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Analysis of Resonance Oscillations of Extruder Elastic Screw Conveyor

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Abstract. The relationship of oscillations amplitude of the granular medium-elastic screw system whilst passing over resonance at different values of the bulk mass per unit length at different motion velocity has been studied. The relation of resonance oscillations of the granular medium-elastic screw system described by ratio $a(t)$ and $\vartheta(t)$ has been shown. Based on these ratios, we plotted time variations of amplitude against quick passing over resonance.

Introduction

The analysis of technologies of extruding and machines allowed to systematize their major types [1-4] and to classify them according to different technical and technological features. It is comfortable to present the complex criterion of the estimation of constructions of extruder in an aspect that will allow to operate not quantitative but quality indexes that unlike the methodology [4] the processes of extruding take place during the process of moving of the environment along the modernized screw

As a result of the complex action on material which is processed the functions of a few technological options combine and the efficiency of the process of extruding rises. On the modern stage of development the most researchers distinguish the range of defects which are characteristic for this type of technological equipment. The most considerable items, undoubtedly are the high power-hungriness of process, the low longevity and relatively high cost of the separate elements of the construction.

Even partial solution of the indicated problem tasks will allow to promote the technical level of extruders having regard to their widespread using to economize considerable material resources. That's why we consider that it will be efficient to pay special attention to development of the new extruders with the usage of the elastic spiral working part which provides high- quality preparation of the extruded feeds. With the aim of increasing the efficiency of the work of the spiral elastic working part of the extruder it is necessary to work out theoretical backgrounds of its planning with showing the analytical dependences on the basis of mathematical and dynamic design of the system of the environment – it is the elastic spiral working part taking into account the change of the structure, the features of elastic-dissipative parts and the friction in the kinematics pairs.

The dynamics of environment in the throat of the screw machine largely determines quality of the final product while speaking about the closeness of packing of the components of the briquette, its homogeneity and the structure, etc.

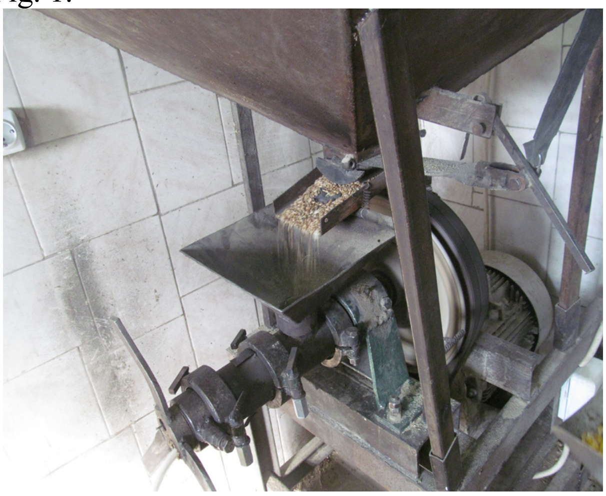
For the research of the mathematical model of the system of the environment it is an elastic spiral working part which is based on combinations of principles of simultaneity of the vibrations in nonlinear mechanical systems [5]; the wave theory of the motion [6]; the basic ideas of the methods of the indignations [5,7], namely to the asymptotic method of nonlinear mechanics [5,8] and to the method of Van der Paul [9], which are adapted for the new classes of the mechanical systems. The problems of granular medium transportation along different surfaces have been considered on the basis of many hypotheses: from motion of the material points system along the surface (Lindner H. [10-12]) to the continuum [13-18] of zero (analog of liquid) or finite rigidity (analog of elastic body).

Therefore the important task which is preceded to the process of forming of environment to feed mixture is its dynamics of the motion of the friable environment in area of the screw that has allowed to get mathematical dependences which describe the qualificatory parameters of the vibrations of the mechanical system and environment of the action of periodic indignation, it is considered the resonant and unresonant vibrations of research object.

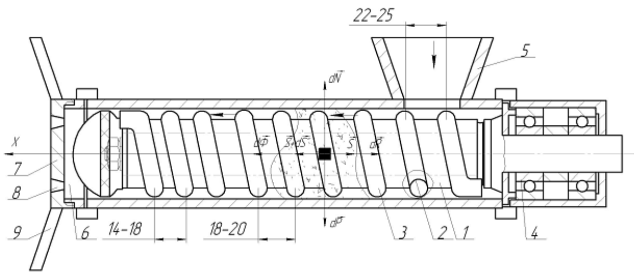
Material and Methods

To investigate the transported material oscillations amplitude whilst main resonance passing at different motion speed of work tool in the extruder.

To describe dynamics of the system under investigation we can use the general principles of mathematical models of mechanical systems dynamics building [6,19-24]. Then according to them we'll consider the dynamic equilibrium of the system material-elastic body selected element. Thus, main characteristics of the mechanical system under investigation and the whole range of forces estimation, system parameters and boundary conditions affecting the dynamic process are shown on Fig. 1.



(a)



(b)

Fig. 1. Design model (a) granular medium-elastic screw conveyor of extruder (b):
1-shaft; 2- helical flute; 3- helical spring; 4- cylindrical case; 5- loading box; 6- unloading area; 7- nut; 8-calibrated orifices; 9 -handle; $d\vec{P}$ - selected element weight; $d\vec{N}$ - normal reaction; $d\vec{R}$ - resistance force; $d\vec{\Phi}$ - inertial force of relative motion of given element with helical spring; $\vec{S}-$ effort acting on the right end of selected element from the elastic screw cut piece side; $\vec{S}+d\vec{S}-$ effort acting on the left end of selected element from the elastic screw cut piece side

Taking into consideration that the suggested model has no deplanation of normal two-dimensional cross-sections of elastic body, it will be enough to know only the cross-section center travel for the most accurate determination of its random cross-section travel. Thus, a one-dimensional elastic body, along which continuum is moving, is taken as a design model. Here, CG motion of a cross-section with x coordinate at random moment of time t is definitively determined by function $u(x,t)$. Therefore, the force of inertia of a specified element equals $dm\frac{d^2u}{dt^2}$, where dm - the mass of a specified element. It is equal to the sum of the masses of continuum dm_1 and the elastic body dm_2, that is $dm = dm_1 + dm_2$ .In turn, $dm_1 = \rho_1(x)dx$, $dm_2 = \rho_2(x)dx$, $\rho_1(x)$ and $\rho_2(x)$ - the volume weight referred to environment and the body. Elastic properties of an auger screw model under study are depicted by applying the quasi-linear law of elasticity $\sigma = E\varepsilon + \mu f(\varepsilon, \dot{\varepsilon})$, where σ - the normal tension in a cross-section of the system model, ε and $\dot{\varepsilon}$ - the relative strain and its rate; $\mu f(\varepsilon, \dot{\varepsilon})$ - a feature that indicates the deviation of elastic model material properties from the linear law; μ - a small parameter, which indicates a small deviation from the specified properties of the linear law.

To build the equation exact solution under boundary conditions without extra restrictions on the material weight distribution along the auger, relative constituent of its motion speed along the helix, force of resistance, harmonic perturbation amplitude etc. is an unsolvable problem so far. So, we impose certain restrictions specific for the actual screw extruder on main characteristics of the mechanical system under consideration, namely:

- continuum mass and helical spiral distribution along its auger length are low variable functions of linear variable x, i.e. $\rho_1(x) = \rho_{10} + \mu\rho_{11}(x)$, $\rho_2(x) = \rho_{20} + \mu\rho_{21}(x)$ ($\rho_{11}(x)$, $\rho_{12}(x)$ - are known continuous functions);- maximum value of resistance force is a value of μ order versus maximum value of restoring force, i.e. max $EA\dfrac{\partial u(x,t)}{\partial x}$ >> max $R\left(\dfrac{du(x,t)}{dt}\right)$; - external disturbance amplitude of screw spiral right end is a small value versus oscillations amplitude of the helical spiral with continuum.

The above-given data allow to simplify the mathematical model of continuum -auger flight dynamics, namely

$$\frac{\partial^2 u(x,t)}{\partial t^2} + \frac{\rho_{20}}{\rho_{10}+\rho_{20}}\frac{\partial^2 u(x,t)}{\partial x \partial t} - \frac{(EA-\rho_{20})}{\rho_{10}+\rho_{20}}\frac{\partial^2 u(x,t)}{\partial x^2} = \mu f_1\left(x, \frac{\partial u(x,t)}{\partial t}, \frac{\partial u(x,t)}{\partial x}\frac{\partial^2 u(x,t)}{\partial t \partial x}\right) \tag{1}$$

where A - the area of its cross section.

$$u(x,t)_{|x=0} = \mu h_0 \sin\theta, \theta = \omega t + \varphi,$$
$$u(x,t)_{|x=l} = 0. \tag{2}$$

where h_0 - amplitude of perturbation at the beginning of the process;

ω - angular speed of the spiral;

φ - is the initial phase of perturbation.

$$f_1\left(x, \frac{\partial u(x,t)}{\partial t}, \frac{\partial u(x,t)}{\partial x}\frac{\partial^2 u(x,t)}{\partial t \partial x}\right) = \frac{1}{\rho_{10}+\rho_{20}}\left\{-\rho_{21}(x)\left[\frac{\partial^2 u(x,t)}{\partial x \partial t} - \frac{(EA-\rho_{20})}{\rho_{10}+\rho_{20}}\frac{\partial^2 u(x,t)}{\partial x^2}\right] + \right.$$
$$\left. + A\frac{\partial}{\partial x} f\left(\frac{\partial u(x,t)}{\partial x}, \frac{\partial^2 u(x,t)}{\partial x \partial t}\right) - R\left(\frac{\partial u(x,t)}{\partial t}\right) - \rho_{21}(x)\left[2\frac{\partial^2 u(x,t)}{\partial x \partial t}V + \frac{\partial^2 u(x,t)}{\partial x^2}V^2 + \frac{\partial u(x,t)}{\partial x}\frac{dV}{dt}\right]\right\}$$

where V - lative velocity.

Left side of the given differential equation is not only a linear one but with constant coefficients as well, and rights sides of the equation (1) and boundary conditions (2) – are proportional to small parameter, i.e. to construct the given problem solution we can use general ideas of approximate analytical methods – disturbance methods [1,3-4, 20,25-26].

Whilst resonance investigating we'll take into consideration only the resonance region. First of all, we'll show that for the first approximation by variables substituting autonomous Eq. (1) under non-autonomous boundary conditions (2) can be reduced to non-autonomous equation but only under homogeneous boundary conditions.

$$u(x,t) = v(x,t) + \mu w(x,t). \tag{3}$$

In fact, if function $w(x,t)$ is considered as a differential equation solution

$$\frac{\partial^2 w(x,t)}{\partial x^2} = 0. \tag{4}$$

and satisfy non-autonomous boundary conditions

$$w(x,t)_{|x=0} = h_0 \sin(\omega t + \varphi),$$
$$w(x,t)_{|x=l} = 0. \tag{5}$$

then function $v(x,t)$ must be a solution of the equation

$$\frac{\partial^2 v(x,t)}{\partial t^2} + \frac{2\rho_{20}}{\rho_{10}+\rho_{20}}\frac{\partial^2 v(x,t)}{\partial x \partial t}V - \frac{(EA-\rho_{20})}{\rho_{10}+\rho_{20}}\frac{\partial^2 v(x,t)}{\partial x^2} =$$
$$= \mu\left\{ f_1\left(x, \frac{\partial v(x,t)}{\partial t}, \frac{\partial v(x,t)}{\partial x}\frac{\partial^2 v(x,t)}{\partial t \partial x}\right) - \frac{\partial^2 w(x,t)}{\partial t^2} - \frac{\rho_{20}}{\rho_{10}+\rho_{20}}\frac{\partial^2 (x,t)}{\partial x \partial t}\right\}. \tag{6}$$

and satisfy homogeneous boundary conditions

$$v(x,t)_{|x=0} = 0,$$
$$v(x,t)_{|x=l} = 0. \tag{7}$$

As solving boundary problem (4), (5) isn't difficult: $w(x,t) = \frac{h_0}{l}(l-x)\sin(\omega t + \varphi)$, then, taking into consideration the above-given, differential equation (6) is as follows

$$\frac{\partial^2 v(x,t)}{\partial t^2} + \frac{2\rho_{20}}{\rho_{10}+\rho_{20}}\frac{\partial^2 v(x,t)}{\partial x \partial t}V - \frac{(EA-\rho_{20})}{\rho_{10}+\rho_{20}}\frac{\partial^2 v(x,t)}{\partial x^2} = \mu\left\{ \tilde{f}_1\left(x, \frac{\partial v(x,t)}{\partial t}, \frac{\partial v(x,t)}{\partial x}\frac{\partial^2 v(x,t)}{\partial t \partial x}, \theta\right)\right\} \tag{8}$$

where

$$\tilde{f}_1\left(x, \frac{\partial v(x,t)}{\partial t}, \frac{\partial v(x,t)}{\partial x}\frac{\partial^2 v(x,t)}{\partial t \partial x}, \theta\right) = f_1\left(x, \frac{\partial v(x,t)}{\partial t}, \frac{\partial v(x,t)}{\partial x}\frac{\partial^2 v(x,t)}{\partial t \partial x}\right) +$$
$$+ \frac{h_0}{l}(l-x)\omega^2 \sin\theta + \frac{2\rho_{20} V \omega}{\rho_{10}+\rho_{20}}\frac{h_0}{l}\cos\theta.$$

Results and Discussion

In this case the problem is to construct the equation (8) resonance solution under homogeneous conditions (7). To determine main ratio describing the given oscillations we'll use basic idea of Van der Pol method fitted for the systems with distributed parameters. Taking into consideration that in resonance case the main parameters, characterizing the oscillation process, greatly depend on phase difference of natural and forced oscillations, we'll introduce formally given parameter ($\vartheta(t) = \phi(t) - \theta(t) \to \phi(t) = \theta(t) + \vartheta(t)$) into Eq. 8 solution, and we have

$$v(x,t) = a(t)\left(\cos\left(\mathrm{K}x + \theta(t) + \vartheta(t)\right) - \cos\left(\mathrm{H}x - \theta(t) - \vartheta(t)\right)\right). \tag{9}$$

Thus, the basis for determining the main amplitude-frequency characteristics of dynamic process is differential Eq. 8 and Eq. 9. Taking into consideration the above-mentioned data, by means of its differentiation with respect to variables *t, x*, we obtain

$$v_t(x,t) = a\vartheta_t[-\sin(\mathrm{K}x + \vartheta + \theta) - \sin(\mathrm{H}y - \vartheta - \theta)] + a_t\left[\cos(\mathrm{K}x + \vartheta + \theta) -\right.$$
$$\left. -\cos(\mathrm{H}x - \vartheta - \theta)\right] - a\frac{r}{s}\omega[-\sin(\mathrm{K}x + \vartheta + \theta) + \sin(\mathrm{H}x - \vartheta - \theta)];$$
$$v_{tt}(x,t) = a_{tt}[\cos(\mathrm{K}x + \vartheta + \theta) - \cos((\mathrm{H}x - \vartheta - \theta))] - 2a_t(\frac{r}{s}\omega + \vartheta_t)\times \tag{10}$$
$$\times\left[\sin(\mathrm{K}x + \vartheta + \theta) + \sin(\mathrm{H}x - \vartheta - \theta)\right] - a\vartheta_{tt}\left[\sin(\mathrm{K}x + \vartheta + \theta) +\right.$$

$$+\sin\left(\mathrm{H}x-\vartheta-\theta\right)\big]-a\left(\frac{r}{s}\omega+\vartheta_t\right)^2[\cos\left(\mathrm{K}x+\vartheta+\theta\right)-\cos\left(\mathrm{H}x-\vartheta-\theta\right)];$$

$$v_{xt}\left(x,t\right)=a_t[-\mathrm{K}\sin\left(\mathrm{K}x+\vartheta+\theta\right)+\mathrm{H}\sin\left(\mathrm{H}x-\vartheta-\theta\right)]$$

$$-a\left(\frac{r}{s}\omega+\vartheta_t\right)[\mathrm{K}\cos\left(\mathrm{K}x+\vartheta+\theta\right)+\mathrm{H}\cos\left(\mathrm{H}x-\vartheta-\theta\right)];$$

$$v_{xx}\left(x,t\right)=a[-\mathrm{K}^2\cos\left(\mathrm{K}x+\vartheta+\theta\right)+\mathrm{H}^2\cos\left(\mathrm{H}x-\vartheta-\theta\right)].$$

where r, s - are relatively prime numbers.

If we substitute the obtained expressions in differential Eq. 8, we'll obtain for the first approximation the system of linear heterogeneous algebraic equations solvable for unknown functions a_t and ϑ_t

$$a_t\left\{-2\omega\sin\left(\mathrm{K}x+\vartheta+\theta\right)-2\omega\sin\left(\mathrm{H}x-\vartheta-\theta\right)-2V\sin\left(\mathrm{K}x+\vartheta+\theta\right)+2V\,\mathrm{H}\sin\left(\mathrm{H}x-\vartheta-\theta\right)\right\}$$
$$+a\left(\vartheta_t+\frac{r}{s}\omega\right)\left\{-2\omega\cos\left(\mathrm{K}x+\vartheta+\theta\right)+2\omega\cos\left(\mathrm{H}x-\vartheta-\theta\right)-\right.$$
$$\left.-2V\mathrm{K}\cos\left(\mathrm{K}t+\vartheta+\theta\right)-2V\mathrm{H}\cos\left(\mathrm{H}x-\vartheta-\theta\right)\right\}=\mu\tilde{f}_1(a,x,\vartheta+\theta,\theta). \quad (11)$$

After simple transformations from Eq. 11 we have

$$\cos(\vartheta+\theta)\left\{a_t\left[(-2\omega-2V\mathrm{K})\sin\mathrm{K}x+(-2\omega+2V\mathrm{H})\sin\mathrm{H}x\right]+\right.$$
$$\left.+a\left(\vartheta_t+\frac{r}{s}\omega-\Omega\right)\left[(-2\Omega-2V\mathrm{K})\cos\mathrm{H}x+(2\Omega-2V\mathrm{H})\cos\mathrm{H}x\right]\right\}+ \quad (12)$$
$$+\sin(\vartheta+\theta)\left\{a\left(\vartheta_t+\frac{r}{s}\omega-\Omega\right)\left[(2\Omega+2V\mathrm{K})\sin\mathrm{K}x+(2\Omega-2V\mathrm{H})\sin\mathrm{H}x\right]+\right.$$
$$\left.+a_t\left[(-2\Omega-2V\mathrm{K})\cos\mathrm{K}x-(-2\Omega+2V\mathrm{H})\cos\mathrm{H}x\right]\right\}=\mu\tilde{f}_1(a,x,\vartheta+\theta,\theta).$$

where K, H - wave numbers, Ω - their frequency

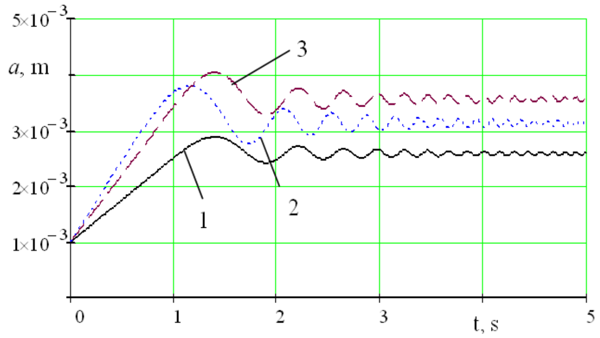
The last ratio determines main parameters of system under discussion oscillations main parameters, i.e., after averaging [2,5-7], the connection between amplitude and phase difference is as follows

$$a_t=\frac{\mu}{2\pi l\left[(\Omega+V\mathrm{K})^2+(\Omega-V\mathrm{H})^2\right]}\times\int_0^l\left(\Psi(x)\int_0^{2\pi}\tilde{f}_1(a,x,\vartheta+\theta,\theta)\cos(\vartheta+\theta)d\theta+\right.$$
$$\left.+\Theta(x)\int_0^{2\pi}\overline{f}(a,x,y,\vartheta+\theta,\theta)\sin(\vartheta+\theta)d\theta\right)dx; \quad (13)$$

$$\vartheta_t=\Omega-\frac{r}{s}\omega-\frac{\varepsilon}{2\pi la\left[(\Omega+V\mathrm{K})^2+(\Omega-V\mathrm{H})^2\right]}\times\int_0^l\left(\Psi(x)\int_0^{2\pi}\tilde{f}_1(a,x,\vartheta+\theta,\theta)\sin(\vartheta+\theta)d\theta-\right.$$
$$\left.-\Theta(x)\int_0^{2\pi}\tilde{f}_1(a,x,\vartheta+\theta,\theta)\cos(\vartheta+\theta)d\theta\right)dx \quad (14)$$

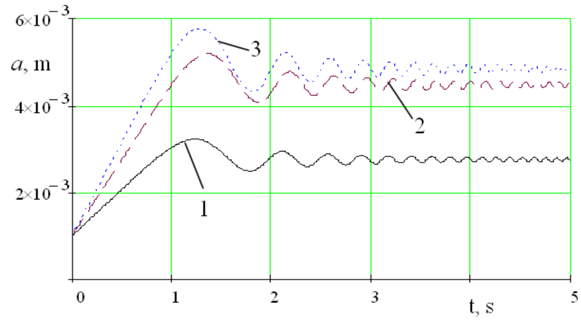
where functions $\Psi(x)$ and $\Theta(x)$ are determined by relations;

So, for the first approximation the resonance oscillations of granular medium-elastic screw system are described by Eq. 9, and parameters $a(t)$ and $\vartheta(t)$, being their constituents are determined by Eq. 13 (Fig. 2). Based on these ratios, we've plotted time variations of amplitude against quick passing over resonance.



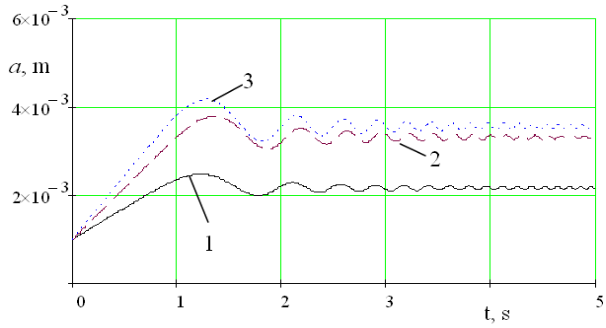
mass per unit length 1- $\rho_{20} = 0$; 2- $\rho_{20} = 3kg/m$; 3- $\rho_{20} = 5kg/m$

(a)



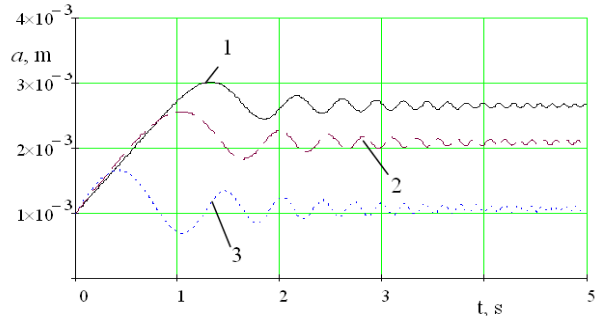
mass per unit length 1- $\rho_{20} = 0$; 2- $\rho_{20} = 3kg/m$; 3- $\rho_{20} = 5kg/m$

(b)



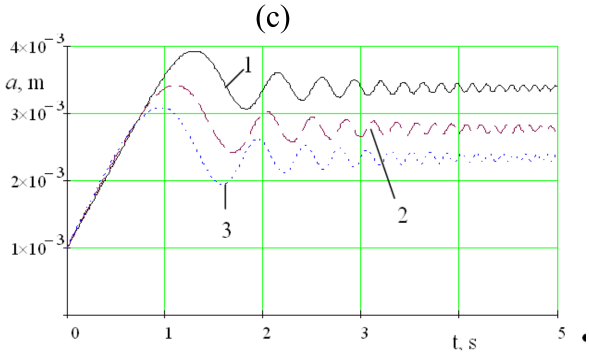
mass per unit length 1- $\rho_{20} = 0$; 2- $\rho_{20} = 3kg/m$; 3- $\rho_{20} = 5kg/m$

(c)



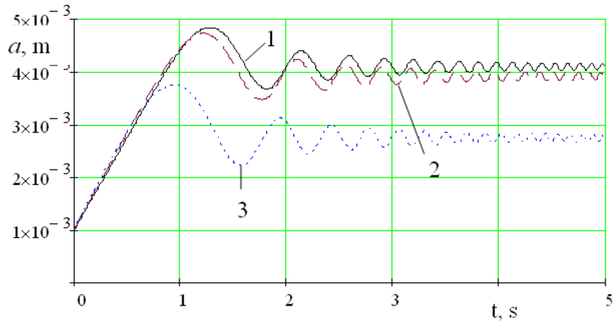
at speed 1- $\vartheta = 0$; 2- $\vartheta = 3m/s$; 3- $\vartheta = 5m/s$; $l = 0.5m$

(d)



at speed 1- $\vartheta = 0$; 2- $\vartheta = 3m/s$; 3- $\vartheta = 4m/s$; $l = 0.75m$

(e)



at speed 1- $\vartheta = 0$; 2- $\vartheta = 3m/s$; 3- $\vartheta = 4m/s$; $l = 1m$

(f)

Fig. 2. Values of oscillations amplitude of granular medium-elastic screw system under resonance passing conditions at different values of bulk mass per unit length – (a), (b), (c); different speed of its motion – (d), (e), (f)

A test facility (Fig. 3) and equipment for adjusting the kinematic parameters of technological process were developed and made to conduct experiments.

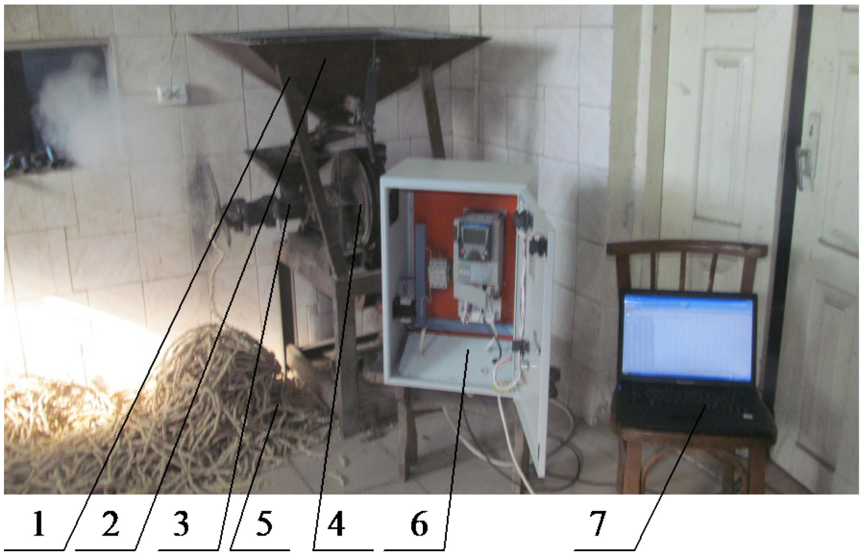


Fig. 3. Picture of a test facility and equipment for feed mix preparation:
1 – frame; 2 – feeder; 3 – feed mix compressing unit; 4 – driven balance wheel; 5 – feed mix;
6 – Altivar 7.1; 7 – PC

To conduct experiments on its rotation frequency adjustment a frequency transducer (ALTIVAR-71) was used from a PC by the program Power Suite of version 2.5.0. The research on the extruder output was being done at such materials transportation with certain volume mass: barley – 700 kg/m^3; wheat – 760 kg/m^3; corn – 800 kg/m^3; humidity W=10…18%, which allowed to build the correspondent analytical retrograde dependencies. The humidity was measured by Grain Moisture Meter MD7822 for bulk materials.

To make feed mix pressing possible at different modes in a press-extruder 3 auger conveyors with different steps of the tool t and the crest width of screw element h_b, screw hole depth of the tool h were used, the rotational frequency of the tool was changed (10, 12, 15, 20 rev/c). Feed mix extruding was done at the following modes: pressure in extruder active zone 2...3 MPa, electric engine consumed power 4,0...4,5 kW, at the tool length 0,4 m, of diameter 0,05 m.

Fig. 4 shows the response surfaces of value Q change caused by simultaneous change of two factors for the feed mix: (a) - $Q = f(h,t)$; (b) - $Q = f(h,h_b)$; (c) - $Q = f(n,h)$; (d) - $Q = f(h_b,t)$; (e) - $Q = f(n,t)$; (f) - $Q = f(h_b,n)$ of geometrical and structural parameters whilst feed mix making by spring-actuated tool at the tool rotation frequency (10, 12, 15, 20 rev/c), depth of the tool screw hole within the limits $h = 0,002 \div 0,006$ m and with different steps of the tool $t = 0.025 \div 0.015$ m and crest width of elastic element $h_b = 0,004 \div 0,012$ m.

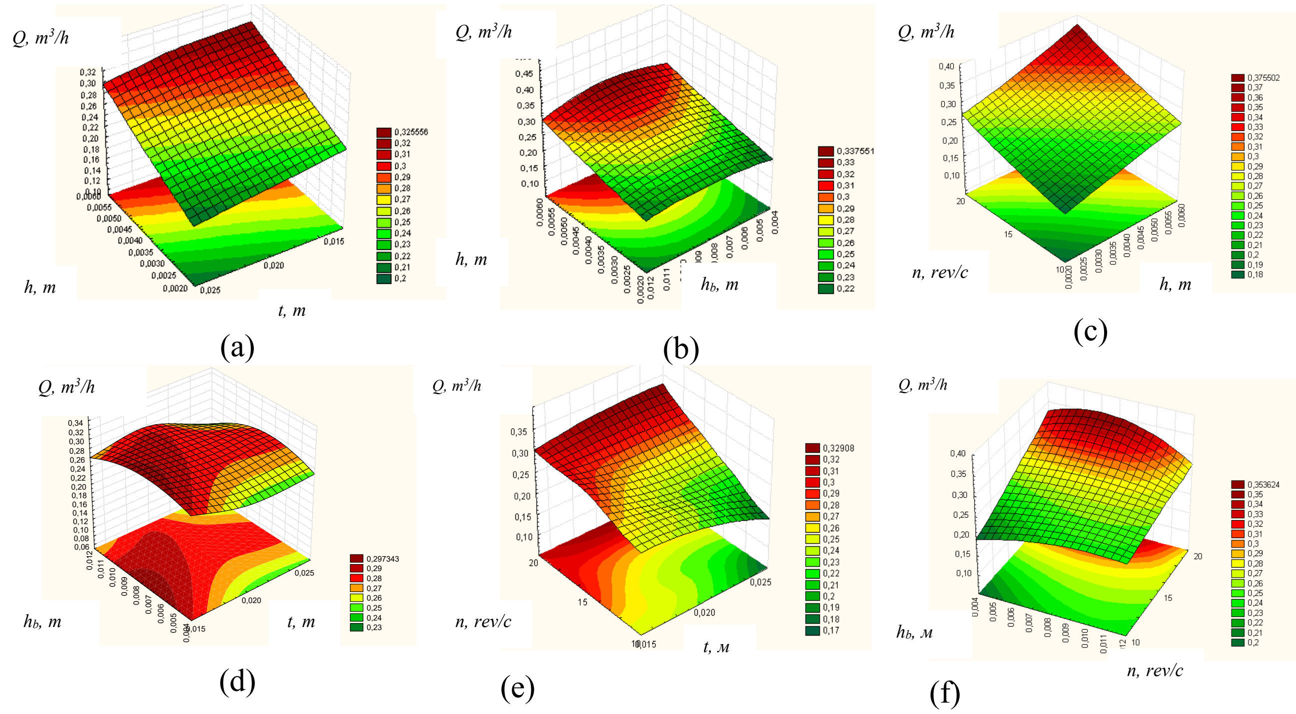


Fig. 4. Response surfaces of dependencies:
(a) - $Q = f(h,t)$; (b) - $Q = f(h,h_b)$; (c) - $Q = f(n,h)$; (d) - $Q = f(h_b,t)$; (e) - $Q = f(n,t)$;
(f) - $Q = f(h_b,n)$

We found out that the most important factors affecting the output are the tool rotation frequency n, its step t and width of the elastic element crest h_b and less important is the depth of the tool screw hole h. To make feed mix in general it's reasonable to use a tool with such parameters: the tool step is within the boundaries $t = 0.025 \div 0.015$, it's depth $h = 0,006$ m, the elastic element crest width $h_b = 0.008$ m at the tool rotation velocity from 12 to 18 rev / c.

Conclusions

According to theoretical results, the graphical dependences present the technique of developing the approximate analytical solution of the dynamic model of a system 'extruder elastic auger working body'. The technique is based on:

- for larger values of continuum relative motion speed the resonance amplitude value is smaller;
- for larger values of continuum mass per unit length the resonance amplitude value is larger;
- for elastic screw of higher rigidity the resonance amplitude is for larger value of driving force frequency and at the same time the resonance amplitude value is smaller;
- the larger the value of oscillation amplitude of auger flight right end the larger the amplitude resonance value;
- the effect of resonance entering amplitude (amplitude initial value) on amplitude resonance value is quite small;
- speed whilst resonance region passing affects the amplitude resonance value.

References

[1] I. Çelik, C. Güneş, Use of disc springs in a pellet fuel machine, Acta Polytechnica, Journal of Advanced Engineering. 57(2), (2017) 89-96. doi: 10.14311/AP.2017.57.0089.
[2] M. Kováčová, M. Matus, P. Krizan, J. Beniak, Design theory for the pressing chamber in the solid biofuel production process, Acta Polytechnica. 54(1), (2014) 28-34. doi: 10.14311/AP.2014.54.0028.
[3] H. Li, W.F. Liu, The Exprimental Research of Screw Conveyor Feeding System. New trends in mechanical engineering and materials, Book Series: Applied Mechanics and Materials. 251 (2013) 101-103.
[4] A. W. Roberts, Bulk Solids: Optimizing Screw Conveyors, Chemical engineering. 122(2), (2015) 62-67.
[5] Y. A. Mitropolskiy, Averaging method in nonlinear mechanics, Naukova dumka, Kyiv, USSR, 1971.
[6] O. Lyashuk, The study on nonlinear model of dynamics of a system 'extruder elastic auger working body', In Acta Technologica Agriculturae. 4 (2016) 102-107.
[7] O. L. Lyashuk et al., Modeling of the vertical screw conveyer loading, INMATEH: Agricultural Engineering. 45/1 (2015) 87-95.
[8] Y. A. Mitropolskiy, On construction of asymptotic solution of Klein-Gordon disturbed equation, Ukr. Math. J. 47/9 (1995) 1209-1216.
[9] O. Lyashuk, M. Sokil, Y. Vovk, A. Tson, A. Gupka, O. Marunych, Torsional oscillations of an auger multifunctional conveyor's screw working body with consideration of the dynamics of a processed medium continuous flow, Ukrainian Food Journal. 7(3), (2018) 499-510.
[10] I. V. Andronov, N. S. Bulanova, Unquasilinear asymptotics of problems of bars and plates oscillations on nonlinear elastic foundation. Report NAS of Ukraine, Kyiv, Ukraine. 9 (1995) 28-30.
[11] O. Blakier, Nonlinear systems analysis, Nauka, Moscow, USSR, 1969.
[12] L. Q. Chen, B. Wang, H. Ding, Nonlinear parametric vibration of axially moving beams: asymptotic analysis and differential quadrature verification, Journal of Physics: Conference Series 181 (2009) 1-8.
[13] P. D. Dotsenko, On oscillations and straight-line pipeline resistance, Applied Mechanics. 3 (1971) 85-91.
[14] I. V. Kuzyo, B. I. Sokil, Longitudinal motion impact on lateral oscillations of nonlinear elastic systems, Vibrations in engineering and technologies. 2/14 (2000) 44-46.
[15] Y. Kharchenko, M. Sokil, Multi-frequency oscillations of one-dimensional nonlinear elastic operate media and construction procedure of describing them boundary problems asymptotic approximations, Mechanical engineering. Ukrainian Monthly Scientific-Technical and Production Journal. 1 (2007) 19-25.
[16] Y. A. Mitropolskiy, On construction of asymptotic solution of Klein-Gordon disturbed equation, Ukr. Math. J. 47/9 (1995) 1209-1216.
[17] A. P. Subach, Dynamics of machines and processes of bulk vibration and centrifuging process of bulk details. Znanie, Riga, Latvia 1991.
[18] A. P. Subach, Forced vibrations of the vibro-impact system in an inelastic collision of the masses. On a problem of dynamics. Znanie, Riga, Latvia. 18 (1996) 67-78.
[19] N. N. Boholyubov, Y. A. Mitropolskiy, Asymptotic methods in nonlinear oscillations theory, Nauka, Moscow, USSR, 1974.
[20] B. Wan der Pol, A Theory of the Amplitude of Free and Forced Triode Vibrations, Radio Review. 1 (1920).
[21] R. B. Hevko et al, Development and investigation of reciprocating screw with flexible helical surface, INMATEH: Agricultural Engineering. 46/2 (2015) 133-138.
[22] R. B. Hevko et al., Investigation of a transfer branch of a flexible screw conveyer, INMATEH: Agricultural engineering. 48/1 (2016) 29-34.

[23] V. Rachok, Influence of working elements of various configurations on the process of yeast dough kneading, Ukrainian Food Journal. 7(1) (2018) 119-134.
[24] V. Vytvytskyi, I. Mikulionok, O. Sokolskyi, O. Gavva, Pressure and temperature influence on the friction coefficient of granular polymeric materials on the metal surfaces, Ukrainian Food Journal. 6(3) (2017) 543-552.
[25] X. X. Sun, W. J. Meng, Y. Yuan, Design method of a vertical screw conveyor based on Taylor-Couette-Poiseuille stable helical vortex, Advances in mechanical engineering. 9(7) (2017) doi: 10.1177/1687814017714984.
[26] Y. Tian, P. Yuan, F. Yang, J. Gu, M. Chen, J. Tang, et al., Research on the Principle of a New Flexible Screw Conveyor and Its Power Consumption, Applied Sciences. 8(7) (2018), doi: https://doi.org/10.3390/app8071038.