УДК 622.231 DOI: 10.21440/0536-1028-2019-8-125-132

Vibratory conveying equipment with steady elliptical oscillations

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Abstract

Introduction. *Vibratory conveying equipment is widely used in many branches of mining industry at various enterprises (concentrating mills, transfer points at railway stations, steelworks, etc.). Design of vibratory conveying equipment with new qualities requires a more detailed analysis of oscillation parameters, in particular, oscillation parameters of machine working member.*

Research aim *is to investigate the oscillation parameters of vibratory conveying equipment with three vibration exciters by means of vibratory equipment dynamics mathematical model.*

Methodology. *The nature of working member movements is studied by means of vibratory equipment dynamics mathematical model. The model is based on the numerical solution to a system of differential equations governing the dynamics of vibratory conveying equipment with n-unbalance vibration exciters.*

Results. *The present article investigates the parameters of oscillations and the features of the center-of-mass motion in vibratory conveying equipment with three vibration exciters placed on one working member. As a result of numerical experiment, the impact of location of vibration exciters and eccentric torque of unpaired vibration exciters on the working member vibration parameters has been determined. The dependence between the direction of mass center trajectory and the direction of an unpaired vibration exciter rotation is studied.*

Summary. *The quoted results of theoretical studies through a mathematical model show that the addition of a third vibration exciter to vibratory conveying equipment design qualitatively influences working member vibration parameters: by changing the position and eccentric torque of an unpaired vibration exciter, it is possible to get the various options of working member vibrations. Consequently, the study of new types of vibratory equipment is a very promising direction.*

Key words: *vibratory conveying equipment; vibrating screen; self-synchronization; vibration exciter; dynamics; mathematical model.*

Introduction. Vibratory conveying equipment is widely used in many branches of mining industry at various enterprises (concentrating mills, transfer points at railway stations, steelworks, etc.) which is due to a variety of advantages: high capacity, low energy intensity of the process, simple construction, and high availability [1–5].

Design of vibratory conveying equipment with new qualities requires a more detailed analysis of oscillation parameters, in particular, oscillation parameters of machine working member.

The machine represents a single solid body, a working member, which is attached on springs enabling it to carry out plane-parallel motion. Special devices, vibration exciters, generate the motion of the working member. Mechanical unbalance vibrators are used as vibration exciters [6–9].

Vibratory equipment with unbalanced rotors attached to the working member and generated by electric motors operate in synchronization under particular circumstances (despite a possible difference between the parameters of working members and electric motors as well as the absence of kinematic links between their rotors). In this case, the

synchronization of rotors, which are not kinematically interconnected and are generated by two independent electric motors, is reached naturally due to the natural properties of the oscillatory system itself.

Works [10, 12] consider the dynamics of vibratory conveying equipment with independently rotating vibration exciters which base their operation on the phenomenon of vibration exciters self-synchronization. The main attention of these work is focused on the study of transient dynamic processes leading (or not leading) to vibration exciters self-synchronization which ensures steady and reliable operation of vibratory equipment.

In this type of machines, synchrony and the required relations between the rotor phases of the two vibration exciters are achieved due to the adaptability of the synchronization phenomenon, discovered by A. N. Kosolapov [13].

The adaptability is manifested in that under certain conditions the direction of the resultant exciting forces generated by the vibration exciters "controls" the position of the center of inertia of the body it is attached to.

The present article investigates the parameters of oscillations and the features of the center-of-mass motion in vibratory conveying equipment with three vibration exciters placed on one working member.

The method of numerical experiment. The nature of working member motion is investigated with the help of a mathematical model of vibratory equipment dynamics [10, 11]. The model is based on the numerical solution to a system of differential equations governing the dynamics of vibratory conveying equipment with n-unbalance vibration exciters; for the instance with three vibration exciters and non-impact loading, the system is as follows:

$$\begin{cases} \ddot{x} = \dfrac{1}{M}\left[-k_x\dot{x} - k_{x\varphi}\dot{\varphi} - c_x x - c_{x\varphi}\varphi + \sum\limits_{i=1}^{3} m_i\varepsilon_i\left(\ddot{\varphi}_i \sin\varphi_i + \dot{\varphi}_i^2\cos\varphi_i\right)\right], \\ \ddot{y} = \dfrac{1}{M}\left[-k_y\dot{y} - k_{y\varphi}\dot{\varphi} - c_y y - c_{y\varphi}\varphi + \sum\limits_{i=1}^{3} m_i\varepsilon_i\left(\dot{\varphi}_i^2\sin\varphi_i - \ddot{\varphi}_i\cos\varphi_i\right)\right], \\ \ddot{\varphi} = \dfrac{1}{J}\Big[-k_{x\varphi}\dot{x} - k_{y\varphi}\dot{y} - k_\varphi\dot{\varphi} - c_{x\varphi}x - c_{y\varphi}y - c_\varphi\varphi + \\ + \sum\limits_{i=1}^{3} m_i\varepsilon_i r_i(\dot{\varphi}_i^2\sin(\varphi_i - \delta_i - \varphi) - \ddot{\varphi}_i\cos(\varphi_i - \delta_i - \varphi))\Big], \\ \ddot{\varphi}_i = \dfrac{1}{J_i} I_i(L_i(\dot{\varphi}_i) - R_i(\dot{\varphi}_i)) + \dfrac{m_i\varepsilon_i}{J_i}\ (\ddot{x}\sin\varphi_i - \ddot{y}\cos\varphi_i - g\cos\varphi_i - \\ -r_i\ddot{\varphi}\cos(\varphi_i - \delta_i - \varphi) - r_i\dot{\varphi}^2\sin(\varphi_i - \delta_i - \varphi)\Big], \\ (i = 1,\ \ldots,\ 3). \end{cases}$$

Here x, y, φ, φ_i – the generalized coordinates of the system, where x, y – the coordinates of the center of masses of the vibratory equipment working member in some Cartesian coordinate system, rigidly bound with the base; φ – working member angle of rotation about the axis reestablished in the center of masses; φ_i – angle of rotation of the i-unbalance about an axis of an electric motor; $L_i(\dot{\varphi}_i)$ – the torque of the i-unbalance; $R_i(\dot{\varphi}_i)$ – the rotational resistance torque for the i-unbalance; I_i – the indexes of the rotational direction of the i-unbalance, with the value accepted as 1 for the unbalances rotating in a counterclockwise direction (positive direction), and –1 for the unbalances rotating in a clockwise direction; M – the total mass of

the vibratory equipment (the working body and the unbalances); m_i – the mass of the i-unbalance; J – inertia of the vibratory equipment about the center of masses; J_i – inertia of the i-unbalance about the axes of rotation; ε_i – the radius of gyration of the i-unbalance about the axes of rotation; δ_i – the angle which references the position of the i-unbalance; r_i – the distance between the center of masses and the axes of the i-unbalance; c_x, c_y, c_φ, $c_{x\varphi}$, $c_{y\varphi}$ – the generalized stiffness ratios of elastic supporting elements; k_x, k_y, k_φ, $k_{x\varphi}$, $k_{y\varphi}$ – viscous resistance coefficients; g – gravitational acceleration.

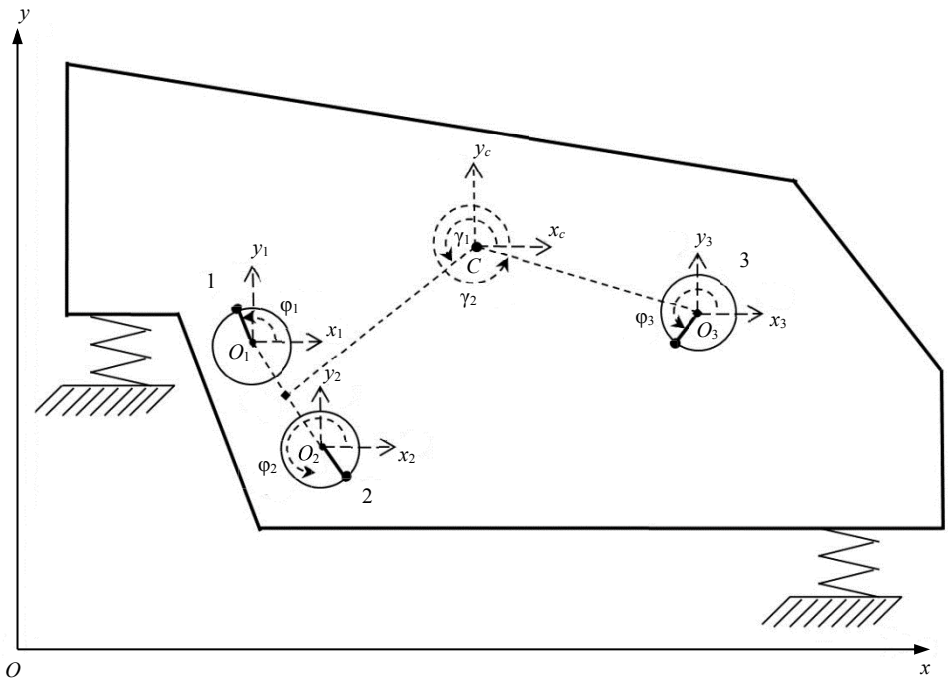

Fig. 1. Scheme of vibratory equipment with three unbalance vibration exciters
Рис. 1. Схема вибромашины с тремя дебалансными вибровозбудителями

The unbalances lay-out diagram shown in fig. 1 was used for the numerical studies.

Fig. 2 presents a graph of behavior of the generalized coordinates of a mechanical system with three vibration exciters within the first 15 seconds after start from the state of rest (fig. 2, *a*) and the trajectory of the center of masses of the working member during stable operation (fig. 2, *b*). Colored lines of a graph correspond to the following generalized system coordinates relative to the initial position: the green line – x (horizontal oscillations of the center of masses); the red line – y (vertical oscillations of the center of masses); and the blue line – φ (the rotational angle of the working member).

Dependence of vibration parameters on the adjustment angles. In order to determine the behavior of vibration parameters of a machine with three vibration exciters when the adjustment members γ_1 and γ_2 are changed, as initial parameters, let us assume that $\gamma_1 = 180°$, $\gamma_2 = 0°$, unbalance 1 rotates in a counterclockwise direction, and unbalances 2 and 3 rotate in a clockwise direction. Working member oscillation dynamics at initial parameters is shown in fig. 2. The arrangement of vibration exciters rotation axes will be changed due to the change of the adjustment angles γ_1 and γ_2. Trajectories of the center of masses of the working member under various values of the adjustment angels are shown in fig. 3.

When the adjustment angle γ_2 of an unpaired vibration exciter is reduced, the ellipse will rotate in the direction of angle alternation ($\gamma_2 = 340°$; $\gamma_2 = 320°$), oscillations of the working member don't change significantly, i. e. remain practically the same as in fig. 2, *a*. When angle γ_2 is reduced by more than 45°, the ellipse stops rotating.

When the angle γ_2 is increased, an oscillation ellipse of a working body will be the same as when angle γ_2 is reduced by the same measures, and the ellipse of motion of the center of masses will be inversely rotated relative to the horizontal axis ($\gamma_2 = 20°$; $\gamma_2 = 40°$).

When the adjustment angle of a pair of vibration exciters γ_1 reduces, the ellipse rotates in the direction of angle alternation by the angle approximately equal to the rotation angle of the axes of the pair ($\gamma_1 = 160°$; $\gamma_1 = 140°$; $\gamma_1 = 120°$). Horizontal oscillations reduce, and the vertical ones increase.

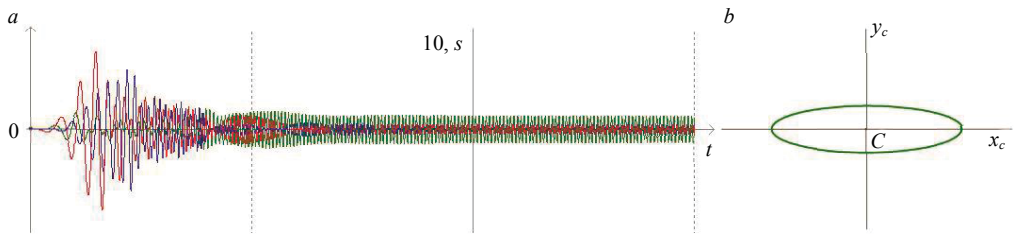

Fig. 2. Vibrations of the working member of vibratory equipment with three vibration exciters:
a – working member oscillations curve; *b* – trajectory of the center of masses
Рис. 2. Вибрации рабочего органа вибромашины с тремя вибровозбудителями:
a – график колебаний рабочего органа; *b* – траектория движения центра масс

When γ_1 angle is increased, the oscillations of the working member will be about the same as when γ_1 angle is reduced by the same measures ($\gamma_1 = 200°$; $\gamma_1 = 220°$; $\gamma_1 = 240°$), and the ellipse of motion of the center of masses, as well as when the axis of an unpaired unbalance vibration exciter is rotated, will be inversely rotated relative to the horizontal axis.

Thus, based on design considerations, it is inefficient to excessively increase the adjustment angle of the unpaired vibration exciter and reduce the adjustment angle of a pair of vibration exciters, because the rise of engines, which generate the vibration exciters, increases. The adjustment angle of a pair of vibration exciters $\gamma_1 = 180°$ should not be kept either, because the engine of each vibration exciter is better to be adjusted on a separate stiff support.

On the authors' opinion, the adjustment angle of an unpaired vibration exciter $\gamma_2 = 330°$ and the adjustment angle of a pair $\gamma_1 = 210°$, will be most optimal. All follow-up studies of this set of experiments were carried out with these exact adjustment angles.

Dependence between the motion of the working member and the eccentric torque of the third vibration exciter. Under the initial parameters the unpaired unbalance was 30 kg and 600 mm radius of gyration, i. e. the eccentric torque ($m\varepsilon$) was 18 kg · m. The parameters of vibrations of vibratory conveying equipment with these values are presented in fig. 2, 3. The influence of eccentric torque change on the trajectory of the center of masses is shown in fig. 4.

When the eccentric torque of the unpaired vibration exciter is reduced ($m\varepsilon = 10$ kg · m), the minor axis of an ellipse is reduced, it becomes more elongated (converges to a line segment) and rotates in a counterclockwise direction, i. e. the effect of the unpaired unbalance of a vibrating exciter on the system is reduced, the oscillations steadily

become the same as the ones of the vibratory conveying equipment with two vibrating exciters.

When the eccentric torque is increased ($m\varepsilon$ = 30 kg · m), the ellipse rotates in a clockwise direction, horizontal oscillations reduce, ellipse becomes more round.

The maximum roundness of an ellipse is achieved when the eccentric torque of the unpaired vibration exciter is numerically equal to the eccentric torque of one of the paired vibration exciters ($m\varepsilon$ = 45 kg · m). In this case, vertical oscillations are about the same as horizontal, with a rather wide inclination angle of ellipse.

It is not necessary to allow too large vertical oscillations, as soon as the conveyed material will be thrown at a great height, and excess energy will be wasted on it, i. e. power consumption increases and the probability of material out-throw beyond the working member increases.

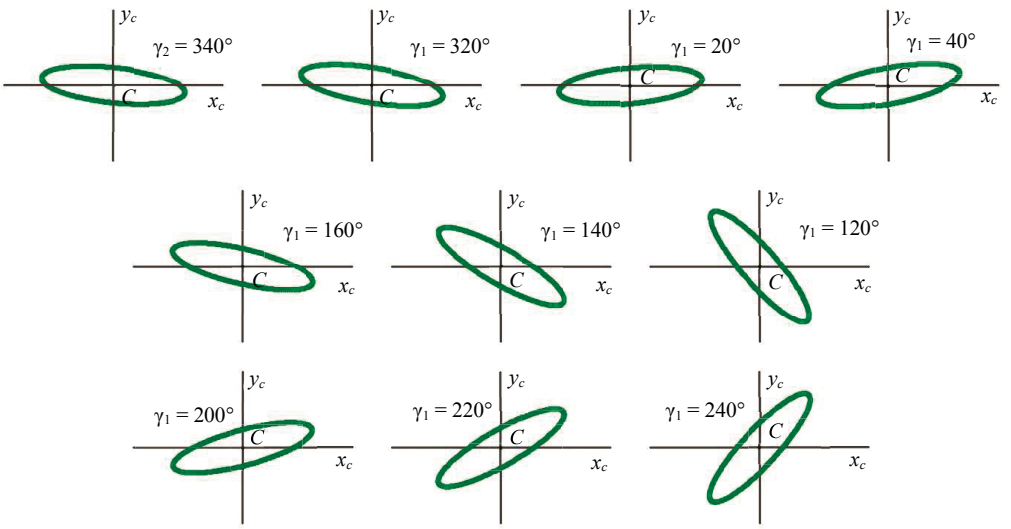

Fig. 3. Trajectories of the center of masses of vibratory equipment working member under various values of adjustment angles γ_1 and γ_2

Рис. 3. Траектории движения центра масс рабочего органа вибромашины при различных значениях установочных углов γ_1 и γ_2

In case the eccentric torque of the unaired vibration exciter is increased, the ellipse will elongate again and will remain rotating in a clockwise direction, and the oscillations will increase significantly.

In the following set of numerical experiments the eccentric torque of the unpaired exciter was accepted as 18 kg · m, with this approach an approximate average thickness of ellipse is achieved.

Dependence between the motion of a working member and the direction of the unpaired vibration exciter rotation. Under the initial conditions, vibration exciter 1 rotates in a counterclockwise direction, and vibration exciters 2 and 3 rotate in a clockwise direction. The character of machine vibration under these parameters is shown in fig. 2.

Change in the direction of an unpaired vibration exciter rotation changes the rotational direction of the ellipse, which characterizes the trajectory of the center of masses. Consequently, it may be concluded that the direction of the unpaired vibration exciter rotation determines the trajectory of the center of masses: ellipse rotates in the same direction as the unpaired vibration exciter.

The parameters of the working member oscillations are not significantly influenced by the direction of the unpaired vibration exciter rotation.

Change in the direction of a pair of vibration exciters rotation does not change the direction of ellipse rotation, oscillation parameters of a working member do not change significantly as well.

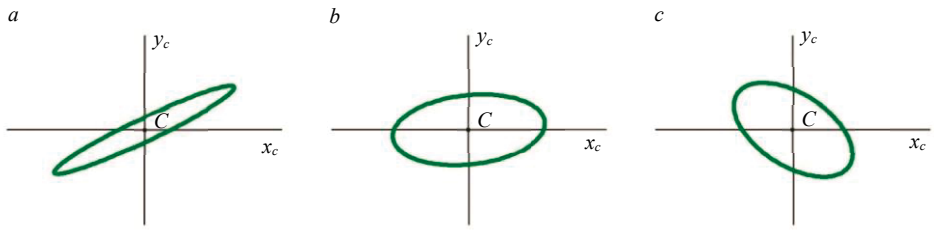

Fig. 4. Trajectories of the center of masses of vibratory equipment working member under various values of eccentric torque $m\varepsilon$:
a – $m\varepsilon$ = 10 kg · m; b – $m\varepsilon$ = 30 kg · m; c – $m\varepsilon$ = 45 kg · m
Рис. 4. Траектории движения центра масс рабочего органа вибромашины при различных значениях эксцентрического момента $m\varepsilon$:
a – $m\varepsilon$ = 10 кг · м; b – $m\varepsilon$ = 30 кг · м; c – $m\varepsilon$ = 45 кг · м

Summary. Addition of the third vibration exciter into the structure of vibratory conveying equipment will therefore qualitatively influence the parameters of its motion (vibration). Elliptical motion of the center of masses can increase the speed of material motion along the working member, consequently, the capacity is improved and the possibility appears to convey along the horizontal plane and the inclined plane in any direction (including material up feed).

Summing up this set of experiments, the following conclusions can made.

Vibration exciters position on the working member influences the vibration parameters of the working member.

When reducing the eccentric torque of the unpaired vibration exciter, ellipse of motion of the center of masses of the vibratory equipment becomes more elongated (converges to a line segment) and rotates in a counterclockwise direction; when the eccentric torque is increased, ellipse becomes more round and rotates in a clockwise direction, horizontal oscillations reduce while the vertical ones increase, and the angle of ellipse inclination increases.

The direction of the unpaired vibration exciter rotation determines the trajectory of the center of masses, and change in the direction of rotation of a pair of vibration exciters does not influence the direction of the trajectory of the center of masses.

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Received 5 July 2019

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DOI: 10.21440/0536-1028-2019-8-125-132

Вибротранспортные машины с устойчивыми эллиптическими колебаниями

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Реферат

Введение. *Вибротранспортные машины нашли широкое применение во многих отраслях горной промышленности и на различных предприятиях (обогатительные фабрики, перегрузочные пункты железнодорожных станций, металлургические заводы и т. д.). Проектирование вибротранспортных машин с новыми качествами требует более подробного анализа параметров колебаний, в частности параметров колебаний рабочего органа машины.*

Цель работы. *С помощью математической модели динамики вибромашины исследовать параметры колебаний вибротранспортной машины с тремя вибровозбудителями.*

Методика. *Исследование характера движений рабочего органа осуществляется с помощью математической модели динамики вибромашины. В основе модели лежит численное решение системы дифференциальных уравнений, описывающих динамику вибротранспортных машин с n-дебалансными вибровозбудителями.*

Результаты. *В статье представлено исследование параметров колебаний и особенностей движения центра масс вибротранспортной машины с тремя вибровозбудителями, расположенными на одном рабочем органе. В результате численного эксперимента определено влияние расположения вибровозбудителей и эксцентрического момента непарного вибровозбудителя на параметры вибраций рабочего органа вибромашины. Изучена зависимость направления траектории движения центра масс от направления вращения одиночного вибровозбудителя.*

Выводы. *Приведенные результаты теоретических исследований с помощью математической модели показывают, что добавление третьего вибровозбудителя в конструкцию вибротранспортной машины качественно влияет на параметры вибраций рабочего органа: изменением положения и эксцентрического момента одиночного вибровозбудителя можно получать различные варианты вибраций рабочего органа. Следовательно, изучение новых типов вибромашин с тремя вибровозбудителями является весьма перспективным.*

Ключевые слова: *вибротранспортные машины; вибрационный грохот; самосинхронизация; вибровозбудитель; динамика; математическая модель.*

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Поступила в редакцию 5 июля 2019 года

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Для цитирования: Шихов А. М., Румянцев С. А., Азаров Е. Б. Вибротранспортные машины с устойчивыми эллиптическими колебаниями // Известия вузов. Горный журнал. 2019. № 8. С. 125–132 (In Eng.). DOI: 10.21440/0536-1028-2019-8-125-132

For citation: Shikhov A. M., Rumiantsev S. A., Azarov E. B. Vibratory conveying equipment with steady elliptical oscillations. *Izvestiya vysshikh uchebnykh zavedenii. Gornyi zhurnal = News of the Higher Institutions. Mining Journal*. 2019; 8: 125–132. DOI: 10.21440/0536-1028-2019-8-125-132