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THE MECHANISM OF VIBRATIONAL MOVEMENT OF TANGENT STRUCTURES IN CLOSED VOLUMES

The **subject** of research in the article is the process of vibratory movement of tangent structures in closed volumes (pipes). The **purpose** of this work is to investigate the mechanism of vibrational movement of tangent structures in closed volumes (pipes). The following **tasks** are solved in the article: to study the oscillating motion of a tangent structure consisting of a cantilever rod with a fixed end at the base, and by means of supports connected by dry friction with two parallel rough planes; the experimental method confirms the possibility of vibrational movement of the inner element of the tangent structure along the cylinder. The following **methods** are used: mathematical modeling and experimental study. The following **results** were obtained: a mathematical model of motion of a tangent structure is proposed, consisting of a cantilever rod with a fixed end, which by means of supports is connected by the force of dry friction with two parallel rough planes when applying a vibrating force perpendicular to the longitudinal axis of the structure; confirmed the possibility of vibration movement of the inner element of the tangent structure (cantileverly mounted rod in a cylindrical basis) along the outer element of the tangent structure (cylinder) when applying a vibrating force perpendicular to the longitudinal axis of the rod. **Conclusions**: 1) the effect of forced oscillations on tangent structures with structural asymmetry of the inner element of the tangent structure may cause the effect of vibrating movement of the inner element of the tangent structure relative to the outer element; 2) possible vibration movement of the inner element of the tangent structure (cantileverly mounted rod in a cylindrical basis) along the outer element of the tangent structure (cylinder) at an angle between the longitudinal axis of the inner element and the direction of external vibration force, which is equal to 900; 3) possible stopping of the inner element of the tangent structure, in the absence of the action of external vibrating force, in the place of the outer cylinder, in which the effect of the external vibrating force has stopped.

Keywords: vibration displacement; effect; frequency; fluctuation; tangent construction, friction force; internal element; external element; cylinder.

Introduction

Modern multi-series production in various industries is based on the current method with extensive use of automatic transport lines [1]. The current method of production and operation of the automatic line are based on the conveyor transfer of products from one technological operation to another, while the necessary operations are performed sequentially on a moving conveyor. One of the types of production lines is vibrating conveying machines. The advantages of transporting vibrating machines are the possibility of complete sealing during transportation of sawdust, toxic and hot cargo, the ability to perform other technological operations in conjunction with transportation, low wear of the load-bearing body. Vibrating conveyors are one of the main means of complex mechanization, automation of transport and loading and unloading operations, with a combination of other technological operations. The operation of vibrating conveyors is based on the effect of vibrating movement. Under the effect of vibrational movement means the emergence of directed in the average movement due to undirected in the average (oscillating) effects [2, 3].

To obtain vibrational movement, one or another asymmetry of the system is required. We can distinguish the following types of asymmetry: force, kinematic, structural (constructive), gradient, wave and initial (ie associated with the initial conditions of motion). It is also possible to combine several types of asymmetry [3, 4].

The vibrating conveyor in general is an open or closed sealed gutter or pipe suspended or supported on a supporting structure. The gutter or pipe with the help of the oscillator is reported reciprocating motion, as a result of which the load in the gutter, one after another short movements forward at a certain speed. The nature of the movement of the load depends on the mode of movement of the gutter, which is determined by the design and performance of the drive, the type of support devices, external loads and internal resistances of the oscillating system [2].

The process of vibratory movement of the product consists of a number of alternating stages: acceleration, joint movement of products with the gutter (pipe), free flight and braking. Vibration displacement modes are determined by the amplitude of oscillations, the frequency of oscillations, the angle of inclination of the working body and the angle of inclination and the shape of the trajectory of oscillations, and so on. As a result, the product moves on the working body by micro throws under the action of directed oscillations (at an angle of 20… 35°) to the axis of the working body (gutter, pipe, etc.) in a given direction [1–3].

The main advantages of the vibrating conveyor are [1]:

- simple design;
- no contamination of the moved material with foreign substances;
- no material losses;
- the load-bearing body is practically not prone to wear even when transporting abrasive materials;
- the ability to combine the process of moving material with technological operations.

At the same time, the vibrations of mechanisms and machines have a negative impact on the operation of equipment and devices, reduce the durability of technical systems, and create dangerous working conditions for maintenance personnel. In general, the area of manifestation of vibrational interactions can be attributed to a fairly developed direction of modern machine dynamics.

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These machines have already become widespread in a number of industries [1]. However, the flow of new ideas and proposals for the development of vibrating transport devices is not exhausted. Vibrating transport devices began to be used in the food industry in the purification of food and seed grains, as well as in mining and processing enterprises in the separation of ore from waste rock, etc. [4-7].

Of interest is the device for vertical movement of the product, proposed by R.M. Brumberg (fig. 1) [8].

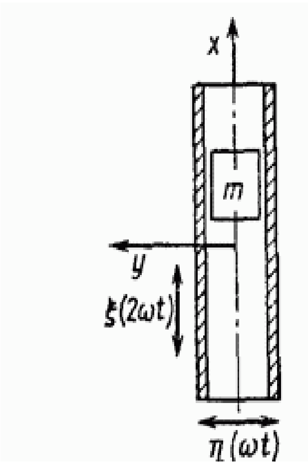

Fig.1. Device for vertical movement of the product

The vibrating body is made in the form of a tube, which is given longitudinal and transverse oscillations, and the frequency of longitudinal oscillations is twice the frequency of transverse oscillations. When the oscillations are properly phased, the longitudinal force of inertia acting on the product in its relative motion is directed upwards precisely at the time intervals when the product is least pressed against the pipe walls by the action of the transverse force of inertia. During the time when the longitudinal force of inertia is directed downwards, the product is most strongly pressed against the walls of the pipe. As a result, a vibrating force arises, which provides a directed upward movement against the action of gravity.

However, the disadvantage of these designs is that the vibration is applied to the entire gutter (pipe) with the products, at an angle of 20 to 400, and in the device for vertical movement of the product (at an angle of 900), after excluding the vibrators, the product (internal body), under the action of gravity, falls down.

Analysis of recent research and publications

The theoretical basis of the direction of application of vibration to the movement of products is formed at the junction of theoretical mechanics, theory of mechanisms and machines, theory of oscillations, theory of vibrational movement, theory of vibrational processes [1-3, 8]. Significant sections of the theory of vibrational processes relate to the field of nonlinear mechanics, nonlinear theory of oscillations and waves [9, 10]. Attention to the issues of vibrational displacement is emphasized when considering individual problems of machine dynamics [11, 12]. Vibration processes are diverse, as well as forms of influence on the dynamic state of technical objects. The emergence of new design and technical solutions, the development of new classes of machines, which include robotic devices for various purposes, initiate the expansion of research. In this regard, the processes of contact interaction of solids are important [13]. Such processes are studied as vibro-shock, which find expression in the development of technical applications related to improving the reliability of parts operating under conditions of intense dynamic loading.

In addition, the processes of optimal control of a new class of mobile mechanisms (robots) that can move in environments that resist without special propellers (wheels, tracks) are promising. Such robots consist of a body that interacts with the external environment, and products that are movably connected to it. The movement of these products relative to the body characterizes the internal degrees of freedom of the robot. Such products are called internal, although they can be placed structurally inside the case. Internal products interact with the housing using forces generated by the drives. Adding force to the internal product causes a reaction force that acts on the housing, changing its speed, which causes a change in the resistance force of the medium to the movement of the housing. Thus, by controlling the movement of internal products, you can control the external force acting on the body and, as a result, the movement of the system as a whole. This principle of movement is suitable for mobile mini and micro robots. The body of these robots can be made sealed and smooth, does not contain protruding parts, which allows them to be used for non-destructive inspection of miniature technical objects, such as thin-walled pipelines of small diameter. Mobile systems that move and resist in the environment due to the movement of internal products attract the attention of not only specialists in robotics, but also researchers and engineers in the fields of vibration and precision mechanics [14-17]. In many cases, the vibration effect is considered as a factor of influence on the state of interacting parties. To a lesser extent, the features of friction bonds that are characteristic of technological processes of vibration displacement, vibration strengthening, and vibration transportation, associated with the contact of touching products and the resulting effects, have been studied.

The **purpose** of the article is to investigate the mechanism of vibrational movement of tangent structures in closed volumes (pipes).

Problem solving. (Presenting main material)

The study of the effect of vibration load on the dynamic properties of the elements of tangential structures will be carried out taking into account the fact that tangent structures are nonlinear mechanical systems in which nonlinearity is due to the presence of forces such as dry friction. Therefore, despite the fact that a number of applied problems of the theory of mechanical oscillations, under certain assumptions, can be solved in a linear formulation, for the study of the dynamics of tangential structures linear formulation is unacceptable. The main difficulty in solving problems of the theory of oscillations

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in the presence of forces such as dry friction is not due to the analytical nature of their characteristics, the differential equations of motion at individual stages are written in different analytical forms. As a rule, at each stage the equations are quite easily integrated. The main difficulty is the search for moments of transition from one stage of movement to another. The general laws of the influence of vibration on the dynamic behavior of nonlinear mechanical systems must be reflected in the oscillations of tangent structures.

Fig. 2 shows a diagram of a single-mass model of a tangent structure placed between two rough planes: the upper 1 and the lower 2.

The mathematical model of the motion of the mass m in the projections on the axis 0X and 0Y associated with the vibrating planes will be as follows:

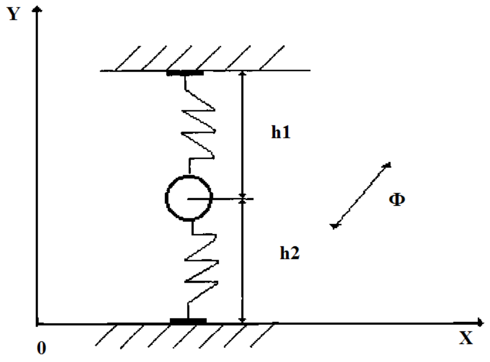

Fig. 2. Scheme of vibrational displacement of a single-mass model of a tangent structure

$$\begin{cases} m\cdot\ddot{x} = m\cdot A\cdot\omega^2\cdot\sin\omega t\cdot\cos\beta + F_1 + F_2 \\ m\cdot\ddot{y} = m\cdot A\cdot\omega^2\cdot\sin\omega t\cdot\sin\beta - N_1 - m\cdot g + N_2. \end{cases}$$

$$F_1 = \begin{cases} -f_1\cdot N_1 \; npu \; \dot{x} > 0 \\ f_1\cdot N_1 \; npu \; \dot{x} < 0 \\ f_{10}\cdot N_1 \; npu \; \dot{x} = 0 \end{cases}; \qquad F_2 = \begin{cases} -f_1\cdot N_2 \; npu \; \dot{x} > 0 \\ f_1\cdot N_2 \; npu \; \dot{x} < 0 \\ f_{10}\cdot N_2 \; npu \; \dot{x} = 0 \end{cases}. \qquad (1)$$

where F_1 is the friction force between the upper support and the upper plane, H; F_2 is the friction force between the lower support and the lower plane, H; $N_{2,}$ – normal reaction between the lower support and the lower plane, H; N_1 is the normal reaction between the upper support and the upper plane, H; $\ddot{x}$ – acceleration of the mass m along the X axis, m/s2; $\ddot{y}$ – acceleration of the mass m along the Y axis, m/s^2; g – acceleration of gravity, m/s^2; $\dot{x}$ – velocity of mass m along the x-axis, m/s; ω – frequency of external force F, Hz; β – angle of action of external force F, Grad.; t – time, s; A – amplitude of forced oscillations, m; f_1 is the effective coefficient of dry friction between the mass supports m and the rough planes; f_{10} is the effective coefficient of dry friction at rest between the supports of mass m and rough planes.

The written system of equations is a nonlinear system of ordinary differential equations with periodic coefficients, which allows numerical integration. System analysis allows you to describe the process that is happening. Let's consider the action of forces, starting from t=0, when the force of inertia is zero, and then begins to increase in absolute value, being directed forward (in the direction of the X axis) up (the force F acts). During the first half of the period, while 0 < t< π/ω, the horizontal component of the inertia force is directed along the X axis, tends to shift the mass m to the right. This is facilitated by the vertical component of the force of inertia, which, subtracting from the weight, reduces the normal response of $N_{2,}$ to the value $m\cdot A\cdot\omega^2\cdot\sin\omega t\cdot\sin\beta$ and, thus, reduces the modulus of friction force F_2. In this case, the friction force F_1 increases by the same amount. Normal reactions in this case are determined by expression:

$$\begin{aligned} N_2 &= k\cdot(\Delta y_2 - y) + m\cdot g - m\cdot A\cdot\omega^2\cdot\sin\omega t\cdot\sin\beta; \\ N_1 &= k\cdot(\Delta y_1 - y) + m\cdot A\cdot\omega^2\cdot\sin\omega t\cdot\sin\beta, \end{aligned} \qquad (2)$$

where Δy_1, Δy_2 is the value of the pre-compression of the upper and lower elastic elements of the model, m; k is the stiffness of the elastic elements of the model, N/m.

As a result, the horizontal component of the force of inertia $m\cdot A\cdot\omega^2\cdot\cos\omega t\cdot\cos\beta$ on the shoulder h_1 will create a moment that is directed counterclockwise. The force of friction F_2 on the shoulder (h_1 + h_2) will create a moment that prevents the rotation of the inner element of the structure. If the condition $F_2\cdot\left(h_1+h_2\right) = h_1\cdot m\cdot A\cdot\omega^2\cdot\sin\omega t\cdot\cos\beta$ is met, the lower (2) support will be displaced in the positive direction of the X axis.

During the second half of the period, when π/ω < t < 2π/ω, the force of inertia is directed in the opposite direction and its horizontal component tries to shift the mass m to the left. In this case, the vertical component of the inertia force reduces the normal reaction N_1 and increases the normal reaction N_2. The friction force F_1 decreases, the friction force F_2 increases. The horizontal component of the force of inertia Ig on the shoulder h_2 creates a moment that is directed clockwise. The friction force F_1 on the shoulder (h_1 + h_2) creates a moment that resists the rotation of the inner element of the structure. If the condition $F_1\cdot\left(h_1+h_2\right) = h_2\cdot m\cdot A\cdot\omega^2\cdot\sin\omega t\cdot\cos\beta$ is met, the upper (1) support will be displaced in the negative direction of the X axis.

As a result, the directional movement of the tangent structure in the form of mass m on the elastic supports

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relative to the rough planes will not occur. Thus, in contrast to the classical problem of body motion on a vibrating rough plane, a necessary and sufficient condition for vibration is the presence of friction between a point and a plane obeying Coulomb's law and excitation asymmetry (difference of vibration angle from $\pi/2$ and from 0), these conditions do not lead to vibrational displacement of the elementary tangent structure (mass connected by elastic supports with two rough parallel planes). To carry out the process of vibrational movement of the elements of tangent structures relative to each other, a prerequisite is the presence of structural asymmetry of the model.

Consider the process of vibrational movement of a tangent structure, the scheme of which is shown in fig. 3.

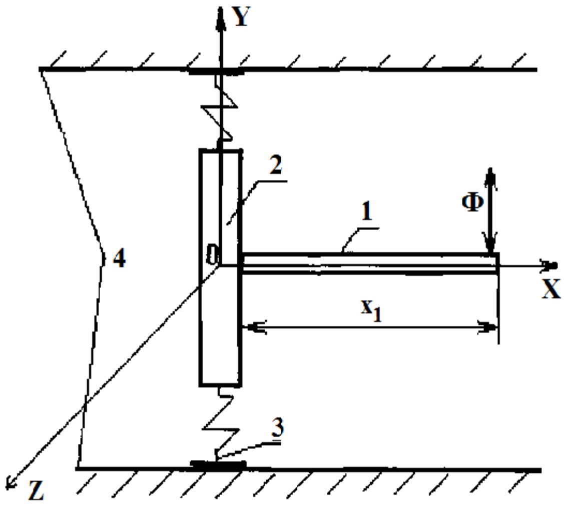

Fig. 3. Scheme of the tangent structure of the cantilever type

Fig. 2 presents a tangent structure that consists of a cantilever rod 1 with the end fixed in the base 2. The base of the beam 2 is connected by means of supports 3 by the force of dry friction with two parallel rough planes. Let's link the core of the rod to the XOY coordinate system. Let the rod be affected by a harmonic force F, which is directed perpendicular to the rod, applied at a distance X_1 from the base. Consider the first half of the period when the force F is directed towards the negative values of the Y axis (down). In this case, the rod starts moving in the same direction. As the rod moves down, the friction force between the lower support and the lower plane F_1 will increase, and between the upper support and the upper plane F_2 will decrease. The force F on the shoulders of X_1 will result in a pair of friction forces F_1 and F_2. The force F_2 is directed toward the negative X-axis value (left), and the force F_1 in the direction of the positive X-axis (right). Since $|F_2|<|F_1|$, the resultant of these forces will be directed towards the positive values of the X axis and is not equal to 0. The resulting friction force on the shoulder r will result in a moment relative to the axis that passes through the lower support, which will lead to a micro-rotation of the rod base in the XOY plane relative to the axis that passes through the lower support. At the change the direction of the force F (the second half of the period) the direction and magnitude of the friction forces F_1 and F_2 also changes. The force F_1 is directed toward negative values of X-axis and the force F_2 in the direction of the positive x-axis. Since the rod is moving up, $|F_2|>|F_1|$. In this case, the resulting friction force is directed towards the positive values of the x-axis. The resulting friction force on the shoulder r will lead to a micro-rotation of the rod base relative to the axis passing through the upper support. Therefore, for any direction of action of the force F along the Y axis, the resulting friction force will be directed in one direction. The action of this force on the shoulder r leads to the process of vibrational movement of the rod base along parallel planes.

Based on the considered process of vibrational movement of elements of tangent structures, the following mathematical model of motion of inner element of tangent structure relative to outer element (in the form of two parallel rough planes) under the action of forced oscillations directed perpendicular to outer planes is proposed (fig. 2). The harmonic force F acts on the rod, which is directed perpendicular to the longitudinal axis of the rod.

The equation of motion of the inner element of the tangent structure relative to the outer is represented in the form:

$$m_1 \cdot \ddot{\varphi} = M_f + M_\varphi, \quad (3)$$

$$\Delta x = d \cdot tg(t), \quad (4)$$

$$x_i + 1 = x_0 + \Delta x_i, \quad (5)$$

where m_1 is the mass moment of inertia of the base, $kg \cdot m^2$; M_φ – the moment created by the force F on the shoulder X_1, relative to the axis, $n \cdot m$; φ is the angle of rotation of the base, at the plane XOY, Grad.; M_f – moment of friction forces, $n \cdot m$; Δx_i – change in the movement of the base along the X axis, m; d is the distance between the outer planes, m

$$M_\varphi = X_1 \cdot \Phi \quad (6)$$

$$M_f = f \cdot d \cdot \left(2 - \frac{A \cdot \omega^2}{\left|\left(p^2 - \omega^2\right) \cdot \Delta y\right|}\right) \cdot k \cdot \Delta y, \quad (7)$$

where p – natural oscillation frequency of the cantilever rod.

If $M_\varphi \le M_{f0}$, then x=0, there is no movement of the rod base along parallel planes.

And if $M_\varphi > M_{f0}$, then the process of vibrational movement of the internal element of the tangent structure relative to the external one takes place.

Experimental studies carried out on the experimental setup shown in fig. 4 confirmed the possibility of vibrational movement of the inner element of the tangent structure (cantilevered rod in a cylindrical base) along the outer element of the tangent structure (cylinder) when applying vibration perpendicular to the longitudinal. In

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this case, the inner element of the tangent structure was subjected to vibration. Experimental studies have shown that it is possible to change the direction of motion, both by changing the forced frequency of oscillations, and by changing the coordinates of the point of application of external harmonic force. As for the magnitude of the force under which the movement of the inner element of the tangent structure relative to the cylinder, it is about 20% of the dry friction force between the supports of the inner element of the tangent structure and the cylinder in the absence of oscillations of the tangent structure.

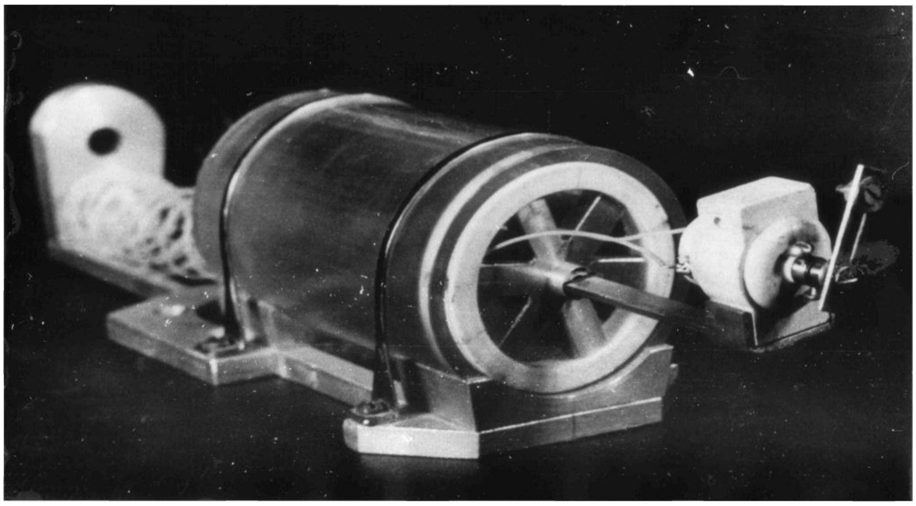

Fig. 4. General view of the experimental model of the tangent structure

In addition, experimental studies have revealed the possibility of vibrating movement of the inner element of the tangent structure (cantilevered rod in a cylindrical base) along the outer element of the tangent structure (cylinder) with the vertical placement of the experimental installation. But in contrast to the device of R.M. Brumberg, when the external vibrating force stops, the inner element of the tangent structure, due to the friction force of rest, stops in the place relative to the cylinder in which the external vibrating force stopped (the base with the rod does not fall down the pipe).

Conclusions

Analysis of research results allows us to draw the following conclusions:

1) under the action of forced oscillations on tangent structures with structural asymmetry of the inner element of the tangent structure, the effect of vibrational movement of the inner element of the tangent structure relative to the outer element is possible;

2) it is possible to vibrate the inner element of the tangent structure (cantilevered rod in a cylindrical base) along the outer element of the tangent structure (cylinder) at an angle between the longitudinal axis of the inner element and the direction of external vibration force equal to 900;

3) it is possible to stop the inner element of the tangent structure, in the absence of external vibrating force, in the place of the outer cylinder, where the external vibrating force has stopped.

Further research is related to the development of technology for vibratory movement of goods over long distances based on the considered effect of vibration movement of tangent structures.

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МЕХАНІЗМ ВІБРАЦІЙНОГО ПЕРЕМІЩЕННЯ ДОТИЧНИХ КОНСТРУКЦІЙ В ЗАМКНУТИХ ОБ'ЄМАХ

Предметом дослідження в статті є процес вібраційного переміщення дотичних конструкцій в замкнутих об'ємах (трубах). **Мета** роботи – дослідити механізм вібраційного переміщення дотичних конструкцій в замкнутих об'ємах (трубах). В статті вирішуються наступні **завдання**: провести дослідження коливального руху дотичної конструкції, що складається з консольного стрижня з закріпленим на основі кінцем, і за допомогою опор пов'язаний силою сухого тертя з двома паралельними шорсткими площинами; експериментальним методом підтверджується можливість вібраційного переміщення внутрішнього елементу дотичної конструкції вздовж циліндру. Використовуються таки **методи:** математичного моделювання та експериментального дослідження. Отримано наступні **результати**: запропонована математична модель руху дотичної конструкції, яка складається з консольного стрижня з закріпленим у основі кінцем, що за допомогою опор пов'язана силою сухого тертя з двома паралельними шорсткими площинками при прикладанні вібраційної сили перпендикулярно повздовжній осі конструкції; підтверджена можливість вібраційного переміщення внутрішнього елементу дотичної конструкції (консольно закріпленого стрижня в циліндричній основі) вздовж зовнішнього елементу дотичної конструкції (циліндру) при прикладанні вібраційної сили перпендикулярно повздовжній осі стрижня. **Висновки**: 1) при дії вимушених коливань на дотичні конструкції з конструктивною асиметрією внутрішнього елемента дотичної конструкції можливе виникнення ефекту вібраційного переміщення внутрішнього елемента дотичної конструкції відносно зовнішнього елемента; 2) можливе здійснення вібраційного переміщення внутрішнього елементу дотичної конструкції (консольно

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закріпленого стрижня в циліндричній основі) вздовж зовнішнього елементу дотичної конструкції (циліндру) при куті між повздовжньою віссю внутрішнього елементу та напрямком дії зовнішньої вібраційної сили, який дорівнює 900 ; 3) mможлива зупинка внутрішнього елемента дотичної конструкції, при відсутності дії зовнішньої вібраційної сили, в тому місці зовнішнього циліндра, в якому припинилась дія зовнішньої вібраційної сили.

Ключові слова: вібрація; переміщення; ефект; частота; коливання; дотична конструкція, сила тертя; внутрішній елемент; зовнішній елемент; циліндр.

МЕХАНИЗМ ВИБРАЦИОННОГО ПЕРЕМЕЩЕНИЯ СОПРИКАСАЮЩИХСЯ КОНСТРУКЦИЙ В ЗАМКНУТЫХ ОБЪЕМАХ

Предметом исследования в статье является процесс вибрационного перемещения соприкасающихся конструкций в замкнутых объемах (трубах). **Цель** работы – исследовать механизм вибрационного перемещения соприкасающихся конструкций в замкнутых объемах (трубах). В статье решаются следующие **задачи**: провести исследования колебательного движения касательной конструкции, состоящей из консольного стержня с закрепленным на основе концом, и с помощью опор связан силой сухого трения с двумя параллельными шероховатыми плоскостями; экспериментальным методом подтверждается возможность вибрационного перемещения внутреннего элемента касательной конструкции вдоль цилиндра. Используются следующие **методы**: математического моделирования и экспериментального исследования. Получены следующие **результаты**: предложена математическая модель движения соприкасающейся конструкции, состоящей из консольного стержня с закрепленным на основе концом, с помощью опор связана силой сухого трения с двумя параллельными шероховатыми плоскостями при приложении вибрационной силы перпендикулярно продольной оси стержня; подтверждена возможность вибрационного перемещения внутреннего элемента соприкасающейся конструкции (консольно закрепленного стержня в цилиндрическом основании) вдоль внешнего элемента соприкасающейся конструкции (цилиндра) при приложении вибрационной силы перпендикулярно продольной оси стержня. **Выводы**: 1) при действии вынужденных колебаний на соприкасающейся конструкции с конструктивной асимметрией внутреннего элемента соприкасающейся конструкции возможно возникновение эффекта вибрационного перемещения внутреннего элемента соприкасающейся конструкции относительно внешнего элемента; 2) возможно осуществление вибрационного перемещения внутреннего элемента соприкасающейся конструкции (консольно закрепленного стержня в цилиндрической основе) вдоль внешнего элемента соприкасающейся конструкции (цилиндра) при угле между продольной осью внутреннего элемента и направлением действия внешней вибрационной силы, равном 900; 3) возможна остановка внутреннего элемента соприкасающейся конструкции, при отсутствии действия внешней вибрационной силы, в том месте внешнего цилиндра, в котором прекратилась действие внешней вибрационной силы.

Ключевые слова: вибрация; перемещение; эффект; частота; колебания; соприкасающаяся конструкция, сила трения; внутренний элемент; внешний элемент; цилиндр.

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