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EXPERIMENTAL DETERMINATION OF DYNAMIC COEFFICIENT OF AMONTON-COULOMB DRY FRICTION

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Abstract. *The purpose of the study is to experimentally determine the dynamic coefficient of dry friction between different materials under vibrations due to the initial deflection. The principle of dry friction between the grillage and the foundation is used for the seismic isolation of buildings and structures. A measuring complex with corresponding strain-gauge measuring channels was prepared on the laboratory one-component shaking stand to record the relative and absolute displacements of two-mass systems. A theoretical solution to this nonlinear problem was obtained with the additional use of a special logical algorithm to determine the direction of the dry friction force between two masses. The value of the dynamic coefficient of dry friction was determined by comparing the numerical solution to the problem with experimental records by selecting the value of the dry friction coefficient. The values of the mass of rubbing elements with the surface treatment of the steel-on-steel contact and a separate option with lubrication of the contact surface with fluoroplastic 4-on-fluoroplastic 4 gaskets were changed in the experiment. The maximum velocity of the platform in experiments corresponds to a 9-point earthquake on the MSK-64 scale.*

Keywords*:* *Experiment, Shaking Table, Dry Friction, Fluoroplastic, Steel, Seismic Isolation*

1. INTRODUCTION

Friction forces are important phenomena in our lives; without these forces, there would be no life on earth. A great number of scientific works are devoted to the study of the nature of sliding friction force. References to the basic publications in this direction can be found in Popov's monography [1], where the mechanics of contact interaction of bodies in

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relation to the physics of friction is presented; such closely related phenomena as contact, adhesion, capillary forces, friction, lubrication, and wear are discussed from a unified point of view.

Filippov et al. [2] presented a model of friction in a system of two rigid plates connected by links (springs) and experiencing an external drive. It is shown that macroscopic frictional properties of the system are directly related to the dynamics of rupture and formation of microscopic bonds. Different modes of motion are characterized by different rates of rupture and bond formation with respect to the velocity of motion. In particular, it is shown that the stick-slip regime corresponds to a cooperative bond breaking.

Elmer [3] studied the dynamical behavior caused by dry friction for a spring-block system pulled with constant velocity over a surface. The dynamical consequences of a general type of phenomenological friction law (stick-time-dependent static friction, velocity-dependent kinetic friction) are investigated. Three possible types of motion are shown: sticking-sliding, continuous sliding, and oscillations without sticking. Wojewoda et al. [4] considered problems with dry friction for various models that did not require determining the beginning of sliding.

Lyashenko [5] used the dry friction model to study the vibration of a body that has an elastic link with a fixed support, while the body is affected by the friction force of another body by a given law of motion and an externally applied load. Popov et al. [6] devoted their studies to the theoretical analysis of sliding friction under the action of oscillations perpendicular to the plane of sliding for a massless system. The influence of the stiffness of tribological contact is analyzed in detail, and the case of large amplitudes of oscillations is considered, at which the contact is lost during a part of the oscillation period, as a result of which the specimen starts to "jump". It is shown that the macroscopic friction coefficient is a function of only two dimensionless parameters-dimensionless sliding velocity and dimensionless vibration amplitude.

Kluge et al. [7] considered various models of interaction between the base and the structure and also noted that the friction force is unknown in the absence of sliding.

Harouz et al. [8] conducted a comparative analysis of the friction and wear rate for three segments NB, NC, and ND with TiC addition ratios of 5%, 10%, and 15%, respectively. The comparison was performed concerning a reference sample NA, with no TiC addition, for dry rotational sliding friction tests against Al_2O_3 ball, at two sliding velocities 0.5 m/s and 0.75 m/s and a fixed temperature of 450℃.

Brzakovic et al. [9] presented theoretical and experimental analyses of the kinetic friction coefficient of a ball bearing under rotational motion initiated by dynamic impact force. A method and measuring system were developed to determine the value of the kinetic coefficient of friction by measuring the angular acceleration.

Recently, a trend has been developed towards the widespread use of seismic isolation of buildings and structures using the principle of dry friction between the grillage and the foundation. Dynamic problems in the presence of dry friction forces are nonlinear. Mirzaev et al. [10-12] obtained a numerical solution to the nonlinear problem with the additional use of a special logical algorithm to determine the direction of the dry friction force between two masses. A logical algorithm determines the beginning of sliding of the upper mass relative to the bottom one, and the beginning of their joint motion. Mamatov et al. [13] devoted their studies to the analysis of the current state of residential buildings with sliding supports in the foundation, in Bishkek city. Based on the results of the research of residential buildings with seismic protection systems were recommended to use energy absorbers. The energy absorbers consist of rubbing surfaces of steel, fluoroplastic and a layer of bulk material placed between surfaces.

Buckle et al. [14] recommended to use of sliders for seismic isolation of bridges.

Banović et al. [15] conducted laboratory experiments on the shaking table with the implementation of real seismograms and showed that different earthquakes act differently on a body with a seismic isolating layer. Mkrtychev et al. [16,17] presented the results of studies of spatial structures of buildings with seismic isolation under the influence of real earthquakes using the LS-DYNA software package. Sagdiev et al. [18] defined the main principles of modeling multi-storey buildings with seismic isolation and characteristics of seismic isolation devices. In addition, they presented the results of experimental studies on the laboratory shaking table setup under dynamic impacts arising due to the initial deviation from the equilibrium position.

Mogilevsky et al. [19], using the method of characteristics, solved unsteady problems for a rod with external dry friction. Isakov and Kondratenko [20] described the mathematical model of the vertical penetration of a steel pipe in soil by a shock pulse generator. The influence of the external parameters on the attenuation of the shock pulse propagating along the pipe was described, and the generalities of the process were found.

Today, in practice, there are various methods for determining the dynamic coefficient of friction. Bragov et al. [21] and Espinosa et al. [22] used the modifications of Kolsky's method for determining the dynamic coefficient of friction. Nikitin's method described by Mogilevsky et al. [19] also refer to the measurement of the wave propagation through a section with dry friction, and the dry friction coefficient is determined based on the solution to a one-dimensional problem for a rod with lateral dry friction. Miljojković et al. [23] presented the results related to the development of a modular didactic laboratory set for the experimental study of friction and its implementation in engineering education.

This article describes the experimental setup and research methodology using the analytical solution of the corresponding problem of free vibrations of the system to determine the value of the dynamic coefficient of dry friction on the steel-on-steel contact with and without lubrication and on the fluoroplastic-on-fluoroplastic contact.

2. MATERIAL AND METHODS

2.1 The Principle of Conducting Experimental Research

To determine the value of the dynamic coefficient of dry friction on the steel-on-steel and fluoroplastic-on-fluoroplastic contact surfaces, experimental studies were conducted on the small shaking stand for various frequencies and intensities of external impact. The external impact was generated using a special device of the platform pullback on the shaking stand, changing the length of elastic vertical plates and the amplitude of the pullback (Fig. 1a). The shaking table of the setup was fixed on four elastic vertical plates, the length of which could be adjusted vertically using a movable mount, and the required stiffness of elastic plates could be set.

A box made of steel sheets with dimensions of 0.45×0.46×0.17 m was rigidly installed on the shaking table. The steel box was filled with sand to a height of 0.1 m. The steel sheet with dimensions of 0.45×0.46×0.005 m was installed above the sand using a hydraulic level. The total mass of the platform is 131.6 kg. The steel plate with dimensions of

0.355×0.363×0.0224 m is located above the steel plate. The mass of the upper steel plate is 22.4 kg. In the experimental study, the weight of the upper steel plate was changed by the treatment of the steel-on-steel contact surfaces, and different options with the lubrication of the contact surfaces, another one-with the insertion of a pair of fluoroplastic gaskets 4. The laboratory setup is shown in Figs. 1a and 1b.

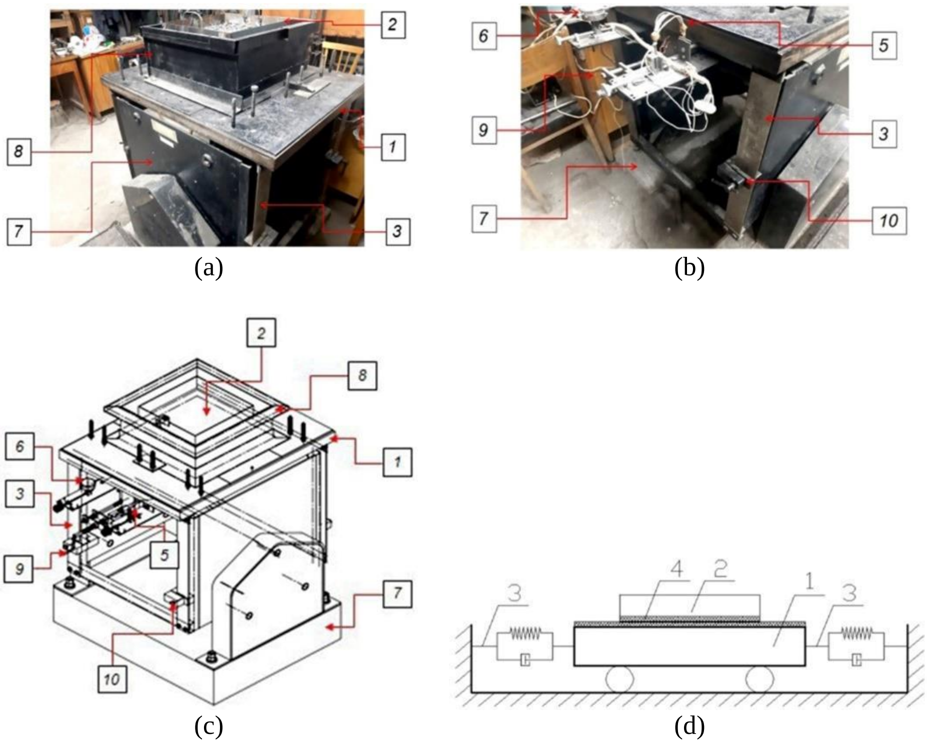


Fig. 1 Laboratory shaking stand (a) General view of the setup (b) Side view of the setup (c) Setup scheme with main elements (d) Simulation scheme of the setup: 1 – moving part of the shaking stand; 2 – plate made of steel sheet for studying the dynamic coefficient of dry friction; 3 – vertical steel plates with viscoelastic property; 4 – fluoroplastic layer; 5 – displacement strain gauge; 6 – movement clock gauge; 7 – rigid base of the shaking stand; 8 – steel box; 9 – screw for shaking table pullback; 10 – movable mount for changing the working length of the plates

When conducting experiments on the laboratory setup, the amplitudes of vibration of the shaking table during pullback reach up to 0.006 m, 0.009 m, and 0.012 m, which is due to the restrictions of using a displacement strain gauge designed to record small amplitudes of vibration (Fig. 1b). To record vibrations of the shaking table relative to the stationary support of the shaking stand, the displacement strain gauge with preliminary calibration was installed at the level of the shaking table, and the second strain gauge connected with the steel box was installed to the upper steel plate. The vibrations of the shaking stand were generated by deflecting (pulling back) the movable shaking table from the zero position and instantly releasing it. The setup scheme with main elements and the simulation scheme of the setup are shown in Figs. 1c and 1d. The main purpose of the experimental research is to study vibrations of the upper steel plate relative to the bottom steel plate located on the shaking table and to measure the value of displacement of the upper steel plate at its different masses relative to the bottom plate due to dry friction after the oscillation of the system has stopped.

2.2 Oscillations of the System with Two Degrees of Freedom during Interaction of Masses According to the Amonton-Coulomb's Law of Dry Friction

In this paragraph, we construct a theoretical solution to the corresponding mathematical problem.

In the simulation model (Fig. 1d), we consider the plates rigid and ignore the rolling friction of the rollers. Let us see the case when the mass of the bottom plate m_1 (which includes the mass of the shaking table with the box and a half of the unit mass of four vertical viscoelastic plates (Fig. 1c)) and the mass of the upper plate m_2 moves without sliding. The motion is described by the equation of motion of a system with one degree of freedom, the solution of which is well known at $t=t_0$ $u_1=u_{00}$, $u_2=u_{00}+u_{02}$, $v_1=v_2=v_{00}$ (u_i, v_i are the displacements and velocities, respectively, u_{00}, u_{02}, are the displacements of the bottom plate and upper plate relative to the bottom plate at time $t=t_0$). In this case, the damping of the system oscillations is taken into account by introducing into the equation a term proportional to the oscillation velocity with damping coefficient μ, determined from the graphical representation of the experimental results by calculating the logarithmic damping decrement and measuring the oscillation period. The damping of the system oscillations without sliding occurs due to the loss of energy in four viscoelastic vertical plates and through the points of their connection with the base. The damping of the oscillations of the system occurs additionally at sliding friction due to the dry friction force, included in the equations of motion. At the initial time $t_0=0$, the system deviates from the state of static equilibrium by $u_1=u_2=u_{00}$ and the system is released without initial velocity $v_{00}=0$. After sliding, for each subsequent joint motion of two masses without sliding, the beginning is set at $t=t_0$, and the displacement and velocity of masses are denoted by u_{00} and v_{00}, respectively.

The resulting solution is true until the plates begin to slide relative to each other.

If the plates slide at $t=t_1$, determined by the special logical algorithm described below, then for each plate there is its equations of motion:

$$m_1 \cdot \ddot{u}_1 + \mu \cdot \dot{u}_1 + c \cdot u_1 = F_{fr} \tag{1}$$

$$m_2 \cdot \ddot{u}_2 = -F_{fr} \tag{2}$$

$$F_{fr} = sign(\dot{u}_2 - \dot{u}_1) \cdot m_2 \cdot g \cdot f_d \tag{3}$$

where m_1, m_2, u_1, u_2 are the masses and displacements of the bottom and upper plates, μ is the damping coefficient, c is the total stiffness of elastic plates of the shaking stand, F_{fr} is the dry friction force, g is the gravitational constant. Let us introduce the generally accepted designations for velocities $v_1=\dot{u}_1$, $v_2=\dot{u}_2$ and accelerations $a_1=\ddot{u}_1$, $a_2=\ddot{u}_2$ of plates, respectively.

At $t=t_1$, $u_1=u_{01}$, $u_2=u_{01}+u_{02}$, $v_1=v_2=v_{01}$, where u_{01}, v_{01} are the displacement and velocity of the bottom plate at the beginning of sliding at time $t=t_1$. The sign of the friction force is determined by the difference in velocities of the plates, denoted by $f=sign(v_2-v_1)\cdot f_d\cdot g$, where f_d is the dynamic coefficient of dry friction between the plates.

The equations of motion of rigid plates in Eqs. (1-3) are written in the following form:

$$\ddot{u}_1 + 2n_2 \cdot \dot{u}_1 + k_2^2 \cdot u_1 = m_2 \cdot f / m_1 \tag{4}$$

$$\ddot{u}_2 = -f \tag{5}$$

where $n_1 = \dfrac{\mu}{2(m_1+m_2)}$, $n_2 = \dfrac{\mu}{2m_1}$ are the damping constants, $k_1 = \sqrt{\dfrac{c}{m_1+m_2}}$, $k_2 = \sqrt{\dfrac{c}{m_1}}$ are the natural circular frequencies of the system without and with slip.

Then the solutions of the system of Eqs. (4) and (5) for the displacements, velocities and accelerations of the two plates (if the sign of the difference of their velocities is retained) are as follows:

$$u_1 = e^{-n_2(t-t_1)}\left\{(u_{01}+\frac{m_2\cdot f}{c})\cdot cos[k_2\cdot(t-t_1)] + \right.$$
$$\left. +\frac{1}{k_2}\left[v_{01}+(u_{01}+\frac{m_2\cdot f}{c})\cdot n_2\right]\cdot sin[k_2\cdot(t-t_1)]\right\} - \frac{m_2\cdot f}{c} \tag{6}$$

$$v_1 = e^{-n_2(t-t_1)}\left\{-\frac{n_2}{k_2}\cdot\left[v_{01}+(u_{01}+\frac{m_2\cdot f}{c})\cdot n_2\right]\cdot sin[k_2\cdot(t-t_1)] - \right.$$
$$\left. -(u_{01}+\frac{m_2\cdot f}{c})\cdot k_2\cdot sin[k_2\cdot(t-t_1)] + v_{01}\cdot cos[k_2\cdot(t-t_1)]\right\} \tag{7}$$

$$a_1 = e^{-n_2(t-t_1)}\left\{\frac{n_2^2}{k_2}\cdot\left[v_{01}+(u_{01}+\frac{m_2\cdot f}{c})\cdot n_2\right] + \right.$$
$$\left. + n_2\cdot(u_{01}+\frac{m_2\cdot f}{c})\cdot k_2 - k_2\cdot v_{01}\right\}\cdot sin\{k_2\cdot(t-t_1)\} -$$
$$- e^{-n_2(t-t_1)}\left\{\left[2\cdot v_{01}\cdot n_2 + (u_{01}+\frac{m_2\cdot f}{c})\cdot(n_2^2+k_2^2)\right]\cdot cos[k_2\cdot(t-t_1)]\right\} \tag{8}$$

$$u_2 = u_{01}+u_{02}+v_{01}\cdot(t-t_1)+\frac{1}{2}\cdot f\cdot(t-t_1)^2\ ; \quad v_2 = v_{01}+f\cdot(t-t_1);\quad a_2 = f \tag{9}$$

These solutions hold until the time when two plates move together without sliding. The time $t=t_0$ of the beginning of motion of plates without sliding is determined when the direction of sliding is changed.

The process of nonlinear oscillations is very complex, it is impossible to predict in advance the direction of the dry friction force, as well as to determine the time of the beginning of sliding of the upper plate on the bottom plate. To solve this problem, we will build an algorithm for determining the time points of the beginning and end of the sliding of the upper plate on the bottom plate [10]. To do this, we will perform calculations with a small step (about 0.0001 s) to determine the displacements and velocities using the formulas for the well-known solution in the case of joint motion of masses without sliding and Eqs. (6-9). At any given time the system can be in one of the following states:

I – for the case of joint motion of the plates without sliding;

II – by formulas given in Eqs. (6-9) for $f > 0$;

III – by formulas given in Eqs. (6-9) for $f < 0$ (the latter means the opposite direction of the dry friction force).

If solutions for states II and III in relative velocities have different signs, then the relative inertia force of the top plate is less than the limiting value of the dry friction force. It means that the friction force between the plates is less than the limiting value of dry friction force, therefore, the plates at this time move without sliding and the true solution to the problem corresponds to state I.

If solutions for states II and III in relative velocities have the same signs, then the true solution to the problem at time $t=t_1$ is the solution that corresponds to the minimum absolute value of the velocity difference of the plates. It follows from the fact that the force of dry friction is always directed against the relative motion of the plates and against each plate separately.

Therefore, having conducted calculations according to the specified formulas and using the described decision-making algorithm at each time step, we obtain the solution to the nonlinear problem in the given time interval.

3. Results and Discussion

We will analyze the effect of the treatment of rubbing plate surfaces and their masses on the oscillatory process, and give a method for determining the dynamic coefficient of dry friction by comparing the analytical solution with the experimental results.

The interpretation of the series of experiments shows the following (Table 1):

ABBMI, A=1 is the value of pullback of the shaking table which equals to 0.012 m to create oscillations;

A=2 is the value of pullback of the shaking table which equals to 0.009 m to create oscillations;

A=3 is the value of pullback of the shaking table which equals to 0.006 m to create oscillations;

BB=FF is the friction of fluoroplastic-on-fluoroplastic contact between the steel plates;

BB=SS is the friction of the steel-on-steel contact;

BB=SSL is the friction of the steel-on-steel contact with lubricant of industrial oil I-20;

M0 is the mass of the upper steel plate without additional load;

M1 is the mass of the upper steel plate with additional mass of 5 kg;

M2 is the mass of the upper steel plate with additional mass of 10 kg;

M3 is the mass of the upper steel plate with additional mass of 20 kg;

f_s is the static coefficient of dry friction;

T is the period of oscillation of the system without sliding;

u_s is the relative displacement between the upper and bottom plates after oscillations.

The results shown in Table 1 are based on experimental studies of the static and dynamic coefficients of dry friction between the upper and bottom plates for different materials under the effect of various additional masses acting on the upper plate. The period of oscillation, the oscillation damping during the period of time the plates are moving without sliding, and the displacement of the upper plate relative to the bottom plate after the oscillation stops were measured from the experimental displacement curves of the system.

Table 1 Results of experimental studies

№	Series of experiments	m_2, [kg]	c, [N/m]	T, [s]	u_s, [m]	n_1, [1/s]	n_2, [1/s]	f_s	f_d	v_{max}, [m/s]	a_{max}, [m/s^2]
1	1FFM0	22.4	6667	0.32	-0.010	0.12	0.17	0.2	0.1	0.22	4.35
2	1FFM1	27.4	6667	0.34	-0.0096	0.07	0.08	0.2	0.1	0.22	4.46
3	1FFM2	32.4	6667	0.36	-0.0092	0.07	0.08	0.2	0.1	0.22	4.52
4	1FFM3	42.4	6667	0.38	-0.0089	0.05	0.07	0.2	0.1	0.23	4.8
5	2FFM0	22.4	10000	0.24	-0.0088	0.16	0.22	0.2	0.12	0.29	9.98
6	2FFM1	27.4	10000	0.26	-0.0083	0.12	0.26	0.2	0.12	0.24	6.6
7	2FFM2	32.4	10000	0.27	-0.0076	0.05	0.07	0.2	0.12	0.3	10.7
8	2FFM3	42.4	10000	0.30	-0.0062	0.16	0.27	0.2	0.12	0.2	4.8
9	3FFM0	22.4	18182	0.20	-0.006	0.23	0.35	0.2	0.12	0.19	6.68
10	3FFM1	27.4	18182	0.21	-0.0058	0.24	0.31	0.2	0.12	0.19	6.84
11	3FFM2	32.4	18182	0.22	-0.0056	0.25	0.32	0.2	0.12	0.19	6.9
12	3FFM3	42.4	18182	0.23	-0.0054	0.26	0.38	0.2	0.12	0.2	7.4
13	1SSM0	22.4	6667	0.30	-0.0078	0.12	0.26	0.4	0.13	0.39	13.5
14	1SSM1	27.4	6667	0.38	-0.0047	0.13	0.16	0.4	0.13	0.18	3.29
15	1SSM2	32.4	6667	0.43	-0.0046	0.1	0.13	0.4	0.13	0.14	2.04
16	1SSM3	42.4	6667	0.47	-0.004	0.13	0.17	0.4	0.13	0.25	6.13
17	2SSM0	22.4	10000	0.25	-0.0054	0.1	0.18	0.4	0.15	0.19	4.37
18	2SSM1	27.4	10000	0.28	-0.0052	0.1	0.13	0.4	0.15	0.19	4.44
19	2SSM2	32.4	10000	0.31	-0.0045	0.13	0.17	0.4	0.15	0.16	3.29
20	2SSM3	42.4	10000	0.33	-0.0042	0.17	0.23	0.4	0.15	0.19	4.7
21	3SSM0	22.4	18182	0.21	-0.0045	0.15	0.23	0.4	0.2	0.19	6.6
22	3SSM1	27.4	18182	0.22	-0.0042	0.24	0.33	0.4	0.2	0.19	6.7
23	3SSM2	32.4	18182	0.23	-0.0045	0.28	0.38	0.4	0.2	0.19	6.9
24	3SSM3	42.4	18182	0.25	-0.0037	0.27	0.37	0.4	0.2	0.19	7.12
25	1SSLM0	22.4	6667	0.33	-0.0132	0.11	0.15	0.3	0.07	0.19	3.3
26	1SSLM1	27.4	6667	0.35	-0.0105	0.1	0.14	0.3	0.07	0.19	3.4
27	1SSLM2	32.4	6667	0.38	-0.0101	0.07	0.09	0.3	0.07	0.19	3.5
28	1SSLM3	42.4	6667	0.45	-0.0092	0.08	0.1	0.3	0.07	0.19	2.27
29	2SSLM0	22.4	10000	0.25	-0.0095	0.07	0.09	0.3	0.08	0.19	4.46
30	2SSLM1	27.4	10000	0.26	-0.0091	0.1	0.13	0.3	0.08	0.19	4.57
31	2SSLM2	32.4	10000	0.32	-0.0088	0.05	0.07	0.3	0.08	0.2	4.7
32	2SSLM3	42.4	10000	0.34	-0.0075	0.05	0.07	0.3	0.08	0.2	4.9
33	3SSLM0	22.4	18182	0.20	-0.0074	0.15	0.18	0.3	0.09	0.19	6.7
34	3SSLM1	27.4	18182	0.21	-0.0064	0.09	0.11	0.3	0.09	0.19	6.9
35	3SSLM2	32.4	18182	0.21	-0.0074	0.102	0.128	0.3	0.09	0.20	7.12
36	3SSLM3	42.4	18182	0.23	-0.0065	0.15	0.18	0.3	0.09	0.20	7.5

Then, using known relationships, the frequencies of oscillations and the stiffness of four vertical plates were calculated for different vibration values of the shaking table. Next, using a specially developed program based on solutions without/with sliding according to Eqs. (6-9), the main indices of the dynamic process were calculated, i.e. dynamic coefficient of dry friction, and absolute maximum values of velocity v_{max} and acceleration a_{max} of the system.

To determine the value of the dynamic coefficient of dry friction, theoretical results were compared with experimental results by gradually decreasing the value of this coefficient until the results coincided with displacements with acceptable accuracy. The mass of the bottom plate with the shaking table when measuring vibrations of the two-mass system was 131.6 kg.

From Table 1 and Fig. 2, it follows that a change in the mass of the upper plate and a change in the oscillation velocity within the considered limits, have a slight effect on the dry friction coefficient, and the properties of the rubbing surfaces and lubrication greatly affect the value of the dry friction coefficient.

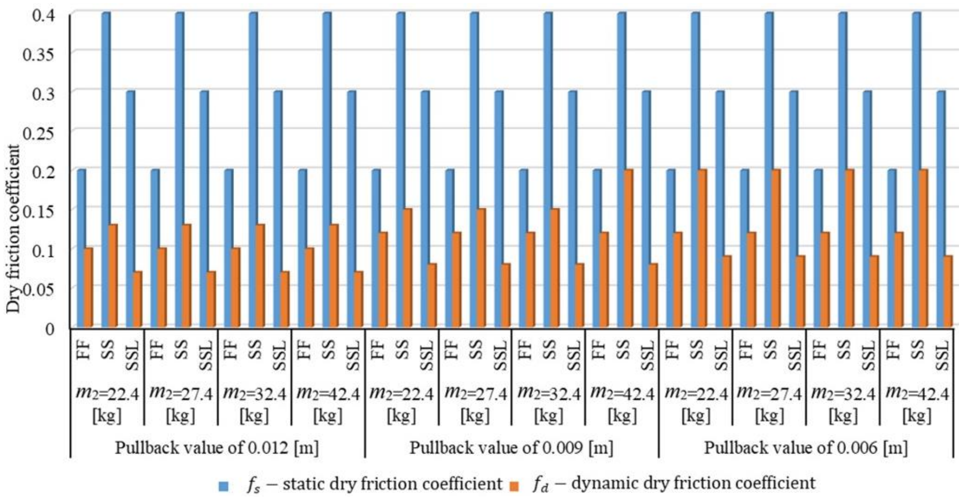
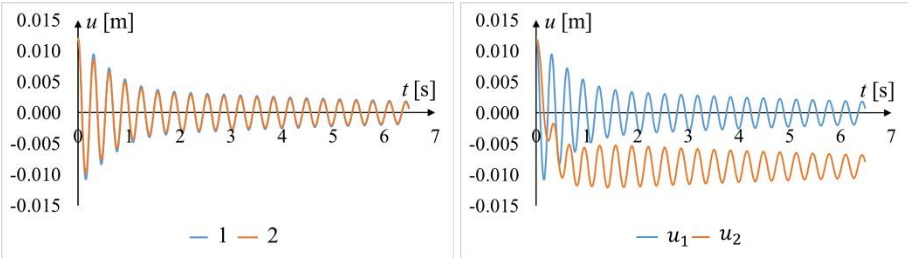


Fig. 2 Histogram of values of static and dynamic dry friction coefficients for various materials

The comparison of the vibrations of the bottom plate according to the result of experiments conducted for 1FFM0 (Table 1) and calculated with the same data by the Eq. (6) is shown in Fig. 3a. Good agreement of these results is due to the fact that the simulation model parameters μ and k_1 were determined by measuring the logarithmic decrement of damping and by accurate measuring the period of oscillation of the system without slip. The graph shows that up to time t=2.5 s, the system oscillates more intensively due to slip. In addition, to determine the value of the dynamic coefficient of dry friction, we perform a computational experiment by comparing the theoretical results with the experimental result.

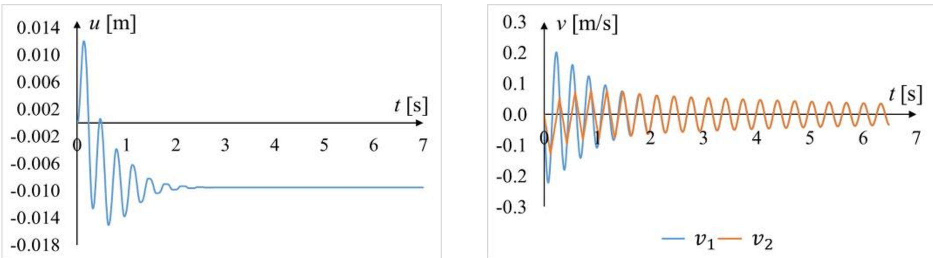
The graphs of vibrations of the bottom and upper plates are shown in Fig. 3b. It shows how the plates oscillate; sliding starts at the initial time of oscillation and occurs until t=2.5 s with very short periods of movements without sliding.



(a) (b)

Fig. 3 Graphs of the displacements depend on time (a) Vibrations of the bottom plate (1 – experiment, 2 – analytical calculation) (b) Vibrations of the bottom plate u_1 and the upper plate u_2 (analytical calculation)

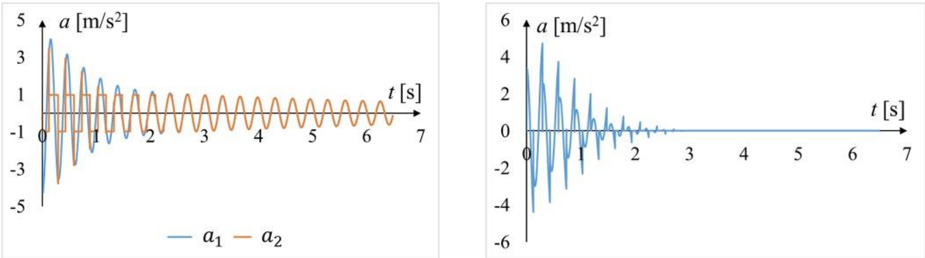
The graph of relative vibrations of the upper plate with account for the sliding on the bottom plate for the same initial data obtained from the experiment for 1FFM0 is shown in Fig. 4a. It can be seen that the relative displacement of the upper plate occurs until time t=2.5 s, then the plates oscillate without sliding. The vibration velocities of the bottom (v_1) and upper (v_2) plates are shown in Fig. 4b, with the maximum values of the velocity modulus of the bottom plate v_{max}=0.22 m/s and the upper plate v_{max}=0.13 m/s are reached at t=0.1 s. The maximum velocity value of the upper plate is less compared to the upper plate due to their sliding. The period of oscillation of the bottom plate in the case of sliding T=0.4 s is larger compared to the period without sliding between the plates T=0.32 s.



(a) (b)

Fig. 4 Graphs of relative vibrations of the upper plate (a) and oscillations of velocity of the bottom v_1 and the upper v_2 plates (b)

The calculated graph of accelerations of the bottom (a_1) and the upper (a_2) plates are shown in Fig. 5a. Maximum values of accelerations for the bottom plate a_{max}=4.35 m/s^2 are reached at t=0 s, and for the upper plate a_{max}=3.75 m/s^2 are reached at t=0.3 s. The acceleration of the upper plate at certain time intervals has a constant value; these time intervals correspond to the time intervals of oscillations of the system with sliding. The relative acceleration of the upper plate, i.e., the difference between the accelerations of the upper and the bottom plates is shown in Fig. 5b. At that, its maximum value a_{max}=4.65 m/s^2 is reached at t=0.3 s. For time t>2.5 s, the relative acceleration of the upper plate is zero since the plates oscillate without sliding.



(a) (b)

Fig. 5 Graphs of accelerations of the bottom a_1, upper a_2 plates (a) and relative acceleration of the upper plate (b)

From Eq. (5) and Fig. 5a, it follows that the transition from joint motion of masses to their motion by sliding occurs when the absolute value of the acceleration of the system exceeds $g \cdot f_d$. When the velocities are equal (Figs. 4b and 5a), a transition from sliding to the joint movement of masses without sliding occurs.

4. Conclusion

The dynamic coefficient of dry friction between different materials was experimentally determined. The value of the dynamic coefficient of friction was determined by comparing the numerical solution of the problem with experimental data. In the experiment, the mass values varied depending on the surface treatment of the steel-on-steel contact and a separate option with lubrication of the contact surface, and with fluoroplastic 4-on-fluoroplastic 4 gaskets. Changing the mass of the upper plate (from 22.4 kg to 42.4 kg) did not affect the value of the dynamic coefficient of dry friction. The maximum velocity of the platform in the experiments varied from 0.14 m/s to 0.39 m/s, which corresponds to a 9-point earthquake on the MSK-64 scale; it also slightly affected the value of the dynamic coefficient of dry friction. Experimental values of the dynamic coefficient of dry friction on the fluoroplastic-on-fluoroplastic contact were up to two times less compared to the static value, and at the steel-on-steel contact, they were three times less. The use of a contact lubricant for rubbing masses greatly reduced the dynamic coefficient of dry friction. It was determined that under the horizontal movement of two plates, one of which lies on the other, sliding with dry friction occurs when the acceleration begins to exceed the values of the dry friction coefficient multiplied by the acceleration of gravity.

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