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## TWO-MASS VIBRATORY CONVEYOR-MANIPULATOR WITH THREE-COMPONENT ELECTROMAGNETIC DRIVE

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**Abstract.** Vibratory conveyor with three-component oscillations provides the opportunity to move the piece goods and details for any trajectory on a plane. Phase difference between independent horizontal (longitudinal or transverse) and vertical (normal) oscillations releases elliptical vibration of conveyor in plane perpendicular to the conveyor's track. Elliptical vibrations allow increasing conveying velocity and inclination angle of conveyor's track in comparison with the simplest linear vibrations. Three-component oscillations of the conveyor's track are implemented by independent exciters of oscillations in the direction of conveying (longitudinal oscillations), oscillations in the direction perpendicular to conveying in plane (transverse oscillations) and oscillations in the direction perpendicular to conveying plane (normal oscillations) with phase difference between them. Conveying velocity of details moving upon the track varies with the change of phase difference angle and reaches a maximum with a certain angle, depending on several parameters. When electromagnetic exciters of longitudinal and normal oscillations are turned on, conveying details move in longitudinal direction. When electromagnetic exciters of transverse and normal oscillations are turned on, conveying details move in transverse direction. When electromagnetic exciters of longitudinal and transverse oscillations are turned on, conveying details rotate around their axes. When all three exciters are turned on, conveying details move at any trajectory. The change in the ratio of longitudinal and transverse amplitudes and phase difference angles between them allows changing the trajectory of details moving on conveyor's track, making them not only move forward but rotate as well. That's why such conveyor can be called a manipulator. The resilient system of two-mass vibratory conveyor-manipulator with three-component oscillations should have elastic pliability in three mutually perpendicular directions. It includes four resilient elements; each of them consists of two latticed leaf springs, fixed at the right angle to each other. The working body with conveying track is joined with reactive frame by resilient elements. Electromagnetic drive includes four electromagnetic exciters of longitudinal oscillations, four electromagnetic exciters of transverse oscillations and one electromagnetic exciter of normal oscillations. The bodies of electromagnets are fixed on the reactive frame and their anchors are fixed on the working body of conveyor-manipulator. A block diagram of the electrical control of conveyor-manipulator is referred. A voltage is supplied from two phases of three-phase electricity to the coils of electromagnets through diodes, auto-transformers, switches and phase-shifter. The amplitudes of oscillations are regulated with aid of auto-transformers, phase difference between them and the change of conveying modes are carried by switches and phase-shifter.

The oscillating system of vibratory conveyor-manipulator has six degrees of freedom and respectively six frequencies of natural oscillation. The formulas for calculating the

vibratory conveyor-manipulator's frequencies of natural oscillation are derived. Vibratory conveyor-manipulator with three-component electromagnetic drive was designed and manufactured. Its research and testing show the possibility of conveying details and piece goods at any trajectory.

**Keywords:** vibratory conveyor, oscillations, electromagnetic exciter, electromagnet, frequency.

### **Introduction**

Vibratory conveying with independent horizontal and vertical oscillations with phase difference provides the essential increasing of conveying velocity especially in the continuous contact modes of the particle moving. Adding of the third component of oscillation, perpendicular to the lines of first and second ones, gives the possibility of details moving on the plane of conveyor's track at any trajectory with changing of the conveying direction and velocity. As a rule the vibratory conveyor with independent three-component oscillations represents three-mass oscillating system with several resilient systems, and it is rather complex construction. Two-mass vibratory conveyor with the resilient element in form of two latticed leaf springs fixed at the right angle to each other, proposed by the author, is quite simple constructively [1]. But its reliable operation requires prior calculations of its parameters.

### **Problem statement**

Two-mass vibratory conveyor-manipulator consists of the working body with track connected by the resilient system with reactive frame. Vibratory conveyor with electromagnetic drive that implements independent oscillations of conveyor's track in three mutually perpendicular directions has three independent vibratory exciters. The resilient system of such conveyor should have the flexibility in these three directions. Such capabilities are provided by the resilient system that consists of four elastic elements, each of which are two latticed leaf springs fixed at the right angle to each other. Vibratory conveyor with electromagnetic drive should provide the near-resonant mode of its operation, so it is necessary to calculate the frequencies of natural oscillations of conveyor. Therefore, the investigation of two-mass vibratory conveyor-manipulator with three-component electromagnetic drive is the actual problem.

### **Analysis of modern information sources on the subject of the article**

Vibratory conveying process within the framework of theory of massive point particle moving along a declined plane considered in [2]. Experimental research of the vibratory conveying with independent oscillations proves the validity of this theory for piece goods [3]. The use of independent component oscillations allows increasing the conveying velocity and the track's inclination angle and provides the possibility to reverse of details moving.

The first vibratory conveyor-manipulators with three-component oscillations represented three-mass oscillating system with two resilient systems; one of them was the system of horizontal oscillations and second was the system of vertical oscillations [4]. Two-mass vibratory conveyor-manipulator with three-component oscillations is described in [5]. The stiffness of resilient system that consist of two latticed leaf springs, fixed at the right angle to each other, is considered in [6; 7].

### **Statement of purpose and problems of research**

The purpose of research is the investigation of construction of two-mass vibratory conveyor-manipulator with three-component electromagnetic drive and creation the calculating methodology of conveyor's parameters: amplitudes of component oscillations and phase difference between them, frequencies of natural oscillations, mass-inertia ratio, sizes of latticed leaf springs that provide the maximum conveyor's productivity.

### The main material presentation

All the forces acting on a point particle with mass  $m$  moving on an inclined to the horizon at an angle  $\alpha$  plane under the action of three-component vibration are shown in Fig. 1:  $F_T$  – force of friction,  $N$  – normal reaction,  $g$  – acceleration of gravity. Vibration consists of three independent components, oscillating in the coordinate system  $X_1O_1Y_1$ , rigidly connected with the oscillating plane, in longitudinal, transverse and normal directions under the law

$$\begin{aligned}x_1 &= A_x \sin(\omega t + \varepsilon_1), \\y_1 &= A_y \sin(\omega t + \varepsilon_2), \\z_1 &= A_z \sin \omega t,\end{aligned}\quad (1)$$

where  $A_x, A_y, A_z$  – amplitudes of longitudinal, transverse and normal oscillations respectively,  $\varepsilon_1$  and  $\varepsilon_2$  – phase difference angles,  $\omega$  – frequency of forced oscillations,  $t$  – time. Differential equations describing the motion of particle in coordinate system  $XOY$ , arising from the analysis of existing forces

$$\begin{aligned}mx'' &= -mx_1'' - mg \sin \alpha + F_T, \\my'' &= -my_1'' - mg \sin \alpha, \\mz'' &= -mz_1'' - mg \cos \alpha + N.\end{aligned}\quad (2)$$

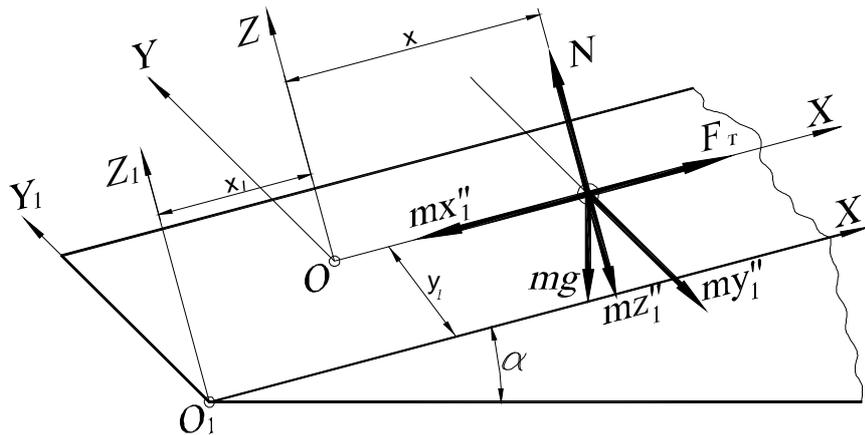


Fig. 1. Diagram of the forces acting on a conveying particle under three-component vibration

Conveying velocity, when moving along the longitudinal direction, can be found by formula [8]

$$V = A_x \cdot \omega \cdot K_V, \quad (3)$$

where  $K_V$  – dimensionless coefficient of velocity, depending on the next dimensionless parameters:  $K_\alpha$  – track angle inclination parameter,  $K_\beta$  – vibration angle parameter,  $w$  – parameter of overload, and

$$K_\alpha = \frac{\tan \alpha}{f}, \quad K_\beta = \frac{A_x}{A_z \cdot f}, \quad w = \frac{A_z \omega^2}{g \cos \alpha}, \quad (4)$$

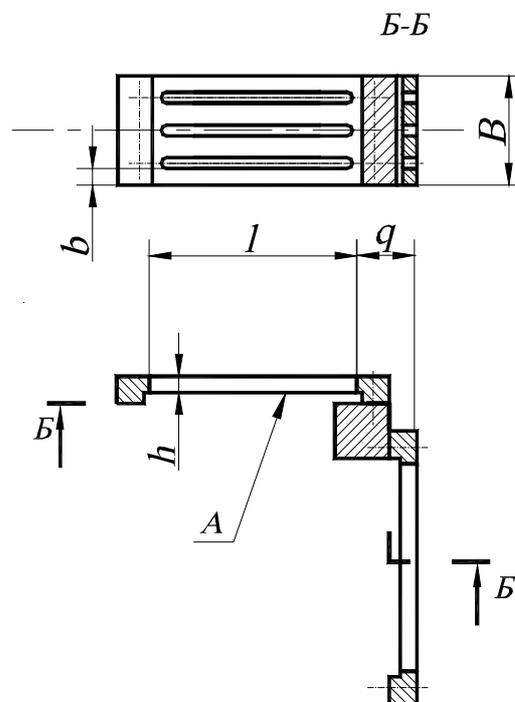
where  $f$  – coefficient of friction. The increase of amplitude  $A_x$  and frequency  $\omega$  of oscillations is limited by the constructive parameters of conveyor, that's why the maximal value of  $K_V$  ensuring is very important. The determining optimum values of parameters in order to provide maximum conveying velocity was made in [9]. Theoretical and experimental investigations prove that using of elliptical vibrations of vibratory conveyor increases the conveying velocity, especially in moving modes without jumping ( $w \leq 1$ ).

The change in the ratio of longitudinal and transverse amplitudes and phase difference angles between them allows changing the trajectory of details moving on conveyor's track, making them not only move forward but rotate as well. That's why such conveyor can be called a manipulator.

The first vibratory conveyor-manipulator with three-component oscillations was created as a three-mass oscillating system with two resilient systems [4]. The system of horizontal oscillations consisted of several vertically disposed latticed leaf springs and it connected the reactive frame with the intermediate frame. The resilient system of vertical oscillations was horizontally disposed leaf springs that connected the working body with the intermediate frame.

The resilient system of two-mass vibratory conveyor with three-component oscillations should have elastic pliability in three mutually perpendicular directions. It includes four resilient elements; each of them consists of two latticed leaf springs, fixed at the right angle to each other (Fig. 2). A latticed leaf spring has  $n-1$  cutouts with length  $l$  that form  $n$  strings.

Construction of two-mass vibratory conveyor-manipulator with three-component electromagnetic drive is shown in Fig. 3. The square track 1, on which the conveying details move, is connected to the housing of working body 2, that is joined with reactive frame 3 by four resilient elements, each of them consists two latticed leaf springs 4, fixed at the right angle to each other. Reactive frame 3 is mounted on elastic vibro-isolators 5. Electromagnetic drive of vibratory conveyor-manipulator includes three vibratory exciters. The exciter of longitudinal oscillations consists of four electromagnets, the body 6 of which is mounted on reactive frame 3 and the anchor 7 is mounted on working body 2. The exciter of transverse oscillations consists of four electromagnets, the body 8 of which is mounted on reactive frame 3 and the anchor 9 is mounted on the working body 2. The exciter of normal oscillations is one electromagnet, the body 10 of which is mounted on reactive frame 3 and the anchor 11 is mounted on the working body 2. The hatch of the working body and the hatch of reactive frame in Fig. 3 are in the different directions.



**Fig. 2.** The element of resilient system that consists of two latticed leaf springs, fixed at the right angle to each other

The spacial model of vibratory conveyor-manipulator with removed track is shown in Fig. 4. The model was made with aid of the graphic computer system AutoCAD. It enables to determine the values of masses and inertia moments of conveyor's components that are necessary for calculating the frequencies of natural oscillations.

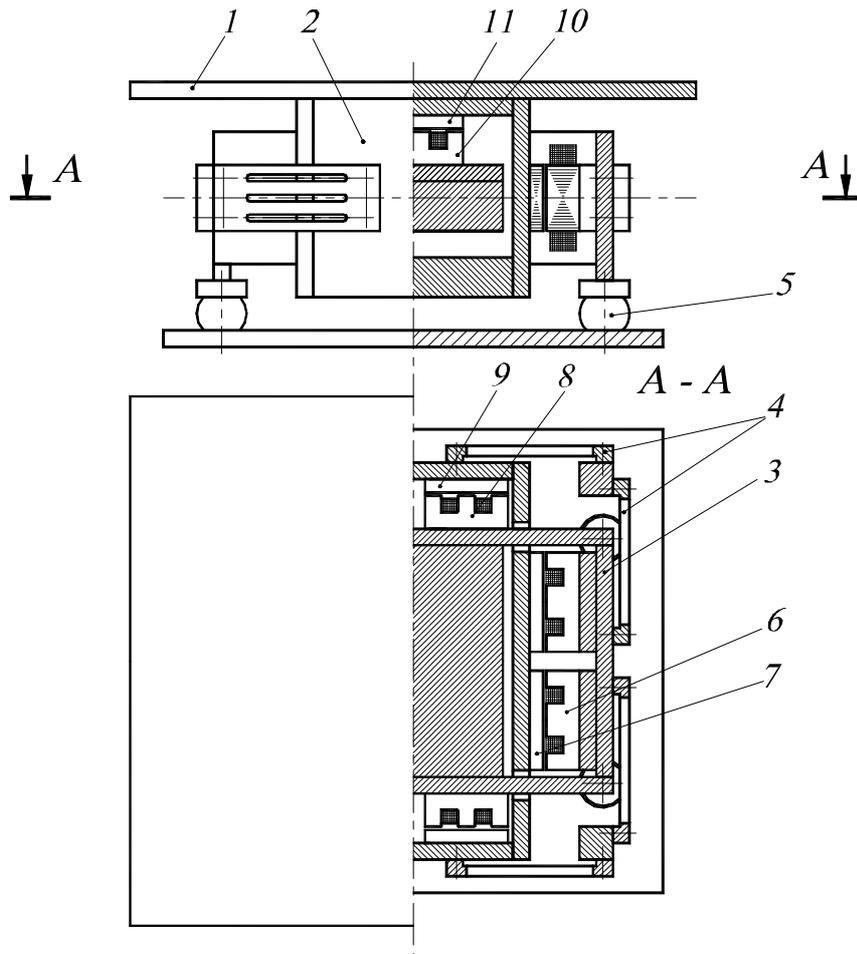
The oscillating system of vibratory conveyor-manipulator has six degrees of freedom and respectively six frequencies of natural oscillation, that are determined in [6, 7]:

$$\omega_x = \sqrt{\frac{c_x}{m}}, \quad \omega_y = \sqrt{\frac{c_y}{m}}, \quad \omega_z = \sqrt{\frac{c_z}{m}}, \quad \omega_\xi = \sqrt{\frac{k_x}{J_x}}, \quad \omega_\varphi = \sqrt{\frac{k_y}{J_y}}, \quad \omega_\zeta = \sqrt{\frac{k_z}{J_z}}, \quad (4)$$

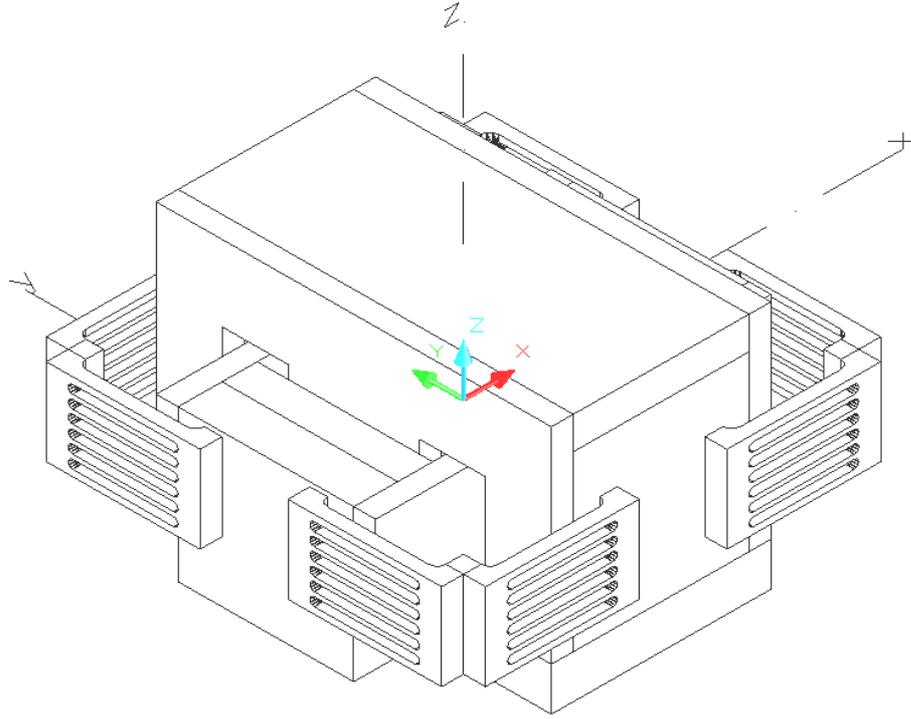
where  $c_x, c_y, c_z$  – longitudinal, transverse and normal stiffness of resilient system of two-mass vibratory conveyor-manipulator respectively;  $k_\xi, k_\psi, k_\zeta$  – torsional stiffness relative to the axes  $x, y, z$  respectively;  $m$  – reduced mass of two-mass vibratory conveyor-manipulator;  $J_x, J_y, J_z$  – reduced inertia moments relative to the axes  $x, y, z$  respectively. The reduced mass and inertia moments are determined as follows:

$$m = \frac{m_1 m_2}{m_1 + m_2}, \quad J_x = \frac{J_{x1} J_{x2}}{J_{x1} + J_{x2}}, \quad J_y = \frac{J_{y1} J_{y2}}{J_{y1} + J_{y2}}, \quad J_z = \frac{J_{z1} J_{z2}}{J_{z1} + J_{z2}}, \quad (5)$$

where  $m_1, J_{x1}, J_{y1}, J_{z1}$  – mass and inertia moments of the working body relative to the axes  $x, y, z$  respectively;  $m_2, J_{x2}, J_{y2}, J_{z2}$  – mass and inertia moments of the reactive frame relative to the axes  $x, y, z$  respectively.



**Fig. 3.** The two-mass vibratory conveyor-manipulator with three-component electromagnetic drive



**Fig. 4.** Spatial model of two-mass vibratory conveyor-manipulator with three-component electromagnetic drive

The oscillating system of two-mass vibratory conveyor-manipulator is shown in Fig. 5. The stiffness of the resilient system of two-mass vibratory conveyor-manipulator can be calculated by the following formulas [10]:

$$c_x = c_y = \frac{nEb^3h^3}{l^3} \times \frac{5l + 6q}{2l + 3q}, \quad c_z = \frac{2nEb^3h}{l^3}, \quad (6)$$

$$k_x = \frac{4nEb^3h}{3l} \left( \frac{1}{1 + \frac{Eb^2}{3\beta Gh^2}} + \frac{3d^2 + 2B^2}{8l^3} \right), \quad k_y = \frac{4nEb^3h}{3l} \left( \frac{1}{1 + \frac{Eb^2}{3\beta Gh^2}} + \frac{3p^2 + 2B^2}{8l^3} \right), \quad (7)$$

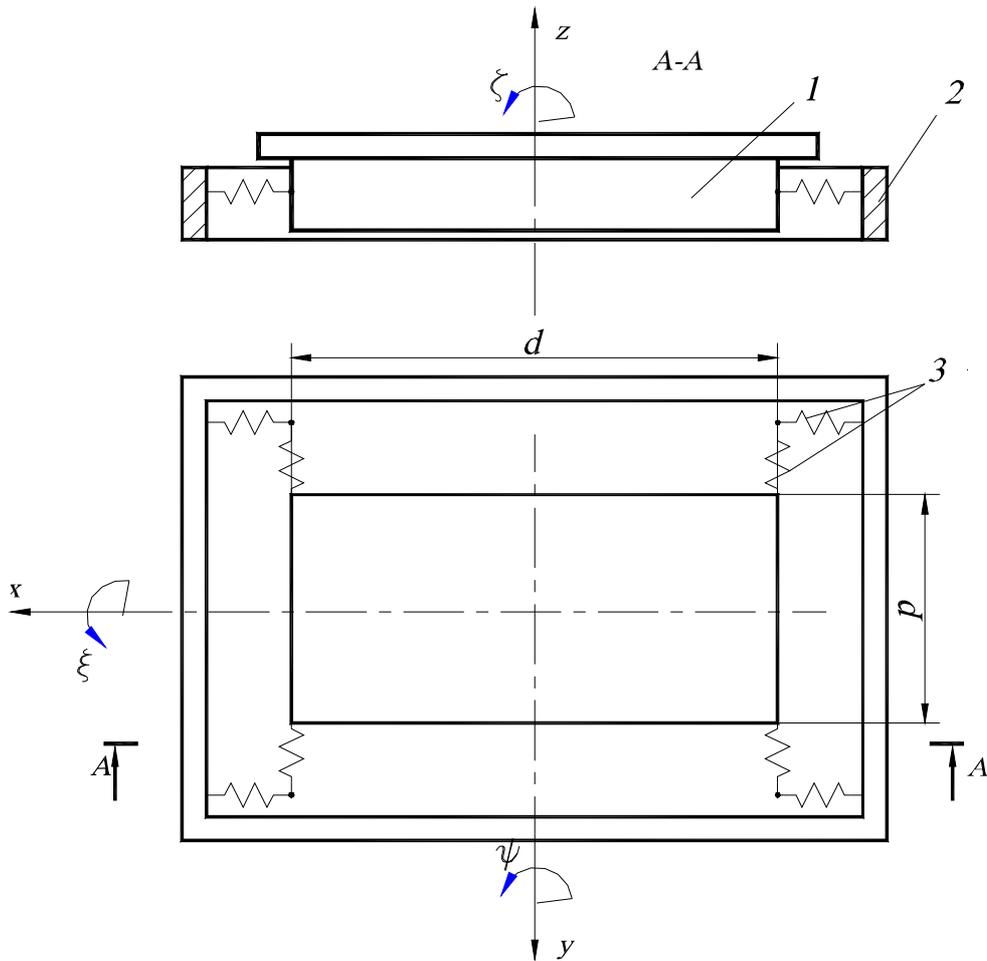
$$k_z = \frac{nEb^3h}{l(2l + 3q)} \left( \frac{7l + 9q}{3} + \frac{(5l + 6q)(d^2 + p^2)}{4l^2} \right),$$

where  $h$ ,  $b$ ,  $l$  – thickness, width and length of the strings of latticed leaf spring;  $E$  and  $G$  – modules of elasticity and modulus of rigidity;  $B$  – width of the leaf spring;  $q$  – distance between the end of the first spring and the second spring (Fig. 2);  $d$  and  $p$  – distances between the elements of resilient system in longitudinal and transverse direction respectively (Fig. 5);  $\beta$  – coefficient depending on  $b/h$  ratio [11].

The stiffness of the resilient system should provide the certain values of the resonant tuning that are the ratios of frequency of forced oscillations to frequencies of natural oscillations [8, 10]

$$\rho_x = \rho_y = \frac{\omega}{\omega_x} = \frac{\omega}{\omega_y} \approx 0.92...0.95; \quad \rho_z = \frac{\omega}{\omega_z} \approx 0.7...0.9; \quad \rho_\zeta = \frac{\omega}{\omega_\zeta} \approx 0.7...0.85; \quad (8)$$

$$\rho_\xi = \frac{\omega}{\omega_\xi} \approx 0.4...0.75; \quad \rho_\psi = \frac{\omega}{\omega_\psi} \approx 0.65...0.8.$$



**Fig. 5.** A scheme of the oscillating system of two-mass vibratory conveyor-manipulator

The longitudinal and transverse oscillations should be near resonance because of need to achieve the large amplitudes. The normal and torsional oscillations around axis  $z$  could be more far from resonance because their amplitudes are smaller. The torsional oscillations around axes  $x$  and  $y$  are the harmful so-called parasite oscillations and they need to be minimized. Dividing the first equation (6) to the second we obtain the expression  $\frac{b}{h} = \frac{\rho_x}{\rho_z} \sqrt{\frac{5l+6q}{2(2l+3q)}}$ . Substituting this expression to the first equation (6), using formulas (5), after transformations we obtain

$$h = \sqrt[8]{2 \left( \frac{\omega^2 m l^3 \rho_z}{n E \rho_x^3} \right)^2 \left( \frac{2l+3q}{5l+6q} \right)^3} . \quad (9)$$

Using the spatial model of vibratory conveying we determine masses and inertia moments and calculate stiffness of the resilient system and frequencies of natural oscillation. Then defining the values of resonant tunings (8), width and length of the strings of latticed leaf spring we determine their thickness  $h$ . If the values of torsional parasite oscillations were nearer to resonance than it is recommended in (8) we need to review the construction, for example the possibility to change values of distances  $d$  or  $p$ . Of course the value of frequencies  $\omega_x$  and  $\omega_y$  are most important. And the thickness of springs  $h$  calculated by (9) should be taken with some excess. After measuring it in a custom conveyor-manipulator we may adjust the thickness  $h$  by grinding of the surface  $A$  (Fig. 2).

A block diagram of the electrical control of conveyor-manipulator is shown in Fig. 6. The exciter of longitudinal oscillations consists of four electromagnets with coils  $L1...L4$ . The exciter of transverse oscillations consists of four electromagnets with coils  $L5...L8$ . The exciter of normal oscillations has electromagnetic coil  $L9$ . An alternating current with a voltage of 380 V from two phases A and B is supplied to the electromagnetic coils through diodes  $V1...V6$  and auto-switching device, consisting of switches  $K1, K2$  and toggles  $K3, K4$ . When the switches  $K1...K4$  are turned on, a voltage supplying on coil  $L9$  of electromagnet of normal oscillations, lags in phase in  $120^\circ$  but with phase shifter  $WT$  it corrects to the optimal value within a range of  $60^\circ...90^\circ$  [9]. Thanks to diodes  $V1$  and  $V2$  the voltage supplying on the coils  $L1$  and  $L3$  is in opposite phase to the one supplying on the coils  $L2$  and  $L4$ . So two pairs of electromagnets of longitudinal oscillations are in opposite phase and when auto-transformer  $T1$  is turned off and auto-transformer  $T2$  is turned on, the track of vibratory conveyor implements elliptical vibrations in the longitudinal plane, perpendicular to the track's plane. The details on track move in longitudinal direction with high velocity, the value of which is regulated by auto-transformer  $T2$ . Thanks to diodes  $V3$  and  $V4$  the voltage supplying on the coils  $L5$  and  $L7$  is in opposite phase to the one supplying on the coils  $L6$  and  $L8$ . So two pairs of electromagnets of transverse oscillations are in opposite phase and when auto-transformer  $T1$  is turned on and auto-transformer  $T2$  is turned off, the track of vibratory conveyor implements elliptical vibrations in the transverse plane, perpendicular to the track's plane. The details on track move in transverse direction with high velocity, the value of which is regulated by auto-transformer  $T1$ . When the both auto-transformer  $T1$  and  $T2$  are turned on, the track implements both longitudinal and transverse oscillation and details on track move progressively at any angle, the value of which depends on the ratio of supplying voltages by auto-transformer  $T1$  and  $T2$ . The reverse of moving is achieved by switching the toggle  $K3$ .

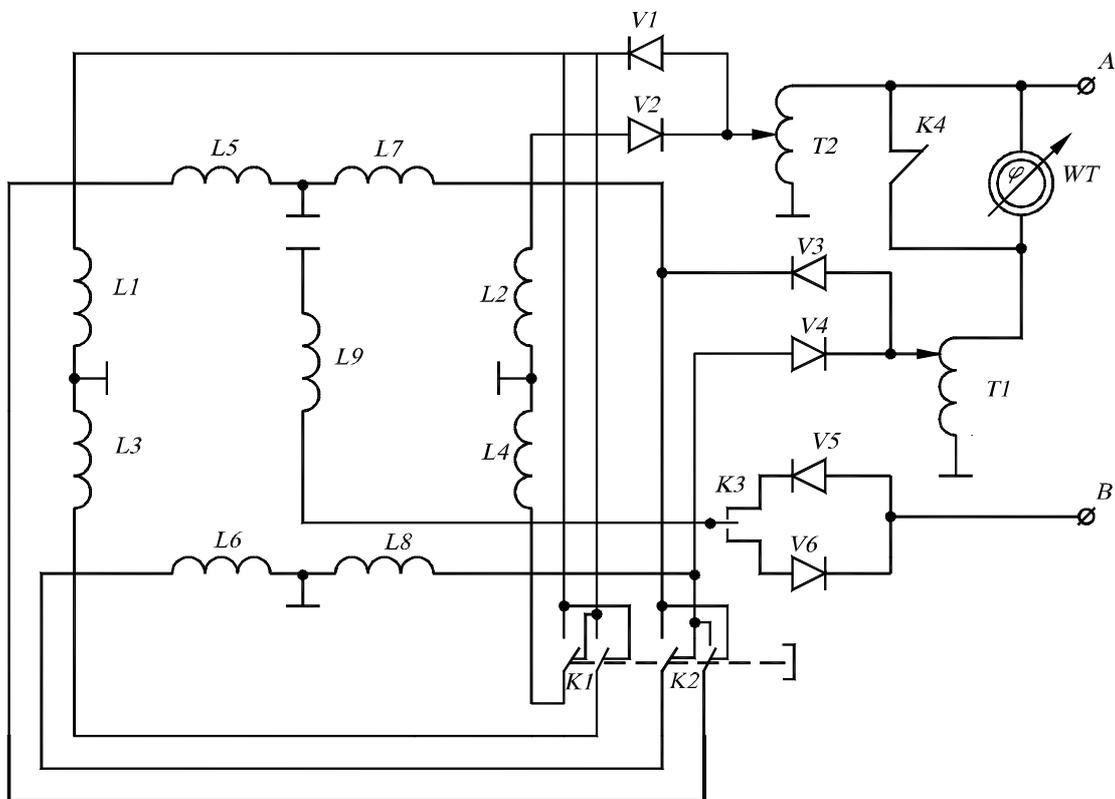


Fig. 6. A block diagram of the electrical control of conveyor-manipulator

When the switches  $K1$  and  $K2$  are turned off, a voltage supplying on the coils  $L1$ ,  $L4$ ,  $L6$  and  $L7$  is in opposite phase to the one supplying on the coils  $L2$ ,  $L3$ ,  $L5$  and  $L8$ . Therefore the variable torque moment arises and the track implements torsional oscillations around axis  $z$ . And details on the track rotate around axis of conveyor-manipulator. Direction of rotation can be changed by switching the toggle  $K3$ . When the toggles  $K3$  and  $K4$  are turned off, the exciter of normal oscillations stops and details on the track rotate around their own axes.

Vibratory conveyor-manipulator with three-component electromagnetic drive of longitudinal, transverse and normal oscillations was designed and manufactured in scientific research laboratory of National University Lviv Polytechnic. The investigations and testing of it show the possibility of conveying details and piece goods at any trajectory: progressive motion in any direction, rotation clockwise or contra clockwise and moving at any curved path.

### Conclusions

Two-mass vibratory conveyor-manipulator with three-component electromagnetic drive of longitudinal, transverse and normal oscillations consists of working body with conveying track connected with reactive frame by four elements of resilient system, each of which consists of two latticed leaf springs, fixed at the right angle to each other. The vibratory conveyor-manipulator has six degrees of freedom and respectively six frequencies of natural oscillation, the specific values of which should be provided. These values are provided by parameters of the latticed leaf springs that depend on the mass-inertia parameters of two-mass vibratory conveyor-manipulator. A block diagram of the electrical control of conveyor-manipulator is described. Formulas that allow determining parameters of latticed leaf springs were derived. The equations obtained by the author allow calculating all parameters of two-mass vibratory conveyor-manipulator necessary for its reliable operation.

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