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Manipulation of a part on a vibrating plane under controlled dry friction

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1. Introduction

Motion of a part on a horizontal plane is predetermined by the dry friction force, the magnitude of which is proportional both to the coefficient of dry friction and magnitude of the normal force. The coefficient of friction depends on the material of contacting bodies and on roughness of their surfaces. To manipulate the body over the plane under high friction coefficient it is necessary to provide higher both the forces and amplitudes of the excitation. Dry friction may be controlled by:

- changing the sliding velocity;
- providing high-frequency excitation in the contact zone of the parts along longitudinal or normal directions;
- providing rotational motion of the body relative to the other body;
- changing normal pressing force between the two contacting bodies.

Elmer [1, 2] analyzed how the sliding velocity of the body and normal pressing force are influencing the friction force. The author carried out experimental analysis of the placed on a horizontal plane and attached to the spring body, which is subjected to tension in a horizontal direction. Elmer's experiments proved the existence of the two-stage slip: slip-stick displacement and constant velocity sliding. The author proved that increasing the velocity of the body motion, it is possible to avoid the slip-stick stage.

The force of dry friction may be decreased exciting high-frequency vibrations in the zone of the bodies' contact. High-frequency vibrations, between the being manipulated part and the plane, may be provided perpendicularly to the plane or along the direction of the body motion. The decrease in dry friction coefficient results better conditions for the part motion and larger distance of the part displacement over the plane.

During the high-frequency excitation of the plane, the effect of reduced dry sliding friction is characterized by the effective coefficient of dry friction, which is the result of dynamic processes in the contact zone [3]. Changing parameters of the vibrations it is possible to control the effective coefficient of dry friction between the plane and the part.

Littmann and Kumar [4, 5] analysed two ways of the plane excitation, i.e. as high-frequency vibrations are provided perpendicularly and parallel to the direction of the body motion. Kumar defined, that high-frequency vibrations may result significant decrease in sliding friction. It was determined, that vibratory excitation, provided along the direction of the body motion, results more significant decrease in sliding friction coefficient if compared to that under provided transverse high-frequency vibrations. Littmann determined, that high-frequency vibrations, provided perpendicularly to the direction of the body motion, result the increase in friction force under increased ratio of motion velocity of the body to vibration velocity. If the mentioned ratio is equal to 1, the friction force changes marginally. As high-frequency vibrations are provided parallel to the direction of the body motion, the friction force remains constant, if the ratio of motion velocity to excitation velocity is higher or equal to 1.

Piezoelectric vibrators are used to excite high-frequency vibrations of the plate [6]. The vibrators are attached to the plate and excited by the frequency, aiming to cause elastic vibrations of the plate.

Fedaravičius and Tarasevičius analyzed motion of a body on a vibrating plane, as the effective coefficient of the dry friction is periodically controlled during each rotation of the vibrating platform [7]. The circular motion is provided to the plane. Controlling the dry friction, it is possible to transfer the bodies along a complex trajectory, change the direction and velocity of the motion. It was defined during the experiments, that motion of the body along any desirable direction may be controlled and movement velocity may be simply changed by decreasing or increasing the duration of high-frequency vibrations and by changing the radius of the circular trajectory of the platform motion. However, only the case, as high-frequency vibrations are excited during one semiperiod and as the part displaces by transitional motion mode, was considered. The experiments were carried out under particular magnitudes of the parameters and analysis was made considering only the parameters which are important for the conveyance. Matching of the connective surfaces, as the most important for automated assembly, was not considered in the analysis of part manipulation on vibrating plane.

Part manipulation under controlled dry friction was analysed by Bakšys and Sokolova [8, 9]. The elastically constrained and damped part is placed on the two-part platform and pressed to it by the particular force. Both the parts of the platform are excited by different frequency vibrators, causing elastic vibrations of separate parts of the platform. The vibrations of different frequencies result different coefficients of friction between the separate parts of the platform and the part. Additionally, the platform is provided with low-frequency vibrations, which result the force of the part motion. It was determined, that in such a way the part is able to move forward, vibrate near the position of dynamic equilibrium and rotate around its own axis.

This study analyzes matching of connective surfaces of cylindrical parts being assembled applying the vibratory search, based on the motion of a body on a vibrating plane under controlled dry friction. This method is classified as passive positioning of the parts and matching of their connective surfaces. The plane is subjected to horizontal vibratory motion in two perpendicular directions and high-frequency vibrations of the plane are excited at the particular time moments. By changing parameters of the vibrations, it is possible to control the effective coefficient of dry friction and also the friction force between the part and the plane.

2. Manipulation of a part by high frequency vibrations in one semiperiod of the excitation

Motion of a part, placed on the vibrating plane, is analyzed. The plane *1* is excited harmonically in two perpendicular directions (Fig. 1). While the plane vibrates, the part *2* moves over the plane under the influence of the resistant friction force, which acts opposite to the direction of relative velocity. Vibrator *3* is attached to the plane. At certain moments high-frequency vibrations are excited, causing elastic vibrations of the plane, thus friction between the part and the plane decreases. Motion of the part, without provided high-frequency vibrations, is described by the Eqs.

$$\begin{cases} \ddot{x} + \mu_1 g \dfrac{\dot{x}}{\sqrt{\dot{x}^2 + \dot{y}^2}} = R_e \omega^2 \cos \omega t \\ \ddot{y} + \mu_1 g \dfrac{\dot{y}}{\sqrt{\dot{x}^2 + \dot{y}^2}} = R_e \omega^2 \sin \omega t \end{cases}$$

where μ_1 is dry friction coefficient, without high-frequency excitation of the plane, R_e is excitation amplitude of the plane; ω is excitation frequency of the plane.

The equations of the part motion, under excited high frequency vibrations and decreased friction, remain the same, only dry friction coefficient μ_2 is different.

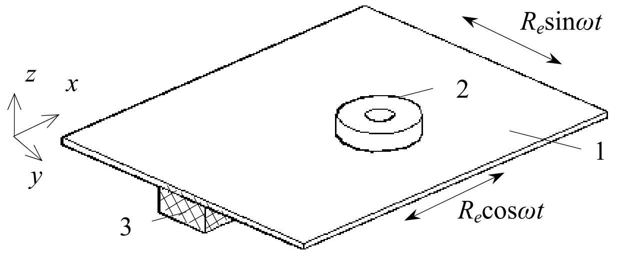


Fig. 1 Scheme of the vibratory search: *1* – plate, *2* – cylindrical part, *3* – piezoceramic vibrator

By decreasing the friction at particular moment during one semiperiod (Fig. 2), the part moves along the particular direction and the motion trajectory is not getting steady, because the friction is reduced only during one semiperiod. Such a trajectory, which never stabilizes, is suitable for the parts' positioning, because they can be displaced along any direction and any distance.

Directional angle γ of the part motion (Figs. 3 and 4) depends both on the friction decrease moment τ_1 (Fig. 5) and duration $d = \tau_2 - \tau_1$ of the maintained decreased friction.

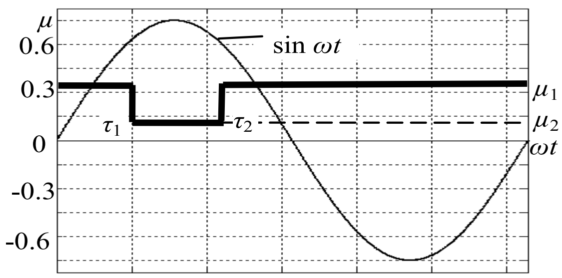


Fig. 2 Variation of dry friction coefficient relative to 2π period of the excitation signal: here τ_1 is the moment of friction decrease, τ_2 is the moment of friction increase, μ_1 is the initial friction coefficient when high frequency vibrations are not provided, μ_2 is the friction coefficient when high frequency vibrations are turned on

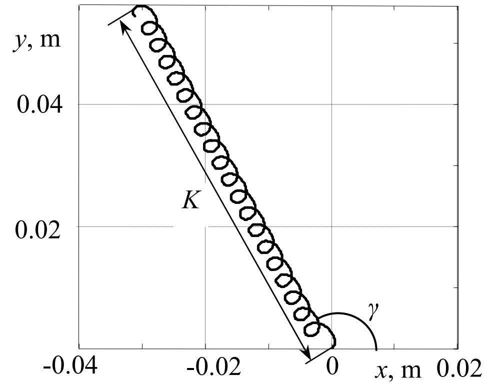


Fig. 3 Motion trajectory of the part, when $\mu_1 = 0.36$, $\mu_2 = 0.1$, $g = 9.81$, $R_e = 0.002$ m, $\omega = 50$ s^{-1}, $\tau_1 = 0.6\,\pi/\omega$, $\tau_2 = \pi/\omega$

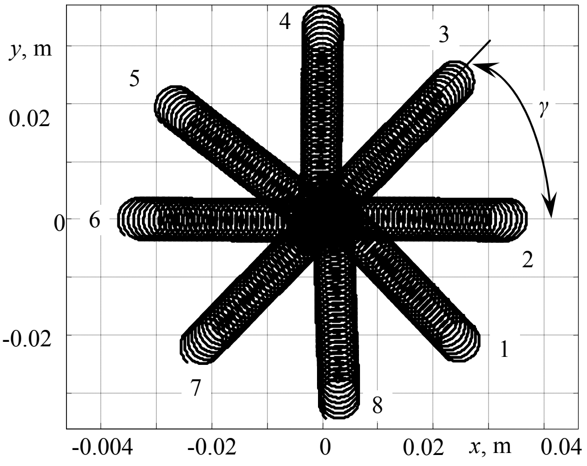
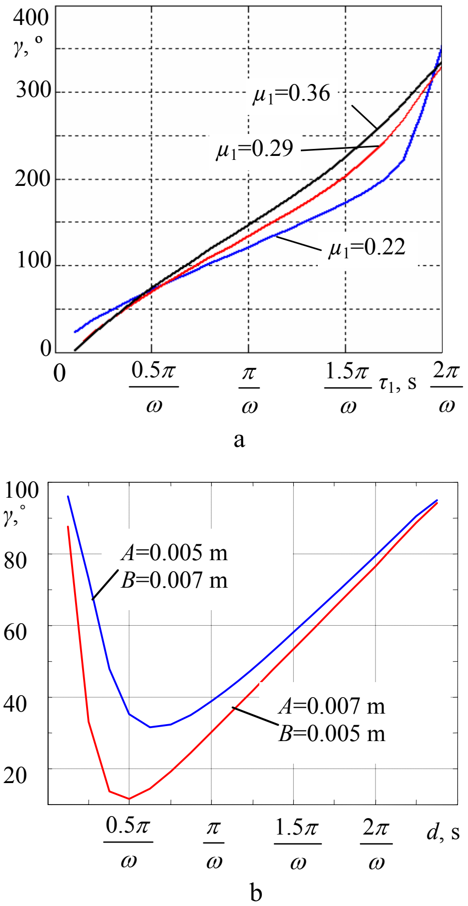


Fig. 4 Motion trajectory of the part versus the moment of friction decrease, as $\mu_1 = 0.2$, $\mu_2 = 0.1$, $\omega = 35$ s^{-1}, $R_e = 0.002$ m, $d = \pi/5\omega$: *1* – $\tau_1 = 0$, *2* – $\tau_1 = \pi/4\omega$; *3* – $\tau_1 = \pi/2\omega$; *4* – $\tau_1 = 3\pi/4\omega$; *5* – $\tau_1 = \pi/\omega$; *6* – $\tau_1 = 5\pi/4\omega$; *7* – $\tau_1 = 3\pi/2\omega$; *8* – $\tau_1 = 7\pi/4\omega$

The directional angle γ of the part motion varies from 0 to 360°. Under higher values of the initial friction coefficient μ_1, the dependence of angle γ on the friction decrease moment τ_1 is almost linear, while under smaller initial friction coefficient, initially the angle varies slower, but at $1.75\pi/\omega$ it changes rapidly (Fig. 5, a). The dependences of the directional angle γ of the being positioned part displacement on duration of the maintained decreased friction have clearly apparent minimum (Fig. 5, b).



a

b

Fig. 5 Dependences of directional angle γ: a – on friction decrease moment τ_1, as $\mu_2 = 0.1$, $\omega = 40\ \mathrm{s}^{-1}$, $R_e = 0.004$ m, $d = 0.1\pi/\omega$; b – on duration of the maintained decreased friction, as $\omega = 40\ \mathrm{s}^{-1}$, $R_e = 0.005$ m, $\mu_2 = 0.1$, $\tau_1 = 0$

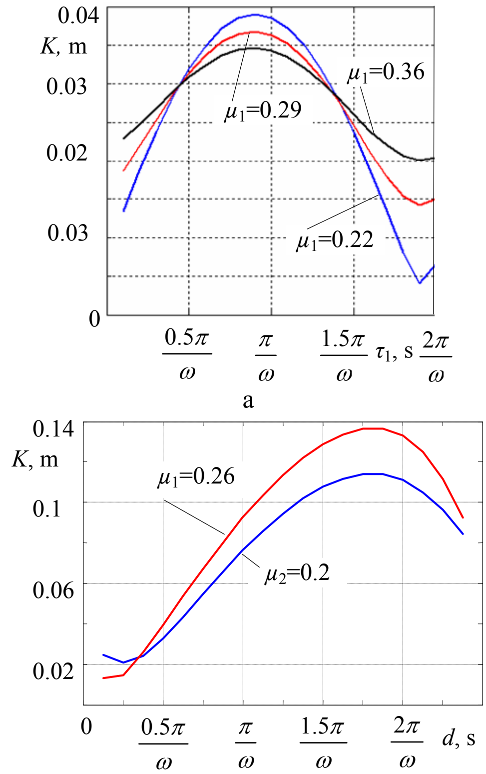
Displacement of the part depends on the moment of friction decrease. Decreasing the friction only in one semiperiod, the part moves continuously. Part displacement K (Fig. 3) is determined under particular number of the plane motion periods. When friction is decreased in first semiperiod of the excitation signal, the part displacement increases and as $\tau_1 = \pi/\omega$, the displacement K is maximum. If the friction decrease moment τ_1 is in the second semiperiod, the displacement starts decreasing (Fig. 6, a). Part displacement K is highly dependent on the duration of the maintained decreased friction (Fig. 6, b).

Motion of the part, as the plane moves elliptically and high-frequency vibrations are not excited on, is expressed by the following equations

$$\begin{cases} \ddot{x} + \mu_1 g \dfrac{\dot{x}}{\sqrt{\dot{x}^2 + \dot{y}^2}} = A_e \omega^2 \cos \omega t \\ \ddot{y} + \mu_1 g \dfrac{\dot{y}}{\sqrt{\dot{x}^2 + \dot{y}^2}} = B_e \omega^2 \sin \omega t \end{cases} \tag{2}$$

where A_e and B_e are excitation amplitudes of the plane.

When high-frequency vibrations are turned on and friction decreases, μ_1 in the equations of motion (Eqs. (2)) is substituted by the other friction coefficient μ_2.



a

b

Fig. 6 Dependences of the part displacement K: a - displacement of the part from initial position to the farthest point of the trajectory, reached in 18 excitation periods, versus actuation moment τ_1 of the decreased friction, as $\mu_2 = 0.1$, $\omega = 40\ \mathrm{s}^{-1}$, $R_e = 0.004$ m, $d = 0.1\pi/\omega$; b - displacement from initial position to the farthest trajectory point, reached by the part in 8 excitation periods, versus duration of the maintained decreased friction, as $\omega = 40\ \mathrm{s}^{-1}$, $R_e = 0.005$ m, $\mu_2 = 0.1$, $\tau_1 = 0$

It was determined, that under the same parameters of excitation, within a particular number of the excitation periods, the part displaces further as the amplitude of excitation along the y axis direction is higher than that along the x (Fig. 7).

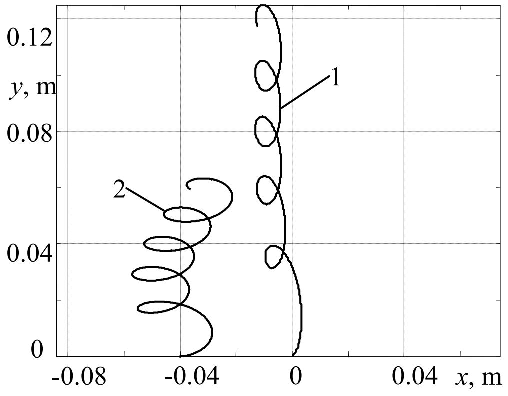


Fig. 7 Part motion trajectories during the 5 periods of the elliptical excitation of the plane: $\mu_1 = 0.36$, $\mu_2 = 0.1$, $\omega = 35\ \mathrm{s}^{-1}$, $A_e = 0.005$ m, $B_e = 0.01$ m, $\tau_1 = 0.5\ \pi/\omega$, $d = 0.5\pi/\omega$: *1 –* $A_e < B_e$, *2 –* $A_e > B_e$

3. Manipulation of the part by high frequency vibrations in both the semiperiods

The equations of part motion along the plane do not change, but friction is reduced in both the semiperiods of the single excitation period of the plane (Fig. 8). Then motion of the part during the positioning is characterized by a transient regime, and by a steady regime –during the search. Though the plane is excited along circular trajectory, the trajectory of the part search motion becomes an ellipse (Fig. 9) with insignificant minor and major axes. Under controlled dry friction, the part displacement from the initial position to the center of the search trajectory is found to be significantly larger than in case of constant dry friction (Fig. 9).

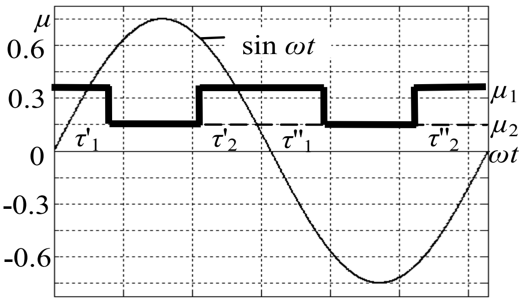


Fig. 8 Variation of the dry friction coefficient in respect of the period 2π of the excitation amplitude

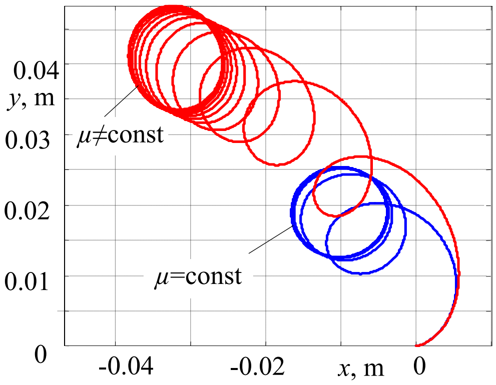


Fig. 9 Motion trajectories of the part for constant and controlled friction cases correspondingly, when $\mu_1 = 0.36$, $\mu_2 = 0.1$, $\omega = 35\ s^{-1}$, $R_e = 0.007$ m, $d = 0.5\pi/\omega$, $\tau'_1 = 0.5\pi/\omega$, $\tau''_1 = \pi/\omega + \tau'_1$

The decrease in friction till the moment $\tau'_1 = \pi/\omega$, characterizes motion of the part as slowly increasing, but later diminishing displacement (Fig. 10), while under higher excitation amplitude R_e, the displacement is more significant.

The displacement K of the part, from the initial position towards the center of steady state trajectory, is highly dependent on duration of the maintained decreased friction. When duration d of the reduced friction is increased, the displacement K increases rapidly (Fig. 11).

The obtained under controlled dry friction, length dependences of the major A and minor B axes of elliptic search trajectory of the part on various parameters are different. By increasing the time duration to friction reducing moment τ'_1, major axis of the elliptic trajectory varies very slightly (Fig. 12), initially the short axis increases, but later it starts decreasing (Fig. 13). Increasing duration d of the maintained decreased friction, major axis A of the elliptic search trajectory increases slightly (Fig. 14), whereas the short axis B varies hardly (Fig. 15).

When the plane is excided elliptically, the same for circular excitation, displacement of the part, from the initial position up to the steady trajectory, under controlled

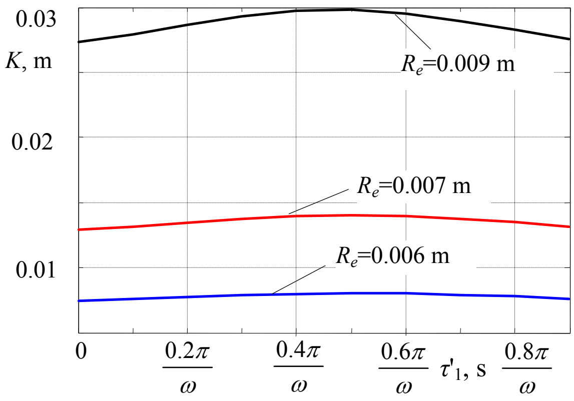


Fig. 10 Dependences of the part's displacement K, from the initial position to the center of steady state motion, on actuation moment τ'_1 of decreased friction, as $\omega = 35\ s^{-1}$, $\mu_1 = 0.36$, $\mu_1 = 0.1$, $d = 0.1\pi/\omega$, $\tau''_1 = \pi/\omega + \tau'_1$

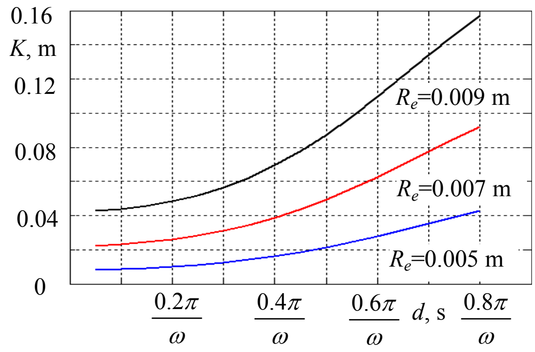


Fig. 11 Dependences of the part's displacement K, from the initial position to the center of the steady state motion, on duration of the maintained decreased friction, as $\omega = 35\ s^{-1}$, $\mu_1 = 0.36$, $\mu_2 = 0.1$, $\tau'_1 = 0$, $\tau''_1 = \pi/\omega$

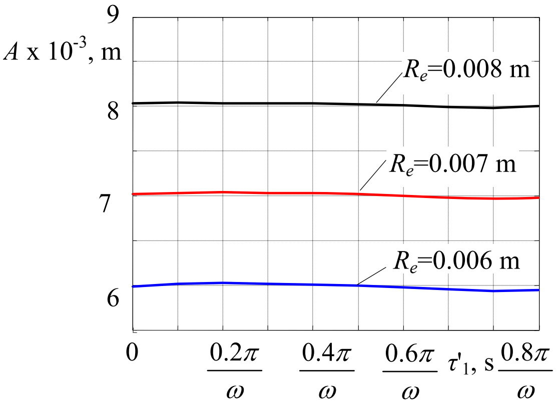


Fig. 12 Dependences of the major axis A on friction decrease moment τ'_1, when $\omega = 70\ s^{-1}$, $\mu_1 = 0.36$, $\mu_2 = 0.1$, $d = 0.1\pi/\omega$, $\tau''_1 = \pi/\omega + \tau'_1$

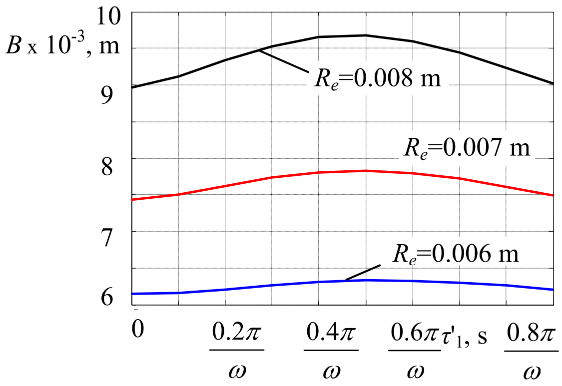


Fig. 13 Dependences of the minor axis B on friction decrease moment τ'_1, when $\omega = 70$ s^{-1}, $\mu_1 = 0.36$, $\mu_2 = 0.1$, $d = 0.1\pi/\omega$, $\tau''_1 = \pi/\omega+\tau'_1$

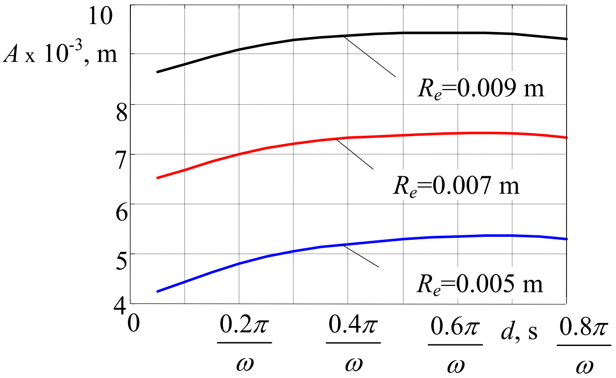


Fig. 14 Dependence of the major axis A on duration d of the maintained decreased friction, when $\omega = 35$ s^{-1}, $\mu_1 = 0.36$, $\mu_2 = 0.1$, $\tau'_1 = 0$, $\tau''_1 = \pi/\omega$

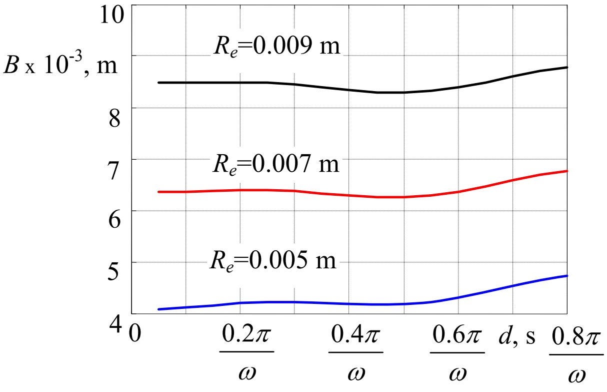
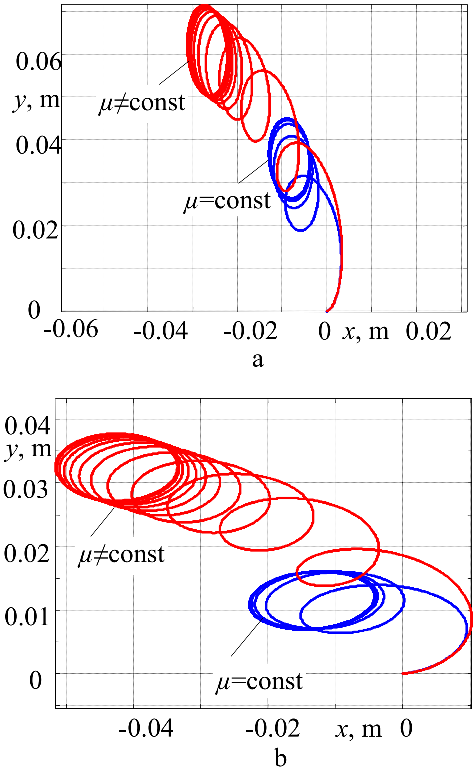


Fig. 15 Dependence of the minor axis B on duration d of the maintained decreased friction, when $\omega = 35$ s^{-1}, $\mu_1 = 0.36$, $\mu_2 = 0.1$, $\tau'_1 = 0$, $\tau''_1 = \pi/\omega$

dry friction is significantly larger, than that under constant friction coefficient (Fig. 16).



a

b

Fig. 16 Parts motion trajectories under constant and controlled friction coefficient, as $\mu_1 = 0.37$, $\mu_2 = 0.1$, $\omega = 35$ s^{-1}, $R_e = 0.007$ m; $d = 0.5\pi$, $\tau'_1 = 0.5\pi/\omega$, $\tau''_1 = \pi/\omega+\tau'_1$: a – $A_e < B_e$, b – $A_e > B_e$

Controlled dry friction improves the conditions for part manipulation and search motion, because under the same parameters of the plane excitation along circular trajectory, providing high frequency vibrations at particular moments, the distance the part displaces is twice as bigger. Furthermore, an elliptic steady motion trajectory is obtained and so the search of mating surfaces is improved.

4. Conclusions

1. When dry friction between the part and the plane is controlled by elastic vibrations of the plane, providing them at particular moments during one semiperiod of the excitation signal, it is possible to perform positioning of the part towards the particular point. Controlling dry friction within both the semiperiods of the excitation, it is possible to position the part and ensure the elliptic search trajectory.

2. As friction is controlled during one semiperiod of the excitation, both the direction of motion and displacement of the part, from the initial position towards the center of steady state trajectory, depend on the moment of the decreased friction, relative to the excitation signal, and on duration of the maintained decreased friction.

3. Controlling dry friction during both the semiperiods of the plane excitation, the part on the plane gets positioned and performs search along elliptic trajectory. Thus, distance, travelled by the part from the initial position towards the center of steady state trajectory, is significantly larger than that under constant dry friction force, whereas the trajectory of steady motion of the part is elliptic.

Acknowledgments

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DETALĖS MANIPULIAVIMAS ANT VIRPANČIOS PLOKŠTUMOS VALDANT SAUSĄJĄ TRINTĮ

Reziumė

Straipsnyje nagrinėjamas detalės judėjimas ant horizontaliai dviem statmenomis kryptimis žadinamos plokštumos, esant valdomam sausosios trinties tarp plokštumos ir detalės koeficientui. Išskirtos detalės judėjimo trajektorijos pozicionavimo ir paieškos metu, kai plokštuma virpa apskritimu ir elipse, o trinties koeficientas valdomas viename ir abiejuose žadinimo signalo pusperiodžiuose. Nustatytos detalės poslinkio nuo pradinės padėties iki nusistovėjusios trajektorijos centro ir judesio trajektorijos krypties kampo priklausomybės nuo trinties sumažėjimo žadinimo signalo atžvilgiu momento ir sumažintos trinties išlaikymo trukmės.

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MANIPULATION OF A PART ON A VIBRATING PLANE UNDER CONTROLLED DRY FRICTION

Summary

Motion of the part over the horizontally excited in two perpendicular directions plane, under controlled dry friction coefficient between the plane and the part, is analyzed in the paper. Motion trajectories of the part during positioning and search were defined, as the plane is excited along the circular and elliptic trajectories and friction coefficient is controlled in one and both the semiperiods of the excitation signal. There were defined dependences of the part displacement, from the initial position towards the center of the steady state trajectory, and directional angle of the motion trajectory both on the moment of decreased friction, relative to the excitation signal, and on duration of the maintained decreased friction.

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МАНИПУЛИРОВАНИЕ ДЕТАЛИ НА ВИБРИРУЮЩЕЙ ПЛОСКОСТИ ПРИ УПРАВЛЕНИИ СУХОГО ТРЕНИЯ

Резюме

В статье рассматривается движение детали на горизонтальной в двух перпендикулярных направлениях возбуждаемой плоскости при управлении коэффициента сухого трения между плоскостью и деталью. Исследованы траектории движения детали во время позиционирования и поиска, при сообщении плоскости вибраций по круговой и эллиптической траекториям и управлении коэффициента трения в одном и обоих полупериодах сигнала возбуждения. Определены зависимости перемещения детали от начального положения до центра траектории установившегося движения и зависимости угла направления траектории движения от момента уменьшения трения относительно сигнала возбуждения и длительности выдержки уменьшенного трения.

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