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Effect of dynamic properties of interacting subsystems on evolution of selective transfer formation in friction units [*]

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Влияние динамических свойств взаимодействующих подсистем на эволюцию формирования избирательного переноса в узлах трения[***]

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Introduction. Selective transfer is a typical example of the self-organization processes in tribosystems. In this case, joint surfaces of the servovite film are formed in the contact area, which changes fundamentally the friction and wear conditions. To form selective transfer in the area of mating surfaces, some power of the irreversible transformations of the input energy is needed, which depends on the elastic-dissipative properties of the contact surfaces.

Materials and Methods. The mathematical model of the dynamic system considering the evolutionarily changing servovite film is given. Its formation depends on the phase path of the irreversible transformations power in the area of surface matching, and it is represented by the Volterra integral operator of the second kind.

Research Results. The outcome analysis including dependences of the servovite film formation on the dynamic parameters of interacting subsystems is provided. The mathematical simulation of the evolution of the friction unit properties with the formation or destruction of the servovite film is first considered.

Discussion and Conclusions. During the evolutionary process of the servovite film formation, the dynamic coupling parameters generated in the friction unit, change. Consequently, the dynamic properties of the system also change. The tribosystem dynamics is first considered under the process of forming the selective transfer.

Keywords: dynamic friction system, selective transfer, servovite film, evolution.

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Введение. Типичным примером процессов самоорганизации в трибосистемах является избирательный перенос. В этом случае в области контакта формируются сопрягающие поверхности сервовитной пленки, что принципиально меняет условия трения и изнашивания. Для образования избирательного переноса в зоне сопряжения контактирующих поверхностей необходима некоторая мощность необратимых преобразований подводимой энергии, которая зависит от упруго-диссипативных свойств контактирующих поверхностей.

Материалы и методы. Приводится математическая модель динамической системы с учетом эволюционно изменяющейся сервовитной пленки. Ее формирование зависит от фазовой траектории мощности необратимых преобразований в зоне сопряжения поверхностей и представляется в виде интегрального оператора Вольтерры второго рода.

Результаты исследования. Приводится анализ результатов исследования, в том числе зависимости формирования сервовитной пленки от динамических параметров взаимодействующих подсистем. Впервые рассматривается проблема математического моделирования эволюции свойств узла трения с образованием или разрушением сервовитной пленки.

Обсуждение и заключение. В ходе эволюционного процесса образования сервовитной пленки меняются параметры динамической связи, формируемой в узле трения. Следовательно, меняются и динамические свойства системы. Впервые проанализирована динамика трибосистемы в процессе образования избирательного переноса.

Ключевые слова: динамическая система трения, избирательный перенос, сервовитная пленка, эволюция.

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Introduction. After publication of the papers by I. Prigogine [1–3] and G. Haken [4, 5], lots of issues on the operation of technical systems interacting with different media are considered from the view point of their self-organization [6–12]. If you follow the synergetic analysis paradigm, then when studying such systems, you should first perform the procedure for extending the state space dimension [7, 8]. That means that it is necessary to additionally consider a model of environment in the coordinates of the system state. There is an exchange of information, material, energy, etc., with the environment. Here, coherent interactions of various physical nature are possible, that is, synergetic phenomena. A typical example of self-organization is the effect of selective transfer discovered by I.V. Kragelsky and D.N. Garkunov in 1956 [13].

The ideas of self-organization were formulated by B.I. Kostetsky [14] in the 60s of the XX century, and then developed in papers on structural adaptability together with L.I. Bershadsky [15] and N.A. Bushe [16]. In a number of papers, the formation of a servovite film in the tribosystem when it enters the selective transfer mode is studied [17–22]. It is shown that definite tribochemical reactions are necessary for the formation of selective transfer, as well as some power trajectory of irreversible transformations in the system-environment interface [17–24]. When entering the selective transfer mode, self-oscillations are observed. In some cases, chaotic attracting sets of deformation displacements of the contacting pairs are formed [17, 22–24].

Materials and Methods. Thus, when studying the transition to the selective transfer mode, it is necessary to consider the tribosystem dynamics in the unity of the subsystems interacting through friction and the dynamic coupling formed by the friction node. The parameters of such a dynamic link and the formation of a servovite film depend on the power path of irreversible transformations on the work done. The mathematical modeling of such an evolutionary system is considered, and the dependence of evolution on the dynamic parameters of interacting subsystems is analyzed.

Research Results

Mathematical system modeling. In mathematical modeling, we use the previously obtained results. In [17, 23, 24–26] it was shown that the basic dynamic properties of the friction system can be disclosed on the basis of the following assumptions:

- the sample is absolutely tough;

- indenter deformations are considered in the plane normal to the contacting surface and passing through the direction of the relative slip velocity.

When studying the dynamics, we can limit ourselves to the first vibration modes. Then, the system model is represented by the equation

$$m\frac{d^2X}{dt^2}+h\frac{dX}{dt}+cX=F_{\Sigma}(t), \tag{1}$$

where $m=\begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix}$, $h=\begin{bmatrix} h_{1,1} & h_{2,1} \\ h_{1,2} & h_{2,2} \end{bmatrix}$, $c=\begin{bmatrix} c_{1,1} & c_{2,1} \\ c_{1,2} & c_{2,2} \end{bmatrix}$ are positively defined, symmetric matrices of inertial, velocity, and elastic coefficients; $X=\{X_1,X_2\}^T$ is vector of the deformation displacements of the indenter tip; $F_{\Sigma}(t)=\{F_{1,\Sigma}(t),F_{2,\Sigma}(t)\}^T$ is vector of forces affecting the indenter tip (Fig. 1).

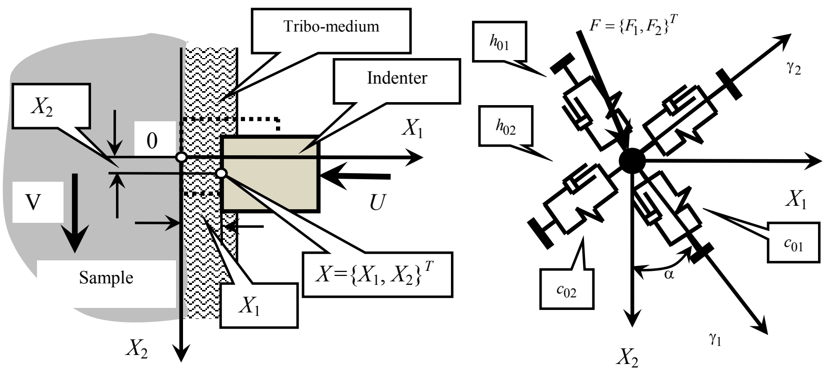


Fig. 1. Dynamic friction system schematic

We will follow the synergistic concept of the analysis, that is, we will represent $F_{\Sigma}(t)$ forces in the coordinates of the state. To do this, we introduce the concept of tribo-medium - this is the third body that is formed in the transition zone between the contacting surfaces. When approaching, the conditions of their interactions change, which physically manifests itself in changing parameters such as the actual contact area, heat production, friction coefficient, molecular interaction conditions, diffusion processes, etc. [27–30]. However, the primary reasons for all changes are interactions due to the contact mechanics.

In this case, due to changing the actual contact area, the normal pressure forces grow disproportionately fast, which prevent the surfaces from approaching. It is convenient to consider modeling these forces [23, 24] as the following function of approach

$$F_1(X_1) = F_{1,0}\exp[-\alpha(X_1)] - U, \quad X_1 \in (0,+\infty), \tag{2}$$

where α is coefficient of the contact force rate in $\left[mm^{-1}\right]$; U is an external force.

The above papers show that when a servovite film is being formed, a potential barrier appears in the function of approach, which actually determines the carrying capacity of the servovite film of the friction unit. The formation of a potential barrier can be conveniently represented as

$$\Phi_1(X_1) = \Phi_{1,0}\exp[-\alpha_1(X_1 - X_{1,0})^2], \tag{3}$$

where α_1 is the parameter characterizing the potential barrier slope in $\left[mm^{-2}\right]$; $X_{1,0}$ is the potential barrier coordinate; $\Phi_{1,0}$ is the evolutionary parameter in [*kg*]. Thus, the function of convergence is $F_{1,\Sigma}(X_1) = \Phi_1(X_1) + F_1(X_1)$ sum. On modeling the tangential component of the force, let us take into account that when forming a servovite film, the friction force is by an order of magnitude less. Therefore

$$F_{2,\Sigma}(t) = \begin{cases} k_T^{(1)} F_{1,\Sigma}(t), at: X_1 \langle X_{1.0}; \\ k_T^{(2)} F_{1,\Sigma}(t), at: X_1 \rangle X_{1.0}, \end{cases} \tag{4}$$

where $k_T^{(1)} \rangle\rangle k_T^{(2)}$.

For example, in the steel – glycerin – brass friction system, after the formation of a servovite film, the friction coefficient decreases by more than an order of magnitude. Previously it was shown that the forces of contact interaction are characterized by a lag in the tangential component of the force (friction force) with respect to the normal pressure forces. In this case, instead of (4), the following relation occurs

$$F_{2,\Sigma}(t) = \begin{cases} k_T^{(1)} F_{1,\Sigma}(t - T^{(1)}), at: X_1 \langle X_{1.0}; \\ k_T^{(2)} F_{1,\Sigma}(t - T^{(2)}), at: X_1 \rangle X_{1.0}, \end{cases} \tag{5}$$

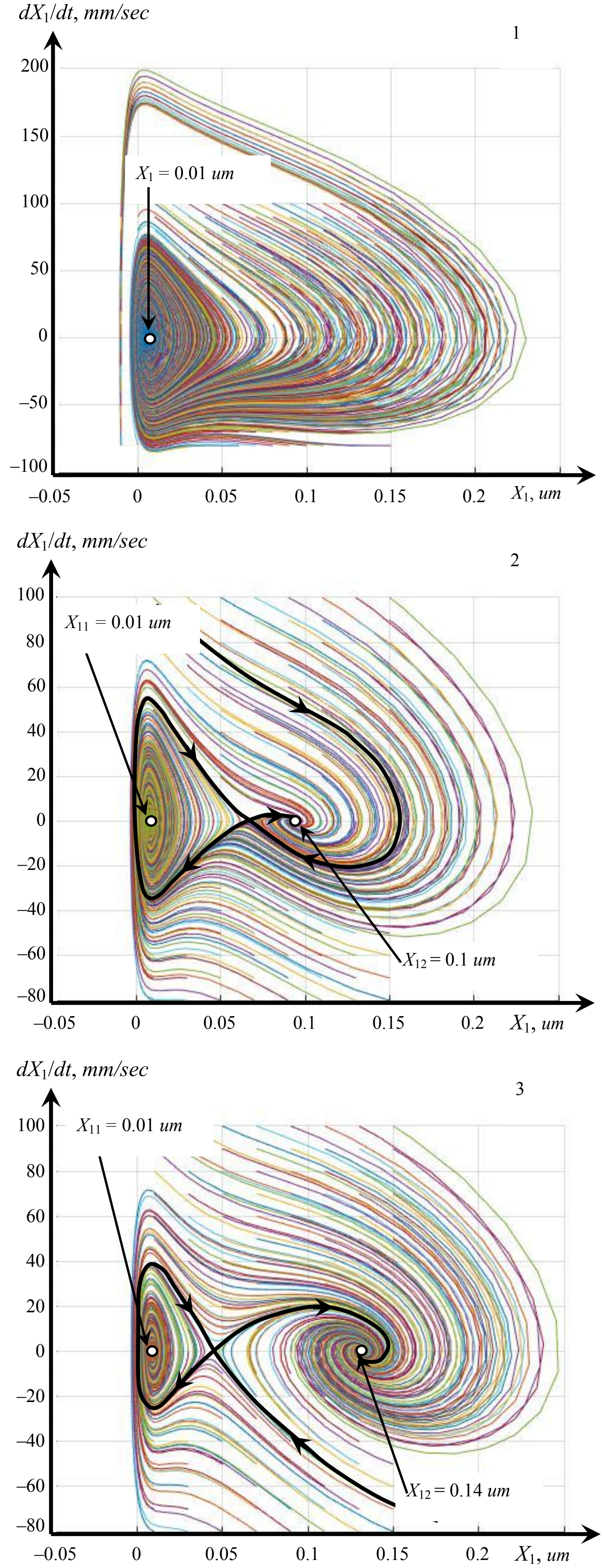
where $T^{(1)}$, $T^{(2)}$ are time-lag constants depending on the properties of the tribo-medium formed in the contact area, and on the relative slip velocity. In (5), $T^{(1)} \rangle\rangle T^{(2)}$ condition is always satisfied. In addition, $T^{(1)}$ and $T^{(2)}$ decrease with increasing the relative slip velocity. Later, the hypothesis was adopted, according to which the potential barrier is formed depending on the work paths and the power of irreversible transformations as the indenter moves relative to the sample in the direction of the relative slip velocity. Moreover, $\Phi_{1.0}$ is affected not only by the current value of power, but also by the preceding values of power. Therefore the following is true:

$$\Phi_{1.0}(N) = \beta \int_0^t w(t - \xi) N(\xi) d\xi , \tag{6}$$

where $N = F_2(V + dX_2 / dt)$ is the power of irreversible transformations; $w(t-\xi) = \{\beta \exp[-\frac{1}{T}(t-\xi)]\}$ is the core of the integral operator considering the effect of the preceding power values; T is the parameter in $\left[s\right]$ characterizing a long-time impact of power on the potential barrier; β is the parameter in $\left[m^{-1}\right]$.

The equations (1) - (6) characterize the mathematical model of a dynamic friction system considering the evolution of its properties during the formation of a servovite film.

Dynamic properties change depending on the potential barrier parameters and the dynamic properties of the indenter. First, consider the properties of the frozen system on the assumption that the parameters of the servovite film are preset and constant. Suppose also that $T^{(1)} = 0$ and $T^{(2)} = 0$. Consider an example of changing system properties depending on the stages of the evolutionary transformation (Fig. 2).


dX1/dt, mm/sec
1
200
150
100
50
0
–50
–100
X1 = 0.01 um
–0.05
0
0.05
0.1
0.15
0.2
X1, um
dX1/dt, mm/sec
2
100
80
60
40
20
0
–20
–40
–60
–80
X11 = 0.01 um
X12 = 0.1 um
–0.05
0
0.05
0.1
0.15
0.2
X1, um
dX1/dt, mm/sec
3
100
80
60
40
20
0
–20
–40
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X11 = 0.01 um
X12 = 0.14 um
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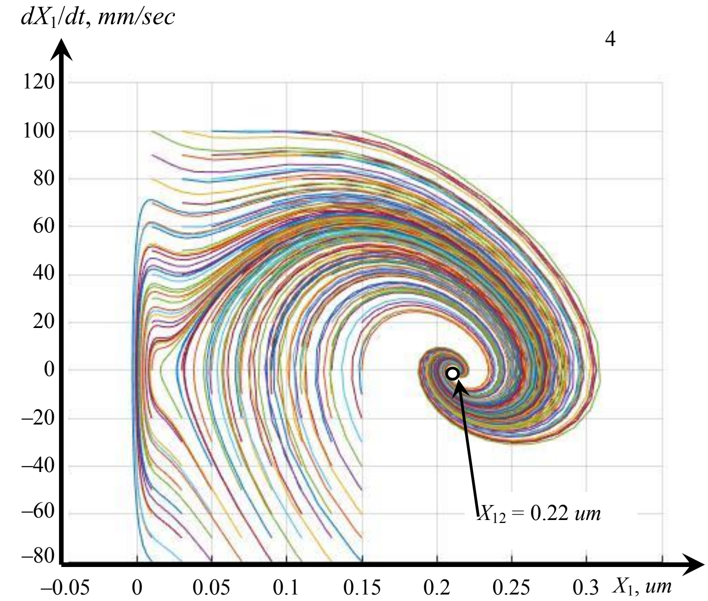

Fig. 2. Transformation of phase path projections onto X_1 — dX_1/dt plane

At the initial stage of transformations (Fig. 2-1), a unique equilibrium point is formed in the system, which corresponds to the friction with a traditional coefficient in the range of 0.2–0.3. Moreover, this point has the property of global attraction. Then (Fig. 2-2), two equilibrium points ($X_{1.1}, X_{1.2}$) are formed during the formation of a servovite film at the initial stage. The domain of attraction of $X_{1.1}$ point is bounded by a saddle-shaped separatrix. The rest of the domain is characterized by the attraction to $X_{1.2}$ point. It is important that at $X_{1.2}$ point of equilibrium, a servovite film is already formed, but its value and properties (determined by $\Phi_{1.0}$) do not allow for the attraction of the trajectories of the whole phase space. Therefore, depending on the initial conditions or disturbances (for example, fluctuations or formable attracting sets of deformation displacements in variations relative to the equilibrium point), it is possible to generate properties of a friction unit that differ fundamentally from each other. Subsequently (Fig. 2-3), the domain bounded by the saddle separatrix decreases and disappears (Fig. 2-4). In the latter case, the servovite film thickness and its carrying capacity increase. In the model, this is shown as an increase in the potential barrier, and the second equilibrium point acquires the properties of global attraction. In this case, a stable selective transfer is formed in the system.

The illustrations characterize the system dynamics considering that the servovite film properties are frozen, that is, they do not evolve. However, even in this case, the domains of attraction of equilibrium points corresponding to the friction with a servovite film and without it depend fundamentally on the dynamic parameters of the indenter, primarily, on the matrices of its stiffness (c) and dissipation (h) (1). In actual practice, there is a time evolution of the system. It depends on the relative slip velocity

(V_0), the force (U), the initial state of the surface of the contacting bodies, etc. The evolution simulated by an integral operator (6) is affected by many physical factors the integral count of which is determined by the kernel of the operator. Therefore, when varying the external conditions (for example, relative slip velocity), it is necessary to consider the velocity – integral operator parameters relationship, as well as the velocity – the power trajectory of irreversible transformations relationship. It is experimentally shown that with increasing speed, $T_i, i=1,2$ parameter in (6) decreases. In addition, frictional forces (and, consequently, the power path of irreversible transformations) depend on the relative slip velocity. Note that it is the time required to establish a stationary servovite film that determines one of the indicators which allow identifying the parameters of the integral operator kernel.

Cursorily, we give an example of changing the phase trajectories of deformation displacements in X_1-direction as the indenter dynamic parameters and the tribological medium properties vary (Fig. 3).

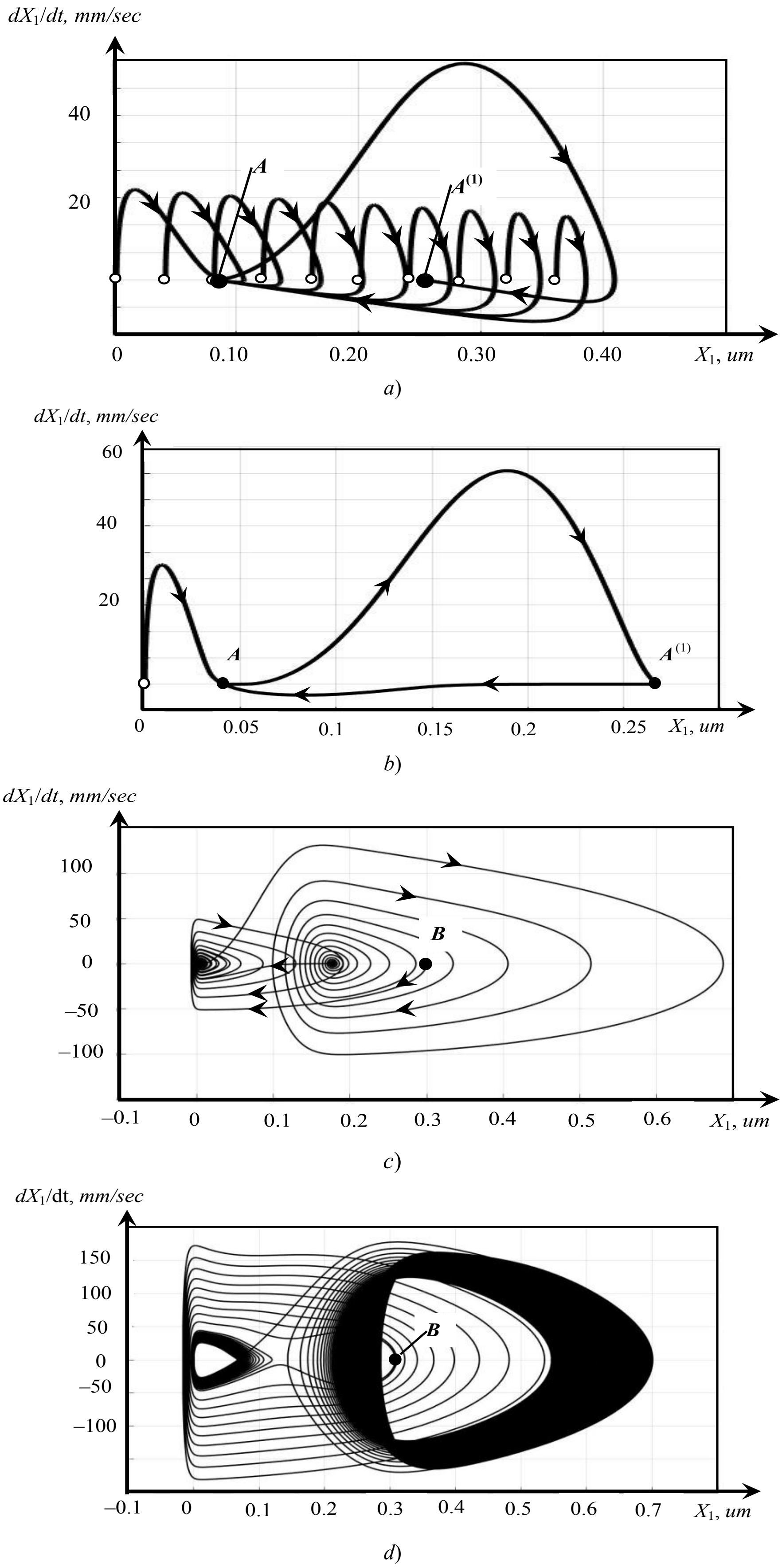

Fig. 3. Transformation of phase path projections onto X_1 — dX_1/dt plane depending on system parameters and friction conditions

First, consider friction with a sufficiently high velocity of relative slip $V_0 = 2.0\ м/с$. In this case, when forming a servovite film, the power of irreversible transformations decreases and the destruction is not observed, since the relative slip velocity is rather high (Fig. 3, *a*). At the initial stage, under various conditions, the trajectories are asymptotically attracted to the equilibrium point without a servovite film (point A in Fig. 3, *a*). After the potential barrier has been established, all trajectories evolve to $A^{(1)}$ equilibrium point on the servovite film. Fig. 3, *b*, *c*, and *d* show evolutionary curves with one initial value corresponding to *B* point. At this, the deformation displacements and the corresponding properties of the friction system deform to one of the two equilibrium points. However, evolutionary curves differ depending on the properties of the tribo-media and the Q-factor of the oscillatory circuits of the indenter subsystem without friction. Fig. 3, *b* shows an example of the evolutionary trajectory under *a* conditions, but at the relative slip velocity of $V_0 = 1.0\, m/s$. In this case, the power released in the friction zone is not enough to maintain the servovite film, and friction is periodically observed in the system with a servovite film and without it. In the deformation displacements, this causes the effect of low-frequency oscillations. Specifically, the formation time and the destruction time of the servovite film differ essentially. In Fig. 3, this is indicated through a significant decrease in the rate at which the indenter tip returns from $A^{(1)}$ point to *A* point.

The Q-factor of the indenter subsystem can be increased (Fig. 3, *c*). In this case, complex oscillatory displacements are formed in the system. Some of their components characterize the low-frequency material exchange between the lubricant and the friction surface, as well as vibration displacements at the frequencies of the indenter oscillators.

In the direction orthogonal to the relative slip velocity, cyclic forces are generated. Due to this, and also due to the dynamic interaction, a short-term formation of forces exceeding the potential barrier is possible. The situation is even more complicated if we additionally consider the lag in the variations of the tangential force components to their normal components (Fig. 3, *d*). Depending on the lag, various attracting sets of deformation displacements and, consequently, the forces of contact interaction are formed. The generation of chaotic dynamics in the system, which introduces great uncertainty in the regularities of servovite film formation, is also observed.

Discussion of the results. It is known that moving of the tribosystem to the selective transfer mode is determined by tribochemical reactions and the material exchange between the contacting surfaces and the lubricant. In order for the tribosystem to enter the selective transfer mode with the formation of a servovite film and to maintain it in the process of friction, some particular power of irreversible transformations of the input energy of the mechanical system is required [17, 21–24]. During the evolution of the dynamic friction system, the carrying capacity of the servovite film varies, which is simulated by the size of $\Phi_{1.0}$ potential barrier preventing direct contact of the friction surfaces. If the forces of contact interaction in the direction normal to this surface exceed $\Phi_{1.0}$, then a dynamic restructuring of the friction system with partial destruction of the servovite film is observed. Therefore, the friction conditions in the selective transfer mode depend not only on tribochemical reactions and the power of irreversible transformations, but also on the dynamic mode. Here, the stability of the equilibrium point and various attracting sets of deformation displacements (limit cycles, invariant tori, chaotic attractors) formed in its neighborhood are of fundamental importance. In addition, the dynamic system is perturbed, for example, by the out-of-true-running. Moreover, due to a fundamental change in the friction conditions during the direct contact and at the contact through a servovite film, the power of irreversible transformations in the surface matching changes, which changes the evolution and the maintenance conditions of the formed servovite film.

Conclusion. So, in conclusion: the stability of selective transfer is affected by both the dynamic parameters of the subsystems interacting through the friction node, and by disturbances that always occur in a real machine. Therefore, when studying selective transfer to ensure the friction unit wearlessness, it is required to obtain identity of the dynamic systems on a friction machine and in a real machine. For this purpose, the well-known techniques [27, 31] can be used.

The data show that the formation of a servovite film in a tribocontact node is affected not only by the tribochemical characteristics of the mating surfaces, but also by the parameters of the indenter and sample subsystems interacting through the tribology. Therefore, in each specific case, there is a bounded domain of parametric space of the dynamical systems, as well as disturbances in which the formation of selective transfer is a rule.

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