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SUBSTANTIATION OF REGIME PARAMETERS OF VIBRATING CONVEYOR INFRARED DRYERS

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ABSTRACT

The analysis of constructive-technological schemes of vibrating conveyor machines for heat-exchange processing of bulk technological masses in the current mode is carried out, which allowed to substantiate the effectiveness of using a new modification of infrared dryers of vibration-wave execution with a flexible transporting body. For this scheme, a vibrating system is developed which mathematical modelling allowed to determine and substantiate the main parameters of the operating mode of the drive mechanism of the projected device. The experiments, using the developed research model, confirm and refine the results of theoretical analysis, energy efficiency and comparatively low metal consumption of the design structure. The difficulty of working with such a large number of factors led to the application of the second similarity theorem and the introduction of a mathematical model of the criteria of Stanton, Froude, Burdo, whose magnitudes are reflected through the main factors of influence and were found experimentally. After using the "dimension theory" and graph-analytic analysis of power functions, a criterial equation of the investigated process was obtained. This allows recommending the regime parameters and the design series of projected thermo-radiation dryers with vibration-wave transport of products when varying the main factors of influence.

Keywords: vibration; wave conveyor; loose products; system unbalance; infrared drying

INTRODUCTION

The infrared irradiation method is one of the most promising physical methods for processing food products. By using advantages over traditional methods of heat treatment, it is increasingly being used in various branches of the food industry and restaurant industry. Infrared radiation treatment is used for blanching, roasting and drying of fruit and vegetable raw materials, pasteurization of milk, juices, wines and beer, heat treatment of meat products, preparation of grilled products from various types of food raw materials **(Krasnikov et al., 1985; Kolyanovska et al., 2019)**. At the same time, this research raises the task of ensuring uniformity of layer-by-layer processing of bulk products in conditions of such intensive thermal action as infrared, as well as the organization of the current form of agricultural raw materials processing. In order to solve the set problems, an original design solution for the application of a wave conveyor is proposed, and the parameters of the non-vibrating nature of the vibrating system designed to provide the necessary trajectory of the flow of bulk materials with the required speed **(Bubelová et al., 2017; Zverev and Sesikashvili, 2018)**.

Energy is used 2 – 3 times in heat-exchange processes of processing and food technologies of agro-industrial production more than it is physically necessary for a process that determines the energy intensity of production and the quality of products. The drying processes of agricultural products are among the most energy intensive. When using these processes, the share of energy in the cost of production is up to 30%. Therefore, there is a problem of fundamentally new approaches in processing and food technologies, the creation of new energy-saving and intensive technologies, the development of principles and equipment that realize the advantages of combined and targeted supply of infrared and vibro-mechanical energy, pulse and mechanical processing methods **(Krasnikov et al., 1985; Kolyanovska et al., 2019; Czako et al., 2018)**.

In the article it is proposed to realize the process of sufficiently intensive infrared drying in the conditions of the vibrated layer of loose products for continuous processing regimes. The process of transportation of raw materials in the working area is planned to be performed by a vibration-wave method by changing the non-vibrant nature of the vibrating system without the use of additional mechanical devices. At the same time, the use of a deformable transporting body with a vibrowave action will provide significantly less energy consumption than the most common infrared vibrating convection dryers, including Russian ones such as (SWIC), which currently dominate the market of infrared dryers for processing loose agricultural raw materials and are marked by a rather massive and correspondingly metal-intensive vibrational surface **(Palamarchuk et al., 2015; Sukhenko et al., 2017)**, requires considerable energy consumption for its reduction to motion. In the projected drier, vibration to the mass of production is indirectly transmitted through the deformable surface of a special belt, which serves as a wave conveyor in the drying device. Such approach, together with a significant intensification of the process, with a lower energy consumption (7 – 8 times less as in the SWIC device) and material sorption (the metal consumption is less by 9 – 10 times as in the SWIC devices) will significantly improve the quality indices of products, in particular uniformity of the layered processing and maximum preservation of raw materials' initial qualities. The relevance and uniqueness of such results for agro-industrial production lies in the effective maintenance of the level of consumer value of products in the stages of storage and primary processing of raw materials **(Krasnikov et al., 1985; Kolyanovska et al., 2019; Sukhenko et al., 2020)**.

Scientific hypothesis

Research results have been published on the creation and justification of the operating modes of the newest energy-efficient and material-intensive drying equipment. The aim of this scientific work is creation and justification of the operating modes of the newest energy-efficient and material-intensive drying equipment that realize the advantages of combined and targeted energy supply on the basis of a combination of vibro-mechanical and infrared technological action and the current vibrowave organization of transportation of raw materials in the work area.

MATERIAL AND METHODOLOGY

Theoretical research uses modern concepts of physical and mathematical modelling of granular media, the theory of similarity, the theory of vibrational processing of freely granulated masses, the theory of vibrational and wave transport of loose masses, the methods of Lagrange and Cauchy in the mathematical analysis of the equations of motion of the machine's executive organs. MATHCAD and STATGRAPHICS CENTURION XVII software is used to process the data.

During the implementation of the experimental studies, the German Robotron equipment, modern complexes for estimating the kinematic, power and energy characteristics of the vibrowave transport of the rapeseed and soybean masses are used.

Statistic analysis

The statistical evaluation of the results was carried out by standard methods using statistical software Statgraphics Centurion XVII (StatPoint, USA) – multifactor analysis of variance (MANOVA), LSD test.

RESULTS AND DISCUSSION

At the present stage of development of drying equipment and technologies, vibrational and electrophysical methods of processing raw materials are widely introduced, among which the heat treatment with infrared heating is important **(Krasnikov et al., 1985; Kolyanovska et al., 2019; Sukhenko et al., 2020)**. Its use makes it possible to significantly intensify the drying process, reduce the specific energy consumption and processing time, provide rational temperature regimes, improve product quality by reducing mass losses and the rate of undesirable physical and chemical changes, and yields significant economic benefits. In addition, the use of vibration in the process of drying by infrared radiation provides an intensive mixing of the raw material particles among themselves, a constant renewal of the product layer that is in the range of the infrared emitter.

Considering the large number of conducted studies of the application of infrared radiation in various technological processes, let's concentrate on analysing the equipment of combined processes, which include infrared heating and the vibrational effect on the product.

According to the complex of structural and technological classification characteristics in infrared dryers, the following main groups can be noted: chamber, conveyor, vibrating and combined. In modern processing agricultural production, it is the latter that are becoming increasingly popular due to their high productivity and technological flexibility. Depending on the features of the transporting body, conveyor vibratory dryers contain deformable or non-deformable surfaces. The use of conveyor dryers with deformable working surfaces can significantly reduce the energy consumption and metal capacity of the structure that predetermines the choice of such scheme for further research **(Rachmat et al., 2010)**.

When developing the design scheme of the dryer with the given characteristics, vibrating conveyor units are first designed, the characteristic features of which are a perforated conveyor belt covering the system of support rollers (Figure 1 – 3); centrally built-in mechanical vibration exciter; a system of elastic elements that provide the necessary restoring action in vibration, in particular the elements 5 (Figure 2), 13 (Figure 3) or reduce dynamic loads on the supporting rollers (elements 17 in Figures 2 and 12 in Figure 3) **(Krasnikov et al., 1985; Palamarchuk et al., 2013)**. These vibrating conveyor machines have the following features: the installation shown in Figure 1 allows us to divide the working zone into two streams; the water remover in Figure 2 contains a blade mechanism for intensifying the processing process; the unit diagram in Figure 3 allows multi-stage processing of products. However, these mechanical solutions unite mechanical complexity for the realization of the assigned technological tasks, in particular for the fouling of loose agricultural raw materials. Installation of a mechanical vibration exciter in the support rollers of the vibrating conveyor system allowed to level the shortcomings and open a promising direction for the design of vibration-wave dryers that fit organically into the schemes of infrared drying of bulk products in the current processing mode.

Figure 4 shows the developed unit that combines these positive features and contains a flexible load-carrying body on which a traveling or standing wave is created when a mechanical exciter is operating 2, 3 **(Nowak and Lewicki, 2004; Palamarchuk, Turcan and Palamarchuk, 2015; Palamarchuk Bandura and Palamarchuk, 2013)**.

Such wave promotes both the transportation of products coming from the feeder 7 and its intensive mixing. This reduces the thermal intensity to the surface layer while maintaining a sufficiently high flow velocity. In this case, it is sufficient to ensure that only rollers 5, 6 vibrate to maintain the high kinetics of the investigated process, which significantly reduces energy consumption per drive compared to vibrating conveyor systems.

In order to select effective operating conditions, an analysis of the dynamics of the vibration excitation power circuit of the investigated drier is made. At the same time, the following tasks are solved: compilation of the design scheme of the machine with a mechanical unbalance vibration exciter; compilation of equations of motion of mobile links of vibration drives with approximate and numerical methods of analysis; investigation of amplitude-frequency characteristics; determination of drive power **(Palamarchuk Bandura and Palamarchuk, 2013)**.

The following mass distribution takes place for the investigated vibration drier (Figure 5).

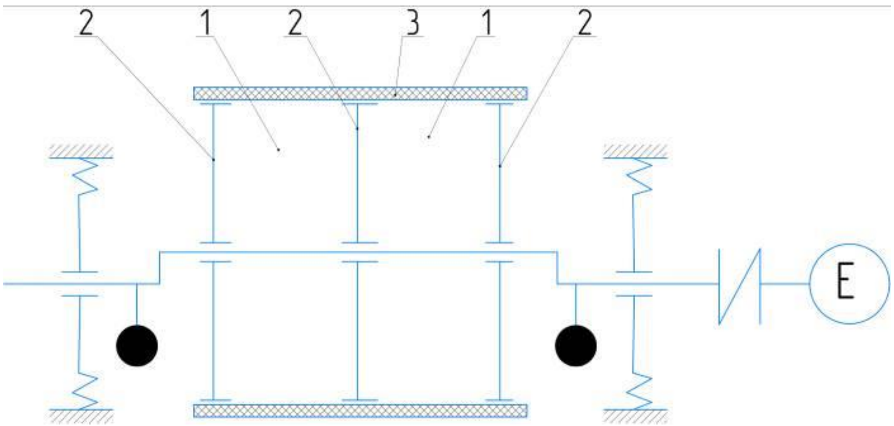

Figure 1 Multi-chamber vibrating conveyor machine with mechanical combined vibration excitation. Note: 1 – working chambers; 2 – side discs; 3 – flexible belt.

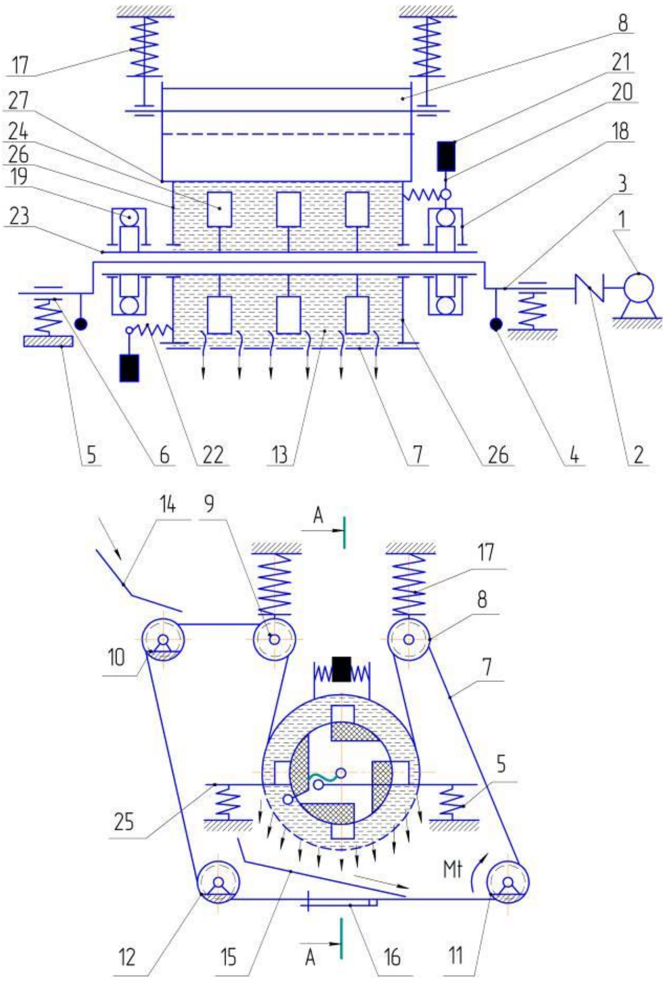

Figure 2 Conveyor vibrating vane machine. Note: 1 – engine, 2 – elastic coupling, 3 – drive shaft of vibration exciter, 4 – counterweight, 5 – elastic elements of vibration exciter; 6, 19 – support nodes, 7 – belt; 8, 9, 10, 11, 12 – support rollers, 13 – loose raw materials; 14, 15 – trays, 16 – door for additional charging, 17 – elastic suspension elements, 18 – freewheel mechanism body, 20 – rod, 21 – pendulum, 22 – elastic elements, 24 – blade, 26 – side disk, 27 – flange.

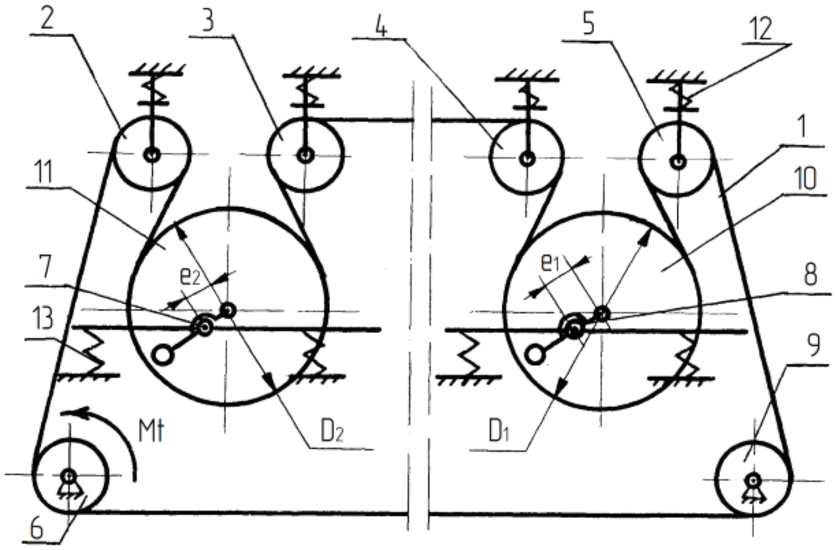

Figure 3 Vibrating conveyor machine for multi-stage processing of products with mechanical combined vibration excitation. Note: 1 – flexible belt; 2, 3, 4, 5, 9 – supporting rollers; 6 – drive roller; 7, 8 – drive shafts; 10, 11 – side discs of the working container; 12 – elastic suspension; 13 – elastic elements of a power shaft.

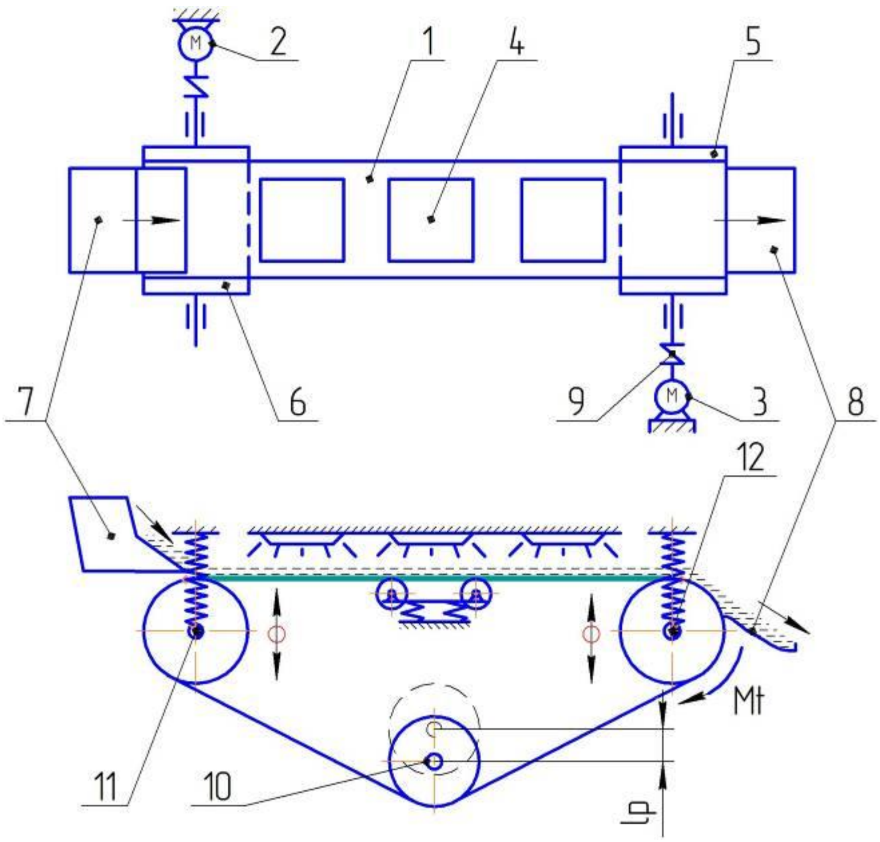

Figure 4 Scheme of the conveyor vibrowave infrared dryer: 1 – belt; 2, 3 – exciter engines; 4 – infrared emitters; 5, 6 – rollers; 7 – feeder; 8 – receiving hopper; 9 – flexible coupling; 10 – tensioning roller; 11, 12 – unbalance vibration exciter.

In order to select effective operating conditions, an analysis of the dynamics of the vibration excitation power circuit of the investigated drier is made. At the same time, the following tasks are solved: compilation of the design scheme of the machine with a mechanical unbalance vibration exciter; compilation of equations of motion of mobile links of vibration drives with approximate and numerical methods of analysis; investigation of amplitude-frequency characteristics; determination of drive power **(Palamarchuk Bandura and Palamarchuk, 2013; Krasnikov et al., 1985; Kolyanovska et al., 2019)**.

The following mass distribution takes place for the investigated vibration drier (Figure 5).

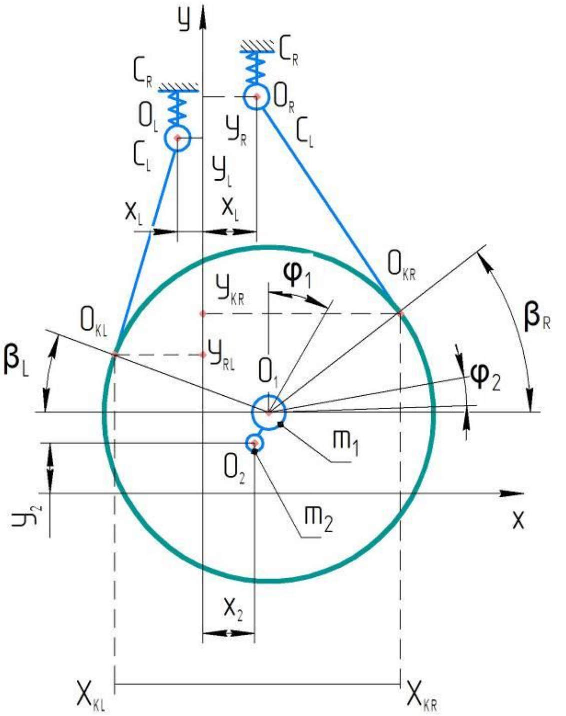

Figure 5 Calculation scheme for vibrating conveyor drier drive with a deformable transporting body.

$$m_1 = m_{unb}; m_2 = m_{d.b} + m_s + m_{d.s} + m_{t.c}; m_0 = m_1 + m_2. \quad (1)$$

where, m_s – masses of the supporting units of the drive shaft; $m_{d.b}$ – mass of side discs and bushings; $m_{d.s}$ – mass of the drive shaft; m_{unb}- mass of unbalances; $m_{t.c}$- mass of technological charging (filler).

The mass distribution in the system is:

$$m = m_1 + m_2; m_1 = m_{unb}; m_2 = m_{d.s} + m_s. \quad (2)$$

The degrees of freedom of the system include: x_1 - horizontal displacement of the drive shaft; y_1 – vertical movement of a drive shaft; ϕ_1 – angular displacement of the drive shaft; ϕ_2 – angular displacement of the side disk of the support roller.

Analysing the geometry of the system, let's found dependencies for the forces of the belt tension.

$$T_L = C_0\sqrt{(X_L - X_2)^2 + (Y_L - Y_2)^2 - R^2} - \sqrt{X_L^2 + Y_L^2 - R^2} + R\varphi_2 \quad (3)$$

$$T_R = C_0\sqrt{(X_L - l_{12}\sin\varphi_1)^2 + (Y_L - l_{12}\sin\varphi_1)^2 - R^2} - \sqrt{X_L^2 + Y_L^2 - R^2} + R\varphi_2 \quad (4)$$

Using Lagrange's method, let's compose the equations of motion of the working bodies of vibration drives.

$$\ddot{X}_2 + \frac{c_X}{m_0}X_2 = \frac{m_1 l_{12}}{m_0}\left[\ddot{\varphi}_1\cos\varphi_1 - \dot{\varphi}_1^2\sin\varphi_1\right] + \frac{1}{m_0}\left[T_L\sin B_L - T_R\cos B_R\right] \quad (5)$$

$$\ddot{Y}_2 + \frac{c_Y}{m_0}Y_2 = \frac{m_1 l_{12}}{m_0}\left[\ddot{\varphi}_1\sin\varphi_1 - \dot{\varphi}_1^2\cos\varphi_1\right] + \frac{1}{m_0}\left[m_0 q - T_L\sin B_L - T_R\cos B_R\right] \quad (6)$$

$$\ddot{\varphi}_2 - \left[T_R - T_L\right]R/J_2 \quad (7)$$

$$\ddot{\varphi}_1 + \frac{\ddot{X}_2}{l_{12}}\cos\varphi_1 + \frac{\ddot{Y}_2 + m_1 q}{l_{12}}\sin\varphi_1 + \frac{M_t}{m_1 l_{12}} \quad (8)$$

When solving these equations, let's use the following assumptions:

$$\beta_L = \beta_R = \text{const}; \quad Y_L = Y_R; \quad |Y_L| = |Y_R|; \quad \dot{\varphi}_1 = \text{const}.$$

Using the assumptions and the Cauchy method for solving linear inhomogeneous differential equations with constant coefficients, the equation of the trajectory of the working bodies of the vibration drives and their graphical dependences is obtained (Figure 6).

$$X_2 = \frac{A_1[\omega_1^2 - k_X^2]}{[\omega_1^2 - k_X^2] + \varphi_X^2\omega_1^2}\sin\omega_1 t + \frac{A_1\varphi_X^2\omega_1^2}{[\omega_1^2 - k_X^2] + \varphi_X^2\omega_1^2}\cos\omega_1 t \quad (9)$$

$$Y_2 = -\frac{A_1[\omega_1^2 - k_Y^2]}{[\omega_1^2 - k_Y^2] + \varphi_Y^2\omega_1^2}\cos\omega_1 t + \frac{A_1\varphi_Y^2\omega_1^2}{[\omega_1^2 - k_Y^2] + \varphi_Y^2\omega_1^2}\sin\omega_1 t \quad (10)$$

Using the obtained equations, the dependencies for the main parameters of the investigated unbalance vibration exciter are formulated.

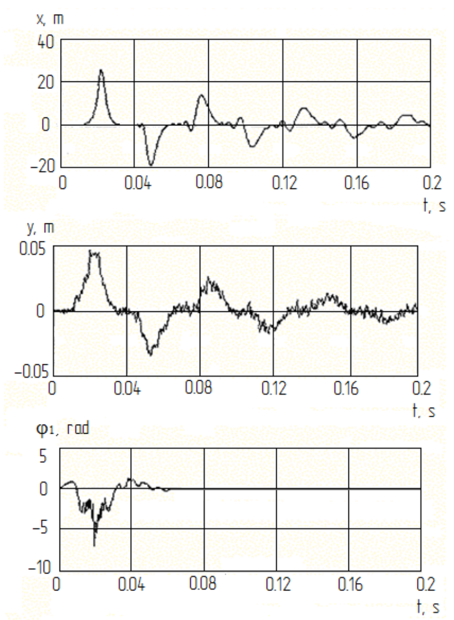

Figure 6 Motion trajectories of the working bodies of dynamic imbalance vibration drive of the flat vibrations of a machine with flexible guide: X, Y – linear movements of the working container; φ – angular displacement of the drive shaft; ω – angular displacement of the platform.

Amplitude-frequency and power characteristics of the machine with a flexible container and dynamic drive are presented as follows.

Absolute vibration amplitude of vibration exciter:

$$A = m_0^{-1} m_1 l_{12} \omega_1^2 \sqrt{\left[\left(\omega_1^2 - k_X^2\right)^2 + \alpha_X^2 \omega_1^2\right]^{-1} + \left[\left(\omega_1^2 - k_Y^2\right)^2 + \alpha_Y^2 \omega_1^2\right]^{-1}} \quad (11)$$

Machine drive power:

$$N_{dr} = m_1 l_{12} \omega_1^2 \eta_{пр}^{-1} \left(0{,}5 d_{ц} \mu + m_1 l_{12} \omega_1^3\right) \cdot m_0^{-1} \sqrt{\left[\frac{\left(\omega_1^2 - k_X^2\right) \cos\omega_1 t - \alpha_X \omega_1 \sin\omega_1 t}{\left[\left(\omega_1^2 - k_X^2\right)^2 + \alpha_X^2 \omega_1^2\right]}\right]^2 + \left[\frac{\left(\omega_1^2 - k_Y^2\right) \omega_1 \sin\omega_1 t - \alpha_Y \omega_1 \cos\omega_1 t}{\left[\left(\omega_1^2 - k_Y^2\right)^2 + \alpha_Y^2 \omega_1^2\right]}\right]^2} \quad (12)$$

Load on the support units of the drive shaft:

$$F_{unb} = m_1 l_{12} \omega_1^4 \sqrt{\left[\frac{\left(\omega_1^2 - k_X^2\right) \cos\omega_1 t - \alpha_X \omega_1 \sin\omega_1 t}{\left[\left(\omega_1^2 - k_X^2\right)^2 + \alpha_X^2 \omega_1^2\right]}\right]^2 + \left[\frac{\left(\omega_1^2 - k_Y^2\right) \omega_1 \sin\omega_1 t - \alpha_Y \omega_1 \cos\omega_1 t}{\left[\left(\omega_1^2 - k_Y^2\right)^2 + \alpha_Y^2 \omega_1^2\right]}\right]^2} \quad (13)$$

Energy of motion of vibrating masses of vibration drive:

$$E_{vib} = 0{,}5 m_0^{-1} m_1 l_{12} \omega_1^6 \left(\left[\frac{\left(\omega_1^2 - k_X^2\right) \cos\omega_1 t - \alpha_X \omega_1 \sin\omega_1 t}{\left[\left(\omega_1^2 - k_X^2\right)^2 + \alpha_X^2 \omega_1^2\right]}\right]^2 + \left[\frac{\left(\omega_1^2 - k_Y^2\right) \sin\omega_1 t - \alpha_Y \omega_1 \cos\omega_1 t}{\left[\left(\omega_1^2 - k_Y^2\right)^2 + \alpha_Y^2 \omega_1^2\right]}\right]^2\right) \quad (14)$$

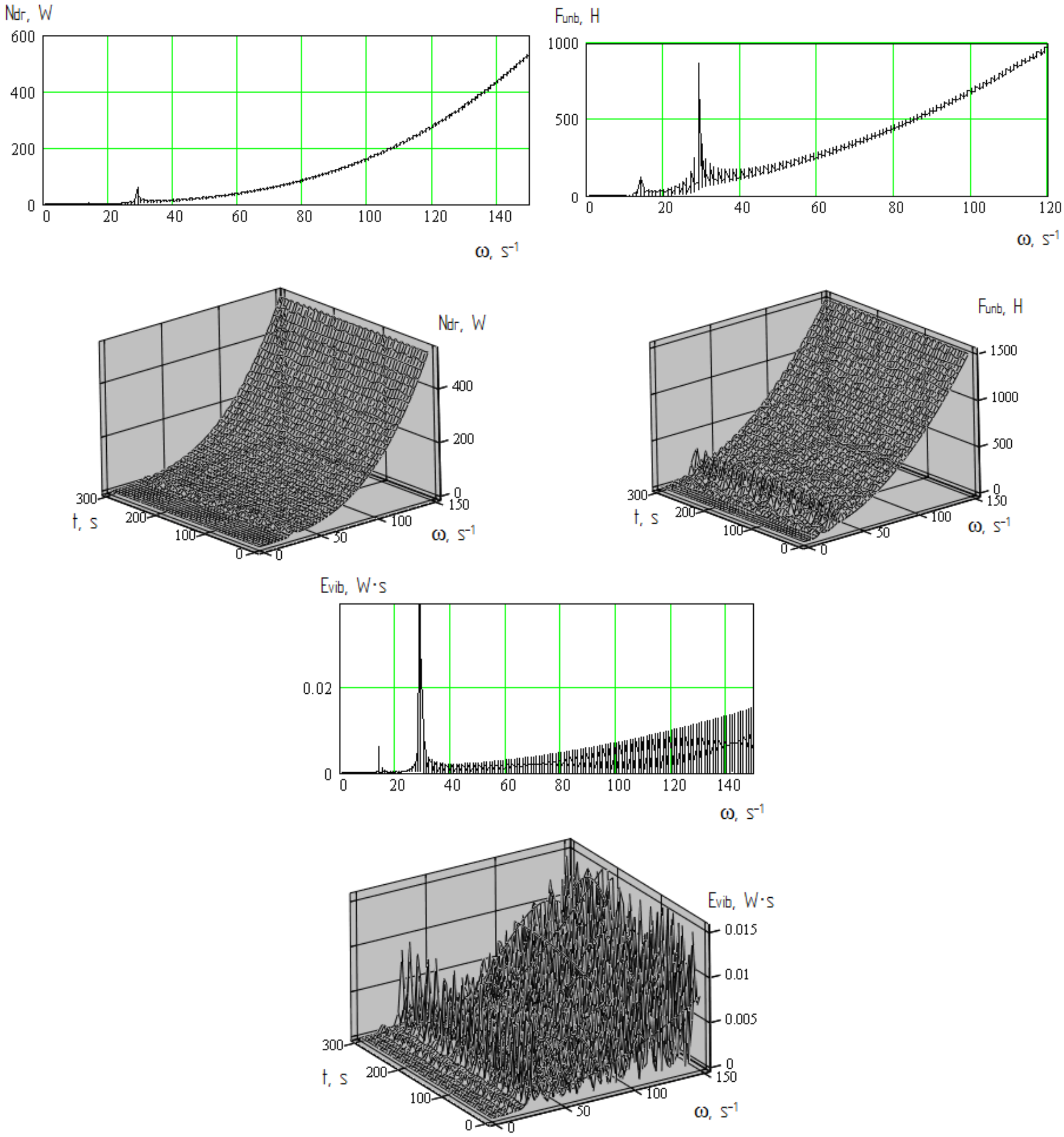

Figure 7 Selection of operating modes of vibration drive operation: A – amplitude of vibrations of the working container; N_{dr} – drive power; F_{unb} – unbalanced forces, loading the support nodes; E_{vib} – the energy of vibrational masses.

Thus, during the study of the dynamics of the conveyor vibration machine, kinematic, power and energy characteristics are obtained: the dynamic unbalanced vibration drive (Figure 7), which allows rate of the effective modes of operation of the vibration unit, in order to ensure the most intensive mode of transmission of the inertial pulse at moderate energy consumption.

The resulting inertial mode should provide the desired wave motion to the belt and is determined by the amplitude-frequency and power characteristics of both vibration exciters that are aggregated in the support rollers of the conveyor vibration machine. The modes are: 2 – 2.5 mm of the vibration amplitude, the angular velocity of the drive shaft of the vibration exciter within 60 – 90 rad/s **(Zavialov et al., 2015; Yanovich et al., 2015)**.

To confirm and refine the theoretical data, experimental studies are carried out using the developed research model of the infrared vibrowave dryer (Figure 8).

Figure 8 The developed design of a vibrowave conveyor infrared dryer. Note: 1 – belt; 2, 3 – exciter engines; 4 – infrared emitters; 5,6 - rollers; 7 – feeder; 8 - receiving hopper; 9 – flexible coupling; 10 – tensioning roller.

During the analysis of the main kinematic and energy characteristics of the vibrating system, an estimation of these parameters is performed at different angles of the location of the unbalances relative to each one. This allows changing a given angle from 0 to π, vary the value of the inertia force of the unbalance elements from the maximum value to zero. The change in such positions of the unbalances makes it possible to obtain the graphical dependences of the basic vibration parameters shown in Figure 9 – 10. The change in the positions of the unbalance elements relative to the vertical axis of the unit makes it possible to obtain variants of the power, moment and combined unbalance of the investigated vibration system.

The developed vibrating conveyor dryer with infrared irradiation of products (Figure 8) is a combination of a belt conveyor and a vibrating transport-technological machine with a dynamic vibration generation method, creating conditions for continuous processing of products, ensuring its suspended state, reducing energy consumption and the metal content of the structure **(Bandura et al., 2015; Palamarchuk et al., 2016)**.

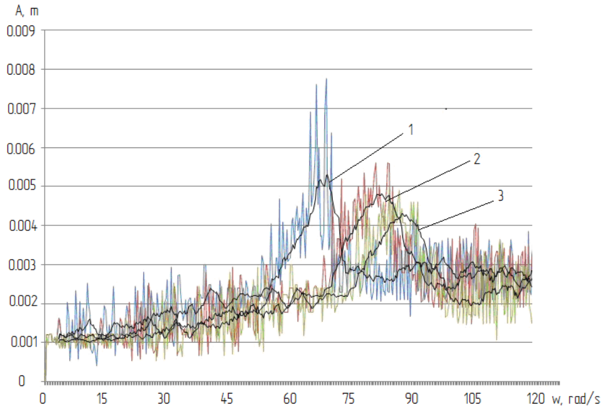

Figure 9 Amplitude-frequency characteristic of the investigated unit, depending on the angular speed of rotation of the drive shaft and the angle of dilution of the unbalances. Note: 1 – at 0 degrees; 2 – at 45 degrees; 3 – at 90 degrees.

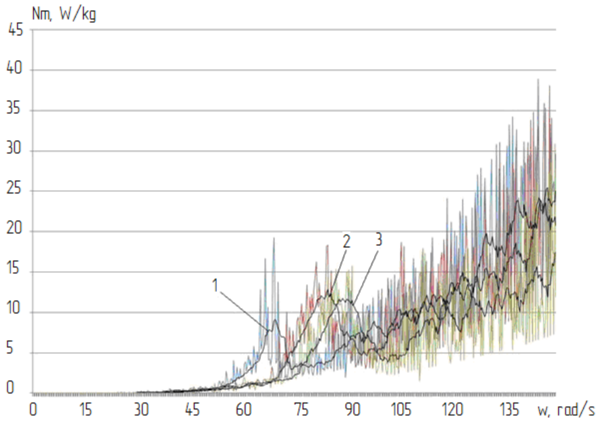

Figure 10 The intensity of the vibrations of the investigated unit as a function of the angular velocity of rotation of the drive shaft and the angle of dilution of the unbalances. Note: 1 – at 0 degrees; 2 – at 45 degrees; 3 – at 90 degrees.

CONCLUSION

1. Based on the analysis, the main trends in the development of conveyor technology machines are formed, the study of the structural and technological schemes of which allows justifying the wave conveyor machine for drying loose agricultural products. Such design makes it possible to significantly increase the surface heat and mass transfer and create conditions for reducing energy consumption during the processing.

2. Graphical representation of the amplitude-strength and energy dependencies allows substantiating the theoretical range of operating modes of the investigated vibration transport-technological machine: 2 – 2.5 mm of the vibration amplitude, angular velocity of the drive shaft of the vibration exciter within 60 – 90 rad/s.

3. The design of the vibrowave infrared drier is developed in the presented scheme. The previous tests confirm the results of the above studies and found the prospects for significant energy savings in this modification of the machine compared to conventional vibrating conveying drying units having a non-deforming transporting body.

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