{\cdot}g{\cdot}d{\cdot}J_A^{-1}$ = 5.144; f = 0.7; $\alpha = \pi{\cdot}4^{-1}$; $\varphi 1 = \pi{\cdot}2^{-1}$, $\varphi 2$ = 0.159

For certain combinations of parameters α, $\varphi 1$, $\varphi 2$, and f there is one half-cycle motion from one rest position to the next rest position (Figs.1,4). In this case, analytically integrating equation (3), the coefficient of sliding friction f can be found by the following formula (4):

$$f = \frac{\tan(\alpha)[\cos(\varphi 2) - \cos(\varphi 1)]}{\varphi 1 + \varphi 2}. \quad (4)$$

The friction coefficient at rest $f0$ can be found from the differential equation (4) by the boundary values of parameters when the motion of the slider begins. Then we get (5):

$$f0 = \tan(\alpha 0) \cdot \sin(\varphi 0), \quad (5)$$

where $\alpha 0$, $\varphi 0$ – angles when the slider starts the motion during the experiment.

Model for determining the coefficient of rolling friction by frame on wheels

The basic scheme of the model is given in Fig. 5. An inclined plane with an angle of inclination α is used to determine the coefficient of rolling friction. A frame with four identical wheels is placed on the inclined plane. The angle of motion direction of the frame with respect to the inclined plane is β. The angle β is changed during an experiment from zero to the angle value when the rolling down of the frame begins. As before, we do not repeat the differential equation of motion of a system with one degree of freedom. At the point when the motion begins (6):

$$fr = \frac{\delta}{r}\tan(\alpha) \cdot \sin(\beta), \quad (6)$$

where δ – rolling friction coefficient with length dimension;
r – wheel radius;
fr – dimensionless rolling friction coefficient;
α – angle of inclination of the inclined plane; β is the angle of motion onset (Fig. 5).

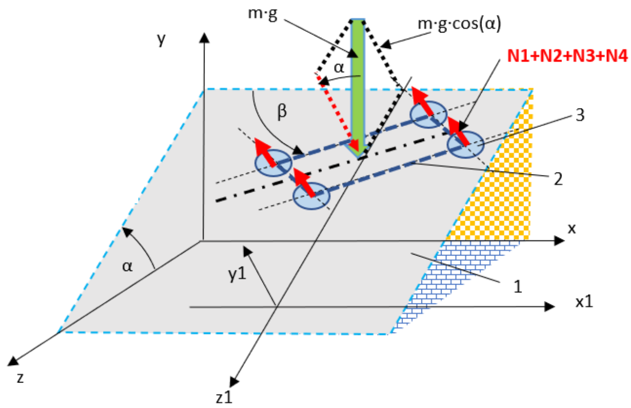

Fig. 5. **Rolling friction identification model by frame on wheels:** 1 – inclined plane; 2 – frame; 3 – four wheels; N1 + N2 + N3 + N4 – normal reactions of the wheels; m·g – total system weight

Model for determining the coefficient of rolling friction by ball

Model for determining the coefficient of rolling friction on an inclined plane by means of a rolling ball is shown in Figure 6.

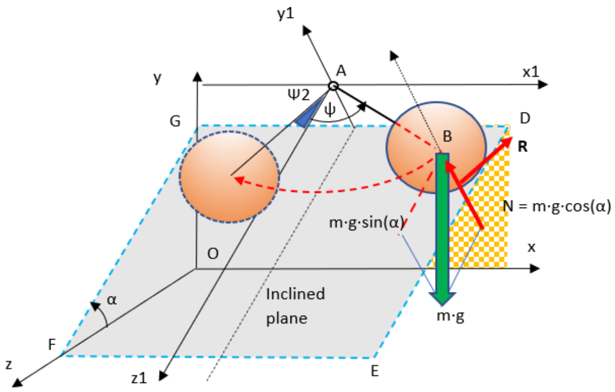

Fig. 6. **Rolling friction identification model by ball**

It is proposed to use a model similar to the one for determining the coefficient of sliding friction (Fig. 1). The main difference is that instead of a sliding object, a rolling object, such as a ball, must be used. The ball must be attached to the inclined plane in such a way that the axis of its connecting rod or the thin string moves parallel to that plane. In the case of a string, the requirement is that there is only one degree of freedom of motion described by the angle ψ (Fig. 6). If such motion does not take into account the resistance of the air and the effect of the gyroscopic moment of the ball rolling on the normal reaction, the differential equation of motion is similar to the equation (4). We do not consider this equation here, but give a ready-made formula for determining the rolling friction coefficients in the following form (7):

$$fr = \frac{\delta}{r}\tan(\alpha)\cdot\frac{\cos(\psi 2)-\cos(\psi 1)}{\psi 1+\psi 2}, \tag{7}$$

where δ – rolling friction coefficient with length dimension;
r – sphere radius;
fr – dimensionless rolling friction coefficient;
$\psi 1$ – angle of the ball at the beginning of the motion from the rest position;
$\psi 2$ – angle of the ball at the end of the motion at a stop when there is a half-cycle oscillation (Fig.4).

Results and discussion

1. Simple analytical formulas for determination of the coefficients of sliding and rolling friction were obtained.
2. The obtained analytical expressions can be used to study friction interactions of the objects made of the same material, as well as different materials.
3. A methodology for the analysis of slipping and rolling interactions on flat, cylindrical, and spherical surfaces has been developed.
4. The developed methodology and experimental models allow us to determine the average values of friction interaction in certain ranges of sliding and rolling friction velocities.
5. The methodology is applicable to the identification of the friction properties of textile and rubber materials, as well as to the study of the interaction of any two friction pairs, for example: metal-textile; metal-rubber; metal-ice; rubber-ice; rubber-asphalt [20-23].
6. The main scientific result of the work is that the three new methods for the identification of sliding and rolling friction parameters have been proposed and developed, in which half-cycle or several-cycle decaying oscillations are used.
7. The proposed methods for the identification of friction parameters of materials expand the knowledge in the field of application of damped oscillations to practical purposes.

Conclusions

1. Interaction of two bodies of same or different materials in terms of sliding and rolling friction can be experimentally identified by means of an inclined plane and object sliding or rolling on it.
2. Using the theorem of the change in kinetic energy simple formulas for determining of the sliding and rolling friction coefficients are obtained.
3. The proposed experimental identification methods significantly increase the accuracy of obtained values of the friction coefficients, in that the result depends not just on the measurement of the angle of inclination of the inclined plane, but also on other adjustable parameters.
4. The proposed methods are very simple and cheap; it requires only the few angles to be measured.
5. In further studies it is planned to supplement the considered prototypes with angle measuring devices and to study in more depth the accuracy of determination of friction parameters at different numbers of oscillation cycles.

Author contributions

Writing-review and editing, S. Sokolova and J. Viba; conceptualization, O. Kononova; methodology, O. Kononova, and J. Viba; software, U.H. Vavaliya. All authors have read and agreed to the published version of the manuscript.

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