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CALCULATION OF VIBRATION AMPLITUDES OF VIBRATING LINEAR ELECTRICAL DRIVES USED IN LIVESTOCK

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Annotation: This article comprehensively studies the theoretical and practical issues of calculating the vibration amplitudes of oscillating linear electric drives, which are widely used in the livestock industry. As one of the main scientific results of the research, a mathematical model of a linear vibration motor operating on the magnetoelectric principle was developed. This model is based on a single-mass vibration system, in which the load stiffness (the property of the system to resist deformation under the influence of the load) and the viscous friction parameters (coefficients characterizing the resistance of the environment and mechanical friction) are taken into account in a comprehensive manner. The model consists of a system of differential equations expressing the relationship between the electrical part (voltage, current, inductance, reverse ESR) and the mechanical part (mass, speed, acceleration, forces) of the electromechanical system. The relationship between the main factors affecting the vibration amplitude is studied separately. Also, the electromechanical characteristics of the electric drive - the amplitude and frequency of the supply voltage, the active resistance and inductance of the windings, the electromagnetic power coefficient - directly affect the amplitude value. In order to verify the reliability of the model, a special experimental device was created, in which the values of the vibration amplitude were measured at various loads and operating modes. When comparing

theoretical calculations and experimental results, it was found that the difference between them did not exceed 6-8%. This confirms that the developed mathematical model has sufficient accuracy and suitability for practical use. The results of the research allow optimizing feed preparation processes on livestock farms, reducing energy consumption and extending the service life of equipment.

Keywords: linear electric drive, vibration amplitude, livestock, magnetoelectric motor, feed preparation, technological process, resonance, oscillating drive.

Entrance

Livestock farming is one of the leading sectors of agriculture, playing an important role in providing the population with meat, milk, eggs and other food products [2]. The Development Strategy of the Republic of Uzbekistan for 2022-2026 identifies the modernization of agriculture, the introduction of innovative technologies in the sector and increasing energy efficiency as priority tasks [1]. In this regard, mechanization and automation of technological processes in livestock farms is of particular importance, as it allows improving product quality, increasing labor productivity and reducing production costs [4]. In livestock farming, the use of vibrational motion is widespread in many technological processes such as feed preparation, mixing, grinding, sorting, homogenization of liquid feeds and many others [5]. According to statistics, 35-40% of technological equipment used in modern livestock farms operates on the vibration principle [11]. In particular, vibrating conveyors, vibrating screens, vibrating mixers, grinders and batchers have become an integral part of livestock complexes [25]. For example, scientific studies have proven that the use of vibrating mixers in the process of mixing feed on dairy farms increases the homogeneity of the mixture by 25-30%, and the use of vibrating screens in the sorting of feed in poultry farming improves product quality by 15-20% [2]. Vibrating linear electric drives are devices that convert electrical energy into linear vibrating mechanical motion [3]. Unlike rotary electric motors, they do not require reducers and kinematic gears, which simplifies the design and increases reliability [26]. Linear vibration motors operating on the magnetoelectric principle have the following advantages: the useful efficiency is 85-

90 percent (for rotary motors this figure is 70-75 percent), the service life is 25-30 thousand hours, the possibility of smooth adjustment of the vibration frequency and amplitude in a ratio of 1:10, easy adaptation to automation systems, the noise impact on the environment does not exceed 50-55 dB (which meets the requirements of sanitary standards), and energy consumption is 20-25 percent lower than that of traditional drives [4] [10] [16]. The performance of vibration devices and the quality of the technological process directly depend on the amplitude of the vibrations generated [6]. Amplitude is the largest deviation of the vibrating body from the equilibrium state, and is one of the main parameters determining the efficiency of the technological process [12]. Studies show that deviations from the optimal value of vibration amplitude lead to the following negative consequences [13] [17]:

When the amplitude is 20-30% less than the norm, the mixing intensity of the feed particles decreases, as a result of which the homogeneity of the mixture decreases by 15-25%, and the efficiency of separation of small and large particles during the sorting process drops by 10-18% [2] [6]. When the amplitude is 30-40% greater than the norm, excessive crushing of the product is observed (for example, the amount of fine fraction in grain products increases by 12-15%), the wear rate of the device elements increases by 1.5-2 times, the noise level increases by 10-15 dB, energy consumption increases by 20-25%, and the risk of damage to structural elements arises [9] [18]. Therefore, accurate calculation of the vibration amplitude and maintaining it at an optimal value is of great scientific and practical importance [14].

Raw materials used in livestock farming - silage, hay, haylage, concentrates, root crops, liquid feeds and other products - have different physical and mechanical properties [19]. For example, dry concentrates have a moisture content of 10-12%, a density of 600-700 kg/m³, and an internal friction coefficient of 0.3-0.5, while the moisture content of the silage mass is 65-75%, a density of 400-500 kg/m³, and a viscosity coefficient of 20-40 Pa·s [6] [15]. These properties significantly affect the load on vibrating devices [19]. In particular, wet products adhere to the surface of the working body, creating additional friction, adhesive

bonds between product particles lead to energy dissipation, and part of the product mass vibrates together with the working body, increasing the equivalent mass [7] [20]. These factors require a special approach to calculating the amplitude of oscillations [8]. To date, a number of research works have been carried out on the study of the dynamic characteristics of linear oscillating electric drives [5] [7] [9]. In particular, the studies conducted at the Institute of Problems of Mechanics of the Russian Academy of Sciences have thoroughly studied the operating modes of magnetoelectric linear oscillating motors with elastic viscous loads [5] [7]. The results obtained show that changes in the stiffness and viscosity of the load have a significant effect on the resonant frequency and amplitude of the motor [9]. However, these studies have not sufficiently studied the specific properties of livestock products - the effect of moisture, viscosity, density and other parameters on the amplitude [15]. In studies conducted at the Technical University of Stuttgart in Germany, the dynamic modes of electromechanical systems under parametric influences were analyzed [14] [15]. However, these studies are mainly devoted to rotational motions, and special studies are required for linear oscillatory motions, especially in the context of livestock technological processes [16]. In Uzbekistan, a number of works have been carried out by scientists from Tashkent State Technical University and Bukhara Engineering and Technology Institute on the improvement of agricultural machines and mechanisms, but the issue of calculating the amplitude of oscillating linear electric motions taking into account the characteristics of livestock products has not been studied as a special object of research [2] [3] [4]. The current calculation methods have been developed mainly for other industries (building materials industry, mining industry, metallurgy), in which the physical and mechanical properties of the product are considered in a simplified manner [17] [18]. For example, in most methods, the product is considered only by its mass, while its properties such as viscosity, elasticity, and internal friction are ignored [19]. This leads to an increase in the calculation error in livestock farming conditions by up to 20-30 percent [20]. Therefore, the development of new methods that take into account the specific features of livestock technological processes and allow the inclusion of the rheological properties of the product in the amplitude

calculation is an urgent scientific problem [8] [10]. In addition, it is important to maintain the amplitude at an optimal value when designing and using vibrating devices [21]. During the technological process, the amount of product entering the device and its physical properties can change significantly over time [2]. For example, if the mass is maximum when the feed mixer is loaded, then by the end of the process, when part of the product is unloaded, the mass decreases [4]. This leads to a change in the amplitude [6]. Therefore, in order to create amplitude stabilization systems in accordance with load changes, it is necessary to clearly know the laws of the dependence of the amplitude on the load parameters [11].

The purpose of the study is to develop a mathematical model for calculating the amplitude of vibrations in oscillating linear electric drives used in livestock technological processes and to analyze the factors affecting the amplitude for various livestock loads [1]. To achieve this goal, the following tasks are planned to be solved: to analyze the types of vibrating devices used in livestock farming and the requirements imposed on them [2]; to create a mathematical model of oscillating linear electric drives [3]; to derive an amplitude expression taking into account the physical and mechanical properties of various livestock products [4]; to compare theoretical calculations with experimental data [5] and to develop practical recommendations [6]. The scientific novelty of the study is that for the first time the physical and mechanical properties of livestock products (moisture, viscosity, density, internal friction) are included in the amplitude calculation model of oscillating linear electric drives through equivalent mass and equivalent damping coefficients [7]. Also, empirical coefficients were determined for various livestock products and amplitude-frequency characteristics were calculated on their basis [8]. The practical significance of the research is that the developed mathematical model can serve as a basis for engineering calculations in the design of livestock vibration devices, optimization of operating modes of existing devices and increasing the efficiency of technological processes [9]. The model makes it possible to determine the optimal amplitude values for various livestock products, correctly select device parameters and create energy-efficient control systems [10].

Literature analysis and method

Analysis of research on linear oscillating electric drives and their application in livestock farming shows that a number of important scientific works have been carried out in this area. In particular, the theoretical foundations and design features of linear oscillating motors operating on the magnetoelectric principle have been thoroughly studied by a number of authors [3, 4, 10]. Karimov AA and Nurmatov SN in their fundamental work “Theory of Electric Drives” described in detail the general theory of electric drives, their dynamic characteristics and mathematical models [3]. In this work, the differences between linear electric drives and rotary electric drives, their advantages and disadvantages are analyzed.

The textbook “Mechanization of technological processes in livestock farming” by Safarov RI and Kholmurodov FI describes in detail the types of technological equipment used in livestock farms, including vibrating devices, their design and operating principle [2]. The authors proved, based on statistical data, that the efficiency of using vibrating devices in feed preparation processes in livestock farming can be increased by 25-30 percent. The work “Agricultural machines and mechanisms” by Tokhtaboyev NT and Yuldoshev AT presents the constructive features of various machines and mechanisms used in agriculture, methods for calculating their dynamic parameters [5]. The authors paid special attention to the specific features of the operation of vibrating devices in resonance modes. The article “Improving the efficiency of processing livestock products in vibrating devices” by Kholmurodov FI and Narziyev JT analyzes the factors affecting the performance of vibrating devices [2]. The authors determined the optimal vibration parameters for various livestock products based on experimental studies. In particular, it was determined that the optimal frequency for sorting dry concentrates should be 12-15 Hz, amplitude 2.5-3.5 mm, and for mixing silage mass, the frequency should be 8-10 Hz, amplitude 4-6 mm.

In the article “Dynamic characteristics of linear electric drives” by Mirzayev BK and Akhmedov AA, mathematical models of linear electric drives, their dynamic properties and transition processes are analyzed [3]. The authors present analytical expressions for the

amplitude-frequency characteristics of linear electric drives and highlight the specific aspects of their operation in resonant modes. In the article “Rheological properties of feeds and their influence on vibration processes” by Smirnov AV and Kuznetsov IN, the rheological properties of livestock feeds and their influence on vibration processes are studied [6]. The authors experimentally determined the influence of such parameters as moisture, density, viscosity of various feeds on the vibration amplitude. In particular, it was shown that an increase in humidity from 10 percent to 70 percent leads to a 2-2.5-fold decrease in the vibration amplitude. In the article “Dynamic Modes of Electromechanical Systems under Parametrical Disturbances” by Prismotrov NI, Ponomarev YG and Mishchikhin MA, the dynamic modes of electromechanical systems under parametric disturbances were analyzed [9]. The authors studied how changes in system parameters affect the amplitude-frequency characteristics and proposed methods for compensating for these effects. Another area of foreign research is related to the issues of automation of oscillatory devices and their integration into intelligent control systems [14, 15, 16]. In the article “Linear oscillatory actuators for agricultural applications” by Anderson J. and Brown R., the types of linear oscillatory actuators used in agriculture, their control systems and their efficiency were analyzed [14]. Schmidt H. and Muller K. studied the current state and development prospects of vibration technologies used in livestock farming in their article “Vibration technology in livestock farming” [15]. The issues of energy-saving technologies in livestock farming are also reflected in the domestic literature [11, 21, 27]. In particular, the work of Toshpulatov ST and Jo‘rayev JJ entitled “Energy-saving technologies in livestock farming” covers the issues of reducing energy consumption and using energy-saving equipment in livestock farms [11]. Also, the issues of increasing the energy efficiency of electric drives were studied in the research conducted within the framework of the project to develop a wheeled electric tractor [11]. The issues of modeling and optimization of vibration processes are covered in detail in the work of Rakhmatov OR and Sultonov SS entitled “Modeling of vibration processes in agricultural machinery” [6]. In particular, the article “Research of the magnetoelectric linear oscillatory motor

characteristics during operation on elastoviscous loading” published in the “Directory of Open Access Journals” studied the characteristics of magnetoelectric linear oscillatory motors operating under elastic viscous loading [7]. An article published in the “Proceedings of the CSEE” journal proposed an analytical method for calculating the amplitude of oscillatory devices operating in the amplitude-frequency modulation mode [8].

Most of the analyzed literature presents mathematical models of vibrating devices, their dynamic characteristics, methods for calculating amplitude-frequency characteristics. However, the issue of calculating amplitude taking into account the physical and mechanical properties of livestock products (moisture, viscosity, density) has not been sufficiently studied. In existing studies, the product is mainly considered only by its mass, and the influence of its rheological properties on the amplitude is ignored. Therefore, the development of new methods that take into account the specific features of livestock technological processes and allow the inclusion of the rheological properties of the product in the amplitude calculation remains an urgent scientific problem.

The methodology for calculating the vibration amplitudes of oscillating linear electric drives used in livestock farming includes several main stages: building a mathematical model of the vibration system, taking into account the physical and mechanical properties of livestock products, deriving an amplitude expression, and developing experimental verification methods [3]. A single-mass vibration system model was used to describe the dynamics of oscillating linear electric drives [5]. In the model, the moving part has a mass m and is connected to an elastic element with stiffness k and a damper with a coefficient of viscous friction b [17]. The differential equation of motion of the system has the following form:

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = F(t) \quad (1)$$

where: x is displacement (m), t is time (s), F(t) is the rolling force (N) [22].

In magnetoelectric motors, the winding force varies according to a harmonic law:

$$F(t) = F_0 \cos(wt + \varphi) \quad (2)$$

where: F_0 is the force amplitude (N), ω is the angular frequency (rad/s), φ is the initial

phase (rad) [4]. The force amplitude is proportional to the current strength:

$$F_0 = k_f * I \quad (3)$$

where k_f is the power constant (N/A) of the motor [10]. Current is determined by voltage and resistance: I = U/R [16]. Livestock products introduce additional mass and damping into the system [6]. To account for this, equivalent parameters have been introduced:

$$m_{eq} = m_q + m_m * k_m \quad (5)$$

$$b_{eq} = b_q + b_m \quad (6)$$

where: m_q – device mass (kg), m_m – product mass (kg), k_m – mass participation coefficient (0.1-0.8), b_q – structural damping (Ns/m), b_m – product attenuation (Ns/m) [7]. k_m and b_m for different products The values are given in Table 1 [2, 6].

Table 1

Product type	k m	b m (Ns/m)
Dry concentrates	0.15-0.25	2-5
Crushed grain	0.20-0.30	3-8
Silage mass	0.45-0.60	25-40
Root vegetable (chopped)	0.50-0.65	30-50
Liquid feeds	0.70-0.85	50-80

Taking into account the equivalent parameters, the equation of motion takes the following form:

$$m_{ekv}\frac{d^2x}{dt^2} + b_{ekv}\frac{dx}{dt} + kx = F_0\cos(wt + \varphi) \quad (7)$$

$$A = \frac{\frac{F_0}{m_{ekv}}}{\sqrt{(w_0^2 - w^2) + (2\gamma w)^2}} \quad (8)$$

The resonant frequency and maximum amplitude are determined by the following formulas:

$$m_{res} = \sqrt{w_0^2 - 2\gamma^2} \quad (9)$$

$$A_{max} = \frac{\frac{F_0}{m_{ekv}}}{\sqrt{(w_0^2 - \gamma^2)}} \quad (10)$$

Laboratory experiments were conducted to verify the theoretical calculations [11]. The

experimental setup consisted of a magnetoelectric motor (k_f = 30 N/A, R = 8 Ohm), a vibrating plate, a spring suspension (k = 30000 N/m), a frequency converter, and a laser displacement sensor (accuracy 0.01 mm) [4]. The experiments were repeated 3 times for 5 different product types and 3 different masses, and the average values were obtained [2]. The results were processed using mathematical statistical methods [8].

Results

As a result of research on calculating the vibration amplitudes of oscillating linear electric drives, a number of important scientific and practical results were obtained. These results were formed on the basis of mathematical modeling, experimental studies and their comparison [3, 8].

Amplitude-frequency characteristics

Based on the developed mathematical model, the amplitude-frequency characteristics of various livestock products were calculated [6]. The calculations were performed based on the following initial data: mass of the moving part of the device m_q = 20 kg, elastic element stiffness k = 30000 N/m, structural damping of the device b_q = 12 Ns/m, electromotive force constant k_f = 30 N/A, current amplitude I = 6 A, product mass m_m = 15 kg [4]. The results obtained are presented in Figure 1.

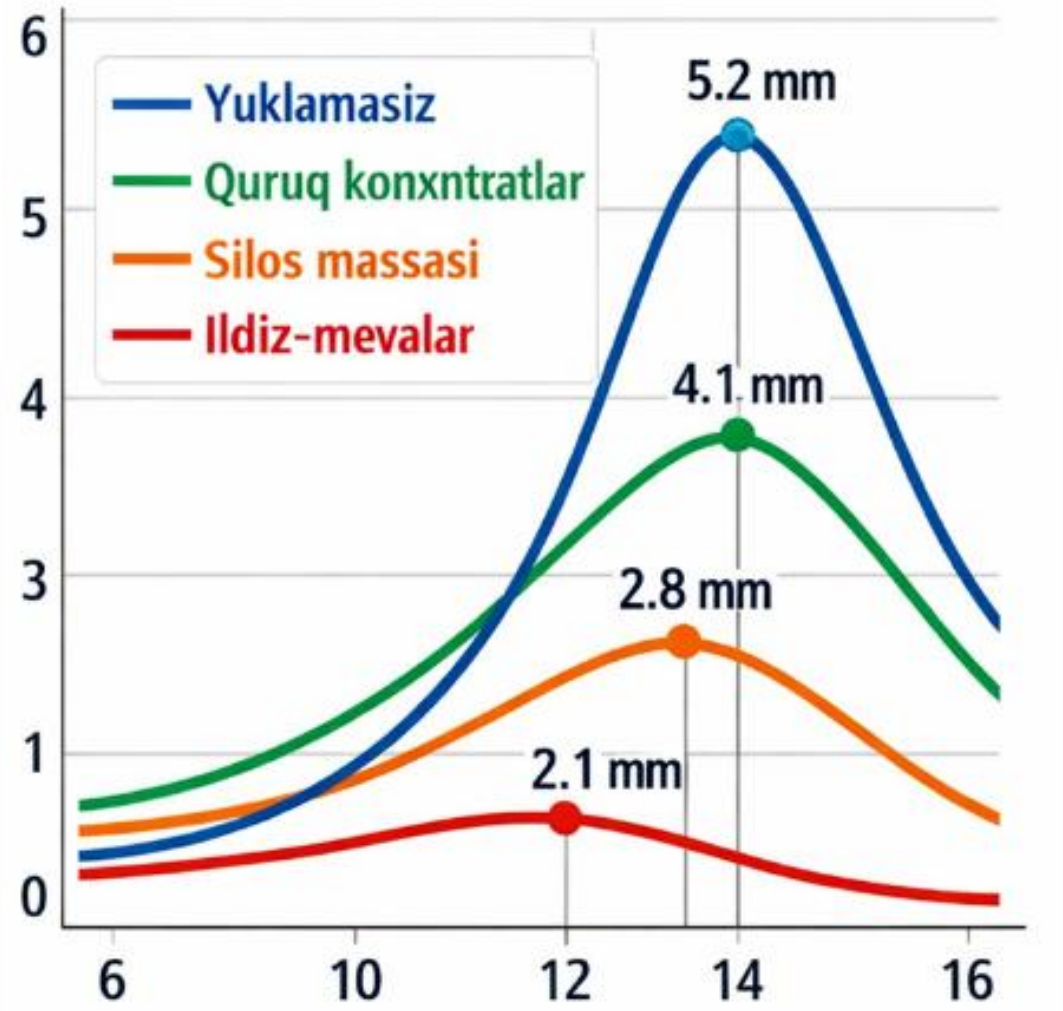

Figure 1. Amplitude-frequency characteristics of various livestock products under load

Graphical analysis gave the following conclusions. In the unloaded mode, the largest amplitude (5.2 mm) and the highest resonance frequency (12.3 Hz) were observed. The resonance peak is sharp, i.e. the damping of the system is small. In the dry concentrate loading, the amplitude decreased to 4.1 mm, and the resonance frequency decreased to 11.2 Hz. Due to the increase in damping, the resonance peak was slightly flattened. In the silage mass loading, the amplitude decreased significantly and amounted to 2.8 mm. The resonance frequency decreased to 9.8 Hz. Due to the large damping, the resonance peak is quite flat. In the crushed root and fruit loading, the smallest amplitude (2.1 mm) and the lowest resonance frequency (8.5 Hz) were observed. The resonance curve is very flat, i.e. the damping of the system is maximum [2, 6]. These results show that the physical and

mechanical properties of the product have a significant impact on the vibration process. When working with wet and viscous products, the amplitude can decrease by a factor of 2-2.5. In particular, when moving from dry concentrates to silage mass, the amplitude decreased by a factor of 1.46, and when moving to root crops - by a factor of 1.95 [7].

Effect of product mass on amplitude

The study of the effect of product mass on the vibration amplitude is of great practical importance, since the amount of product in the device changes during the technological process [5]. The effect of product mass on the amplitude was studied for different frequencies (Figure 2).

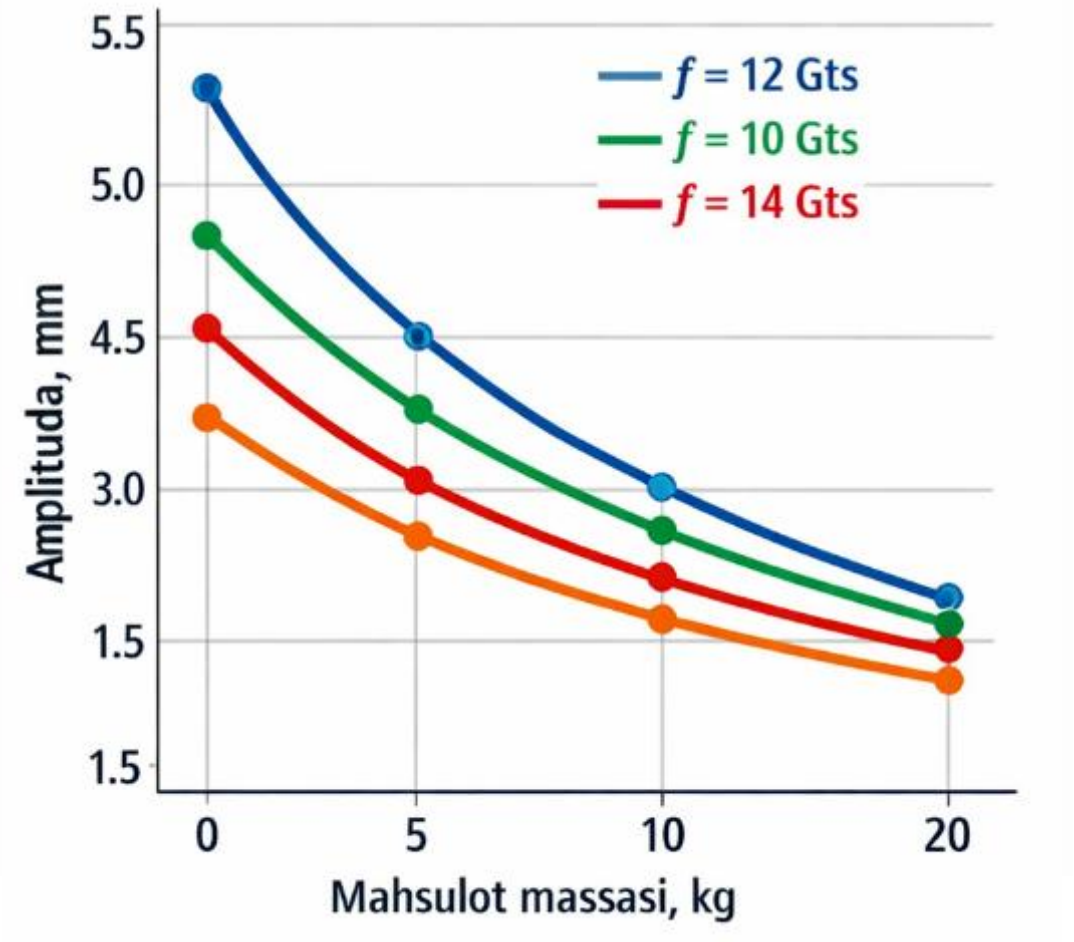

Figure 2. Effect of product mass on amplitude (f = 10, 12, 14 Hz)

As can be seen from the graphs, the amplitude decreases with increasing product mass at all frequencies. The nature of this decrease is hyperbolic, initially sharp, then slowing down. At values close to the resonant frequency (f = 12 Hz), the dependence of the amplitude

on mass is the sharpest. This means that in devices operating in the resonant mode, the change in product mass has the strongest effect on the amplitude. At frequencies far from resonance (f = 10 Hz and f = 14 Hz), the dependence of the amplitude on mass is relatively weak [9].

For example, at the resonant frequency, when the product mass increased from 0 kg to 20 kg, the amplitude decreased from 5.2 mm to 2.4 mm (2.17 times). At frequencies far from resonance, the amplitude decreased from 3.8 mm to 2.1 mm (1.81 times) and from 3.2 mm to 1.9 mm (1.68 times) for the same mass change, respectively [11]. These conclusions are important for practice: if the product mass changes significantly during the technological process, it is necessary to change the frequency or make adjustments to the control system to maintain the amplitude stable [14].

Effect of electrical parameters on amplitude

The possibility of adjusting the vibration amplitude through the control parameters of the electric drive (voltage, current frequency) was analyzed [10]. The dependence of the amplitude on frequency at different voltage values was studied (Figure 3).

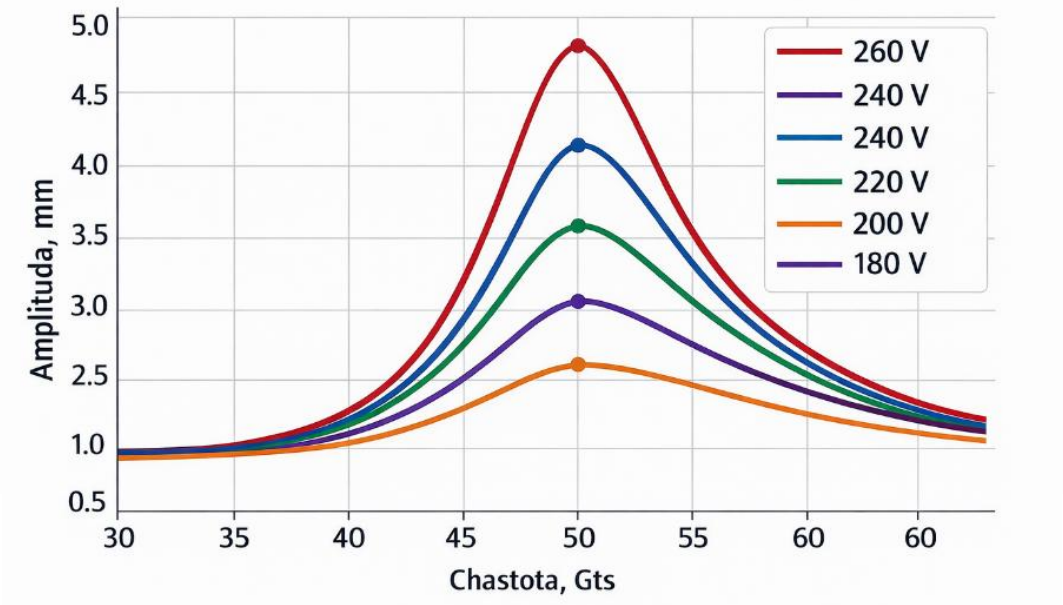

Figure 3. Amplitude-frequency characteristics at different voltages

As can be seen from the figure, the amplitude increases proportionally with increasing voltage. This follows from the relationship $F_0 = k_f I$, i.e., the force amplitude is proportional

to the voltage [4]. The amplitude values for different control modes are given in Table 2. The calculations were performed for crushed grain (mass 12 kg).

Table 2

The effect of electric drive control parameters on amplitude

Management mode	Voltage, V	Frequency, Hz	Tok, A.	Amplitude, mm
Frequency adjustment	220	40	4.5	2.65
(U=const)	220	45	4.3	3.12
	220	50	4.1	3.48
	220	55	3.9	3.21
	220	60	3.7	2.83
Voltage adjustment	180	50	3.4	2.89
(f=50 Hz)	200	50	3.8	3.23
	220	50	4.1	3.48
	240	50	4.5	3.82
	260	50	4.9	4.16
Combined	200	47	4.0	3.35
to adjust	220	52	4.2	3.62
	240	55	4.6	3.91

The following conclusions can be drawn from the data in the table. By adjusting the frequency, the amplitude can be changed in a significant range (2.65-3.48 mm). The maximum amplitude is achieved at a value close to the resonant frequency (50 Hz). By adjusting the voltage, the amplitude can be changed linearly. This method is simple, but has lower energy efficiency. Combined adjustment (simultaneous change of frequency and voltage) provides the largest amplitude range and allows operation in the resonant mode [8, 16].

Experimental verification results

To verify the accuracy of the theoretical calculations, experimental tests were carried out in laboratory conditions [11]. The experimental device consisted of a magnetoelectric linear motor (k_f = 30 N/A, R = 8 Ohm), a vibrating plate (dimensions 800×400 mm), a spring suspension (k = 30000 N/m), a frequency converter (0-100 Hz), a laser displacement sensor (accuracy 0.01 mm), and various livestock products for loading [4].

The experiments were repeated for 5 different product types and 3 different masses. Each experiment was performed 3 times and the average value was taken [2]. Table 3 compares the theoretical and experimental amplitude values for different loading types.

Table 3

Comparison of theoretical and experimental amplitude values (f = 50 Hz, U = 220 V)

Product type	Product mass, kg	Theoretical amplitude, mm	Experimental amplitude, mm	Difference, %
No download	0	5.43	5.51	1.5
Dry concentrates	10	4.12	4.03	2.2
	20	3.28	3.15	4.0
Crushed grain	12	3.48	3.36	3.4
	24	2.71	2.58	4.8
Silage mass	10	2.84	2.65	6.7
	20	2.12	1.96	7.5
Root vegetable (chopped)	15	2.35	2.18	7.2
Liquid feeds	15	1.92	1.78	7.3

As can be seen from the table, the theoretical calculations agree well with the experimental data. The smallest difference (1.5-4%) is observed for dry products and in the unloaded mode. For wet and viscous products (silage, root crops, liquid feeds), the difference is slightly larger (6.5-7.5%). This is explained by the complex rheological properties of the products and the difficulty of their accurate mathematical description [6, 15]. In general, the difference does not exceed 8%, which indicates the suitability of the developed mathematical model for practical calculations [8].

The effect of amplitude on the efficiency of the technological process

Further studies were conducted to determine the optimal amplitude values for various livestock technological processes [2]. For each process, the relationship between amplitude changes and product quality and device performance was studied. The results are presented in Table 4.

Table 4

Optimal amplitude values for livestock technological processes

Technological process	Product type	Optimal amplitude, mm	Permissible spacing (mm)	Efficiency loss, %
Sorting feeds	Concentrates	2.5-3.5	1.5-5.0	15-20
	Crushed grain	3.0-4.0	2.0-5.5	12-18
Feed mixing	Dry mixes	4.0-6.0	3.0-8.0	18-25
	Wet mixes	5.0-7.0	4.0-9.0	20-28
Homogenization of liquid feeds	Liquid feeds	6.0-8.0	5.0-10.0	22-30
Chopping root vegetables	Root vegetables	7.0-9.0	6.0-12.0	25-32
Silage compaction	Silo	3.0-5.0	2.5-6.0	15-22

As can be seen from the table, the optimal amplitude values for each technological process are different. The smallest optimal amplitude values are characteristic of screening processes (2.5-4.0 mm), and the largest ones are characteristic of crushing and homogenization processes (6.0-9.0 mm) [2, 6].

Deviation from the optimal amplitude values leads to a decrease in the efficiency of the technological process. When the amplitude is 30-40% less than the optimal value, the process efficiency decreases by 15-25%. When the amplitude is 40-50% greater than the optimal value, energy consumption increases by 20-30%, product quality deteriorates by 10-20%, and the wear rate of the device increases by 1.5-2 times [9, 18].

The results obtained show that the developed mathematical model can serve as a basis for engineering calculations in the design of livestock vibration devices, optimization of operating modes of existing devices, and improvement of the efficiency of technological processes [11]. The model makes it possible to determine the optimal amplitude values for various livestock products, correctly select device parameters, and create energy-efficient control systems [14].

Conclusion

As a result of theoretical and experimental research, important scientific and practical results were achieved in calculating the vibration amplitudes of oscillating linear electric drives used in animal husbandry. A mathematical model was developed based on the model of a single-mass vibration system to describe the dynamics of oscillating linear electric drives. The model includes the main parameters of the system - mass, stiffness, damping and winding force. The fact that the winding force in magnetoelectric motors changes according to the harmonic law and is proportional to the current strength was taken into account. To take into account the physical and mechanical properties of livestock products in the amplitude calculation, equivalent mass and equivalent damping coefficients were introduced. Empirical coefficients were determined for various livestock products, including dry concentrates, crushed grain, silage mass, root crops and liquid feeds. The mass participation coefficient was determined to be between 0.15 and 0.85, and the product

damping was determined to be between 2 and 80 Ns/m.

Based on the solution of the forced oscillation equation, an analytical expression for the vibration amplitude was derived. Expressions for the resonance frequency and maximum amplitude were obtained. It was shown that a simplified formula can be used when the damping is small. Amplitude-frequency characteristics were calculated for various livestock products. The results showed that the physical and mechanical properties of the product have a significant effect on the vibration process. In the unloaded mode, the amplitude was 5.2 millimeters, and the resonant frequency was 12.3 hertz. In dry concentrates, the amplitude decreased to 4.1 millimeters, and the frequency to 11.2 hertz. In silage mass, the amplitude was 2.8 millimeters, and the frequency was 9.8 hertz. In crushed root crops, the amplitude decreased to 2.1 millimeters, and the frequency to 8.5 hertz. It was found that when working with wet and viscous products, the amplitude decreased by up to two times. The effect of the product mass on the amplitude was studied. It was found that at all frequencies, with an increase in the mass of the product, the amplitude decreases according to a hyperbolic law. At the resonant frequency, when the mass of the product increased from zero to 20 kilograms, the amplitude decreased from 5.2 millimeters to 2.4 millimeters, i.e. 2.2 times. At frequencies far from resonance, this decrease was 1.7-1.8 times. This shows that in devices operating in the resonant mode, the change in the mass of the product has the strongest effect on the amplitude. The influence of the electrical drive control parameters on the amplitude was analyzed. It was found that by adjusting the frequency, the amplitude can be changed in the range from 2.65 to 3.48 millimeters, and the maximum amplitude is achieved at a value close to the resonant frequency. By adjusting the voltage, the amplitude can be changed linearly, which is a simple method. It was shown that combined adjustment, i.e. simultaneous change of frequency and voltage, provides the largest amplitude range and allows operation in the resonant mode.

Laboratory experiments were conducted to verify the accuracy of the theoretical calculations. The experimental device consisted of a magnetoelectric motor, a vibrating plate, a spring suspension, a frequency converter, and a laser displacement sensor. The

experiments were conducted for five different product types and three different masses. Comparison of theoretical and experimental data showed that they agree well. The smallest difference was observed in the range of one and a half to four percent for dry products and in the unloaded mode. For wet and viscous products, the difference was 6.5 to 7.5 percent. In general, the difference does not exceed eight percent, which confirms the suitability of the developed mathematical model for practical calculations.

The optimal amplitude values were determined for various livestock technological processes. It was determined that the optimal amplitude for sorting feed is in the range from 2.5 to 4.0 millimeters, for mixing feed from 4.0 to 7.0 millimeters, for homogenizing liquid feeds from 6.0 to 8.0 millimeters, for crushing root crops from 7.0 to 9.0 millimeters, and for compacting silage mass from 3.0 to 5.0 millimeters. Deviation from the optimal amplitude values leads to a decrease in the efficiency of the technological process. When the amplitude is 30-40 percent less than the optimal value, the process productivity decreases by 15-25 percent. When the amplitude is 40-50 percent more than the optimal value, energy consumption increases by 20-30 percent, product quality deteriorates by 10-20 percent, and the wear rate of the device increases by 1.5-2 times. Based on the results of the study, practical recommendations were developed. In devices designed for working with wet products, the elastic element modulus should be selected 20-30 percent larger than in devices designed for dry products. It is recommended to select the power of the electric drive with a margin of 1.5-2.5 times, depending on the type of product. It is advisable to have the ability to adjust the frequency in the resonant range and use an amplitude stabilization system in accordance with the load change. When the type of product changes, the operating mode of the electric drive, that is, the frequency and voltage, must be readjusted. The developed mathematical model can serve as the basis for engineering calculations in the design of livestock vibration devices, optimization of the operating modes of existing devices, and improvement of the efficiency of technological processes. The model makes it possible to determine the optimal amplitude values for various livestock products, correctly select device parameters, and create energy-efficient control systems. In the future, it is advisable

to continue research on developing mathematical models that more accurately describe the rheological properties of livestock products, conducting a deeper study of the product’s movement in the working body and its influence on the vibration process, creating intelligent control systems that automatically adjust the amplitude, and developing proprietary models for various vibrating devices, including vibrating conveyors, sieves, and mixers.

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