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On the issue of limiting the irregular motion of a technological machine within specified limits

Yuriy Podgornyj [1, 2, a, *], *Tatyana Martynova* [1, b], *Vadim Skeeba* [1, c]

[1] Novosibirsk State Technical University, 20 Prospekt K. Marksa, Novosibirsk, 630073, Russian Federation
[2] Novosibirsk Technological Institute (branch) Moscow State University of Design and Technology, 35 Krasny prospect (5 Potaninskayast.), Novosibirsk, 630099, Russian Federation

[a] https://orcid.org/0000-0002-1664-5351, pjui@mail.ru, [b] https://orcid.org/0000-0002-5811-5519, martynova@corp.nstu.ru,
[c] https://orcid.org/0000-0002-8242-2295, skeeba_vadim@mail.ru

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ABSTRACT

Introduction. The problem of regulating speed fluctuations for any mechanism is essential, because the time interval of this movement is the working time during which the main technological operation is performed. In this case, the question may arise about the regulation of motion speeds both during acceleration, idling of the machine, and during the execution of the main technological operation. The main qualitative indicator of the satisfactory operation of any machine is the motion irregularity ratio, the value of which depends on the ratio of the maximum, minimum and average speeds of the drive shaft. Particularly acute is the problem of determining the motion irregularity ratio of the machine, taking into account the characteristics of the motor. In this case, the machine is considered as a system consisting of a single mass. The elasticity of the elements included in the machine is neglected. An analysis of the scientific literature in this area indicates that insufficient attention is paid to the study of rotation irregularities and its influence on the dynamics of mechanisms, especially when it comes to solving equations taking into account the characteristics of the motor. **The purpose of this work** is to develop a methodology that allows determining and regulate the non-uniform rotation of the drive shaft, taking into account the characteristics of the motor, the forces of useful resistance and the inertia of the masses of the mechanism. The relevance of the study is due to the lack of a unified methodology that allows adjusting the non-uniform rotation of the drive shaft at the stage of designing mechanisms of this type. **Theory and methods**. It is proposed to use the *Lagrange equation of the second kind* to determine the equation of machine motion in differential form. Mathematical simulation is carried out using the *Mathcad* and *KOMPAS-3D* application packages. **Results and discussion**. A methodology is presented that makes it possible to regulate the non-uniform rotation of the shaft. The *CAE* of the *Mathcad* system are used to determine the value of the irregularity ratio and patterns of change in these indicators are identified for total operating values that are in the range of 22-46 Nm. An analysis of the results of the calculations performed indicates that the irregularity ratio of the drive shaft rotation is 0.101. It is possible to change this ratio by changing the reduced moment of inertia by installing an additional flywheel or changing the torque of the motor shaft. The obtained results of the research made it possible to develop specific recommendations for the modernization of the drive designs for machines for mixing bulk materials and to outline ways for further research in this direction.

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Introduction

Motion irregularity is one of the main problems of the dynamics of mechanisms. The determination of its values allows choosing rational relationships between the acting external forces, the inertial components of the mechanism and its velocities. The irregular motion of the drive shaft of the machine (main shaft)

*** Corresponding author**
Podgornyj Yuriy I., D.Sc. (Engineering), Professor
Novosibirsk State Technical University,
20 Prospekt K. Marksa,
Novosibirsk, 630073, Russian Federation
Tel: +7 (383) 346-17-79,**e-mail:** pjui@mail.ru

occurs when the moment created by the motor is not constant or the moment of useful resistance is variable [1–11].

Increasing interest in the practice of designing machines for mixing bulk materials is given to drives with irregular motion of the working body. This is due to the fact that in this case the shortening of the entire kinematic chain of the drive is ensured, and at the same time, the quality of the agitated product is improved due to the elimination of dead zones during mixing of the specified type of product [4–7, 9, 10, 12–20]. The problem of regulating speed fluctuations for any mechanism is essential, because the time interval of this movement is the working time during which the main technological operation is performed – mixing the bulk product [21–23]. In this case, the question may arise about the regulation of motion speeds both during the idling of the machine and during the execution of the main technological operation. The structure of the device may include various types of mechanisms, including lever type, cam, gear, as well as cam-gear-lever, mechanisms with elliptical wheels, differential, etc.

In this paper, the authors propose the design of a device with a planetary gear in its drive. The use of such a drive will increase the performance of the equipment, its technical and economic efficiency, which in turn will improve the competitiveness of newly designed machines. When synthesizing mechanisms of this type at the design stage of drives, it is necessary to know the amplitudes of oscillations of the speeds of the drive shaft both during the acceleration of this machine and during steady motion [24–27]. The identification of patterns of change in the speeds of the drive shaft will allow determining the motion irregularity ratio and actively introducing in the design process of the machine, regulating it with the help of rational placement of the inertial-mass components of the designed product and correctly setting the magnitude and pattern of changes in the technological load. An analysis of the scientific literature in this area indicates that insufficient attention is paid to the study of rotation irregularities and its influence on the dynamics of mechanisms, especially when it comes to solving equations taking into account the characteristics of the motor. [1–10, 12, 14, 15, 17–22, 24–27].

The control of the drive devices of machines for mixing bulk materials between the energy inflow and its consumption to overcome external resistances can have different goals, including maintaining a certain performance [24–27].

Graph analytical methods are usually used to determine the moments of inertia of the flywheel masses (flywheels) for a given maximum of the machine irregular motion since analytical expression of the motor mechanical properties is problematic [6–10, 14–17]. Usually, driving moments are set as an arbitrary function of the rotation angle or assumed constant. In this case, it is not possible to take into account feedback, i.e., the influence of the magnitude of the external resistance on the motion speed of the driver and, as a consequence, on the magnitude of the irregular motion of the drive shaft [16–22, 23–27].

The reduced moments of inertia of the machine may be constant or dependent on the position of the driver. For a wide variety of machine mechanisms, the main power and kinematic characteristics depend on the functions of the driver position [1–11], including in the case under consideration. Most problems in the kinematic analysis of mechanisms assume that the driver moves at a constant speed. However, such an assumption can only be attributed to mechanisms that have a constant moment of inertia (a reduced one). The situation is more complicated with the reduced inertial forces. |It can practically be constant only for bodies having the coordinates of centers on the axis of rotation [5–14, 17–20].

The purpose of this work is to develop a methodology that allows determining and regulate the non-uniform rotation of the drive shaft, taking into account the characteristics of the motor, the forces of useful resistance and the inertia of the masses of the mechanism. The relevance of the study is due to the lack of a unified methodology that allows adjusting the non-uniform rotation of the drive shaft at the stage of designing mechanisms of this type.

Theory and methodology

It is supposed to consider the above model of the mechanism on the example of a food machine designed for mixing bulk material, in which the moments of resistance, inertia forces and the moments of inertia of the masses depend on the angle of rotation of the driver (drive shaft), and the drive has an asynchronous electric motor (see diagram shown in Fig. 1). The development of the mathematical model was carried out by means of the *Mathcad* software product with the direct use of the computer-aided design system *Compass 3D*.

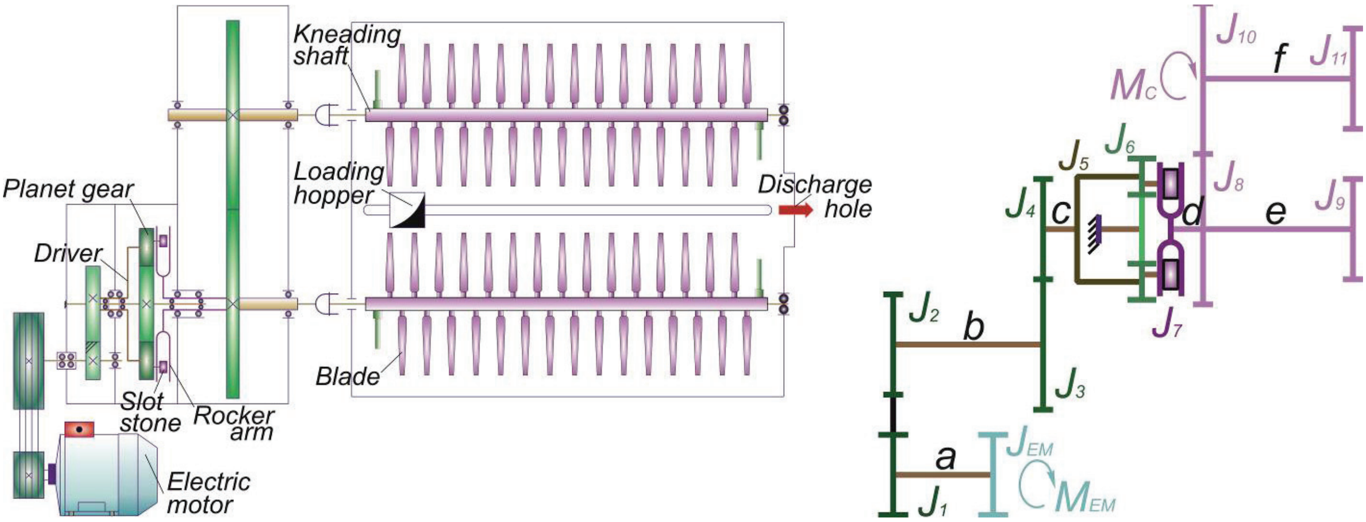

Fig. 1. Kinematic diagram and mathematical model of the kneader design that includes an epicyclic gearing

The nature of the change in the process load acting on the working shafts of the device was presented earlier in [25]. This paper presents only the values and nature of the reduced moments of these forces to the main shaft of the device. In our case, it is presented, consisting of two components: $M_c(\varphi) = 24 + 12\cos(2/16\varphi)$; and the moment of the driving forces is represented by a parabola

$$M_d = A\left(\frac{d\varphi^2}{dt} + B\right), \text{ where } A = -\frac{M_m}{\omega_0^2 - \omega_m^2}; \; B = -\frac{M_m \omega_0^2}{\omega_0^2 - \omega_m^2}.$$

The maximum values of the total moment of the useful resistance and the moment of inertia amounted to 46 N·m, the minimum amounted to 22 N·m and depend on the rotation angle of the kneading shafts blades.

The device operating peculiarities are described in detail in [24–27]. This paper presents a mathematical model of the device, with the following values introduced: the rotor moment of inertia is designed as J_{EM}; the drive pulley moment of inertia is designed as J_1; the driven pulley moment of inertia is designed as J_2; gears moments of inertia are designed as J_3, J_4, J_5, J_6, J_8, J_9, J_{10}, J_{11}; that of carrier is J_7. The shafts that translate motion from the motor to the working shafts are designated as *a*, *b*, *c*, *d*, *e*, *f*.

It is proposed to determine the equation of machine motion using the *Lagrange equation of the second kind*, which in this instance will have the following form:

$$J\frac{d^2\varphi}{dt^2} + \frac{1}{2}\left(\frac{d\varphi}{dt}\right)^2 \frac{dJ}{d\phi} = M_d - M_c, \qquad (1)$$

where J is the reduced moment of inertia; φ is the generalized coordinates of the system; M_d is driving moment; M_c is the moment of resistance.

The drive moment is determined by

$$M_d = \frac{2M_m}{\frac{\sigma}{\sigma_m} + \frac{\sigma_m}{\sigma}}, \qquad (2)$$

where J is the reduced moment of inertia; σ is the slip corresponding to the value of M_d; σ_m is the slip corresponding to the value of M_m; M_m is the maximum (overturning moment).

In equation (1), we replace the M_d value with an expression describing a parabola, then we obtain:

$$M_d = A\left(\frac{d\varphi}{dt}\right)^2 + B, \tag{3}$$

where

$$A = -\frac{M_m}{\omega_0^2 - \omega_m^2}; \qquad B = -\frac{M_m \cdot \omega_0^2}{\omega_0^2 - \omega_m^2}, \tag{4}$$

where ω_0 and ω_m are the angular velocities of the reduced mass of the system corresponding to $M_d = 0$ и $M_d = M_m$.

Then equation (1) can be rewritten as:

$$J\frac{d\omega}{dt} + \frac{1}{2}\omega^2\frac{dJ}{d\varphi} = A\omega^2 + B - M_c, \tag{5}$$

where $\frac{d\varphi}{dt} = \omega$.

Dividing all the terms of this equation by $\omega = \frac{d\varphi}{dt}$ and transforming equation (5), equation becomes:

$$\frac{d\omega}{d\varphi} + \frac{\left(\frac{1}{2}\frac{dJ}{d\varphi} - A\right)\omega}{J} + \frac{M_c - B}{J\omega} = 0, \tag{6}$$

Replacing $\omega^2 = u$, equation becomes:

$$\frac{du}{d\varphi} + 2uf(\varphi) = -2q(\varphi), \tag{7}$$

where

$$f(\varphi) = \frac{\frac{1}{2}\frac{dJ}{d\phi} - A}{J}; \qquad q(\varphi) = \frac{M_c - B}{J}.$$

Under the initial conditions when $t = 0$ and $u = \omega_0^2$, the solution has the following form:

$$\omega = \sqrt{e^{-2\int_0^\varphi f(\varphi)d\varphi}\left[\omega_0^2 - 2\int_0^\varphi q(\varphi)e^{2\int_0^\varphi f(\varphi)d\varphi}d\varphi\right]}, \tag{8}$$

To determine the moment of the flywheel inertia, the following assumption will be taken:

$$J = J_m + J_0 = \text{const},$$

where J_m is the reduced flywheel moment of inertia; J_0 is the reduced kneading machine moment of inertia.

The moment of resistance is considered in the form of:

$$M_c = M_1 + M_2 \sin n\varphi,$$

where M_1 is the constant part of the reduced moment of useful resistances; M_2 is the maximum value of the variable part of the moment; n is the multiplicity of loading within one revolution.

Since $J = \text{const}$,

$$f(\varphi) = -\frac{A}{J}; \quad q(\varphi) = \frac{M_1 + M_2 \sin n\varphi - B}{J}.$$

The angular velocity is determined as:

$$\omega = \sqrt{e^{2\int_0^{\varphi} -\frac{A}{J} d\varphi} \left[\omega_0^2 - 2\int_0^{\varphi} \frac{M_1 + M_2 \sin n\varphi - B}{J} e^{-2\int_0^{\varphi} \frac{A}{J} d\varphi} d\varphi \right]}, \quad (9)$$

Integrating expressions under the root sign, we get:

$$\omega = \sqrt{e^{2\int_0^{\varphi} -\frac{A}{J} d\varphi} \left[\omega_0^2 - 2\int_0^{\varphi} \frac{M_1 + M_2 \sin n\varphi - B}{J} e^{-2\int_0^{\varphi} \frac{A}{J} d\varphi} d\varphi \right]}, \quad (10)$$

where

$$D_1 = \frac{M_m}{J\left(\omega_0^2 - \omega_m^2\right)}; \qquad D_2 = \frac{M_m \omega_0^2 - M_1\left(\omega_0^2 - \omega_m^2\right)}{J\left(\omega_0^2 - \omega_m^2\right)}; \qquad D_3 = \frac{M_2}{J}.$$

Assuming that steady motion occurs at φ tending to infinity, the expression (10) takes the form

$$\omega = \sqrt{\frac{D_2}{D_1} + \frac{2D_3\left(n\cos n\varphi - 2D_1 \sin n\varphi\right)}{4D_1^2 + n^2}}, \quad (11)$$

from which

$$\omega_{max} = \sqrt{\frac{D_2}{D_1} + \frac{2D_3}{\sqrt{4D_1^2 + n^2}}}; \quad \omega_{min} = \sqrt{\frac{D_2}{D_1} - \frac{2D_3}{\sqrt{4D_1^2 + n^2}}}, \quad (12)$$

The resulting equations (12) are substituted into the equation for determining the irregular motion of the drive shaft, which is the following:

$$\delta = 2\frac{\omega_{max} - \omega_{min}}{\omega_{max} + \omega_{min}}. \quad (13)$$

Results and discussion

The intended purpose requires defining the main properties of the motor, which for the case under consideration are: M_d is the drive moment, which is determined in accordance with equation (2); M_m is the maximum (overturning moment).; rates of angular motion: ω_0 = 145 s^{-1} and ω_m = 36 s^{-1} corresponding to M_d = 0 and $M_d = M_m$ = 158 Nm. All these parameters are presented in the form of a graph in Figure 2, where the solid line shows the properties of the motor, and the dashed line is the parabola described by equation (3), in which *A* and *B* are determined by the condition of the parabola passage through the origin and point 0.

The moment of the useful resistance, reduced to the main (modified) shaft is presented in the form of a graph shown in Figure 3.

In accordance with the previously obtained data presented in [24–27], the reduced moment of inertia of all machine masses to the main (modified) shaft is J = 0,323 kg·m^2. The drive shaft speed of rotation was calculated using equation (11). The calculation results are shown in Figure 4.

For the case under consideration, the irregular rotation of the modified shaft was 0.085 (11) with a maximum rotation speed equal to ω_{max} = 145·s^{-1} and a minimum speed equal to ω_{min} = 133.2 s^{-1}.

The analysis of the equation (13) leads to the conclusion that the irregularity ratio depends on the maximum and minimum rotational speeds; the value of the reduced moment of inertia, among other things, depends on the moments of resistance and the driving moment. In this regard, we conducted research in terms of changing the non-uniform of rotation from the value of the reduced moment of inertia and the value of the driving moment. For the former, the change in the value of the motion irregularity is shown in Figure 5, and for the latter in Figure 6.

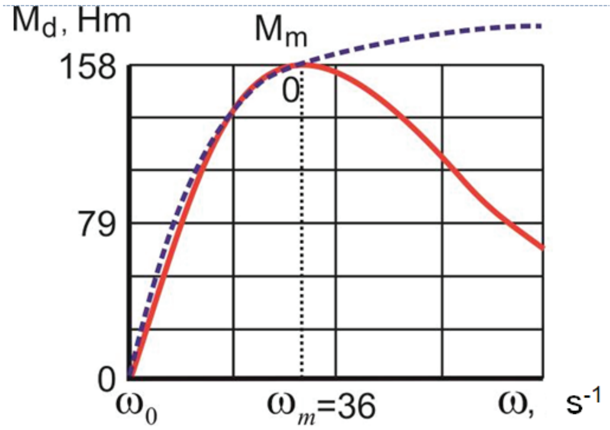

Fig. 2. Graph of an asynchronous motor and its special points

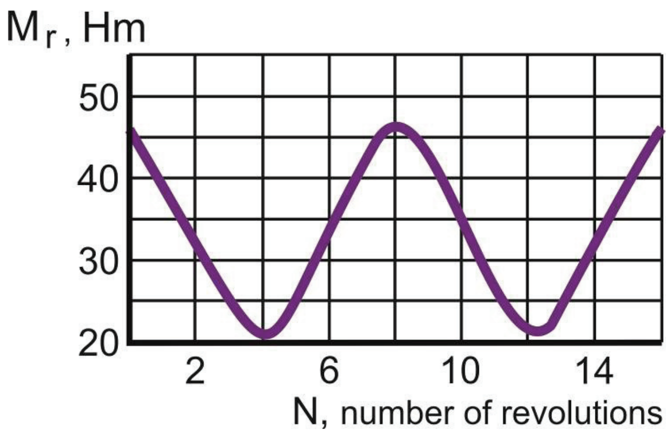

Fig. 3. The moment of resistance, reduced to the main (modified) shaft

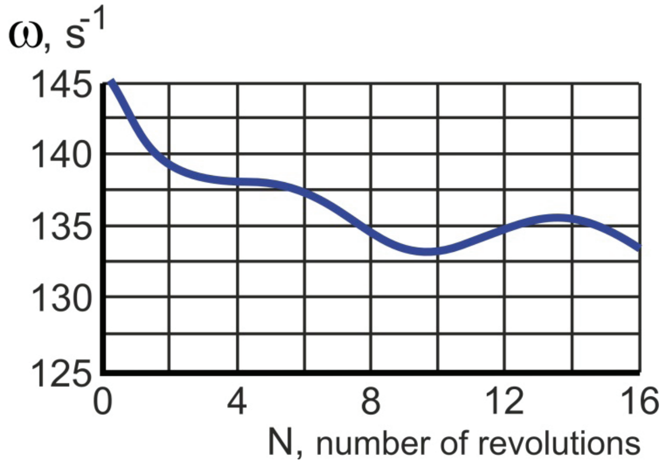

Fig. 4. Speed depending on the revolutions of the drive shaft

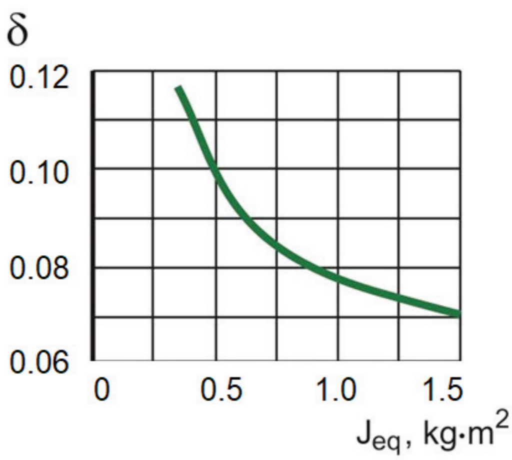

Fig. 5. A graph of the change in the value of the rotation irregularity depending on the mass moment of inertia

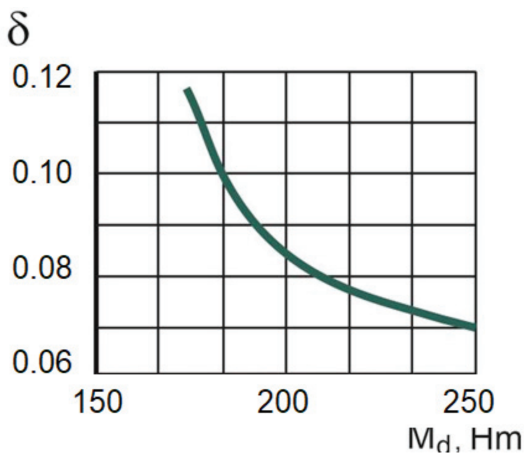

Fig. 6. A graph of the change in the value of the rotation irregularity depending on the value of the torque

Conclusion

A methodology for determining the rotation irregularity ratio of the modified shaft of food machinery, which has an epicyclic gearing with a rocker arm in the drive of kneading shafts is presented, including:

– the mathematical model of the mechanism that allows calculating the speed of the modified shaft. Thus, for the case under consideration, the irregular rotation of the modified shaft was (11) 0.085 with a maximum rotation speed equal to $\omega_{max} = 145 \cdot s^{-1}$ and a minimum speed equal to $\omega_{min} = 133.2\ s^{-1}$, while the rotation irregularity ratio of the modified shaft was $\delta = 0{,}101$;

– the prospect of improving the dynamic characteristics of the machine by decreasing the irregularity ratio due to an additional flywheel mass placed on the modified shaft. Thus, introducing an additional moment of mass inertia up to 0.177 $kg \cdot m^2$ brings its value to 0.06, which meets the requirements for this type of machine;

– the nature and value of the change in the technological and inertial loads acting on the working shafts of the device are determined; the values and nature are presented, taking into account its reduction to the main (modified) shaft of the machine;

– the maximum values of the total moment of the useful resistance were 44–47 N·m, the minimum were 22–24 N·m; it depends on the rotation angle of the kneading shaft blades;

– the pattern of changes in moments from the inertia and technological resistance is determined, which can be expressed by the following general dependence: $M_c(\varphi) = 24 + 12\cos(2/16\varphi)$.

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Conflicts of Interest

The authors declare no conflict of interest.