ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫНЫҢ
Қ. И. Сәтпаев атындағы Қазақ ұлттық техникалық зерттеу университеті

ХАБАРЛАРЫ

ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН
Казахский национальный исследовательский
технический университет им. К. И. Сатпаева

NEWS

OF THE ACADEMY OF SCIENCES
OF THE REPUBLIC OF KAZAKHSTAN
Kazakh national research technical university
named after K. I. Satpayev

ГЕОЛОГИЯ ЖӘНЕ ТЕХНИКАЛЫҚ ҒЫЛЫМДАР СЕРИЯСЫ

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СЕРИЯ ГЕОЛОГИИ И ТЕХНИЧЕСКИХ НАУК

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SERIES OF GEOLOGY AND TECHNICAL SCIENCES

5 (431)

ҚЫРКҮЙЕК – ҚАЗАН 2018 ж.
СЕНТЯБРЬ – ОКТЯБРЬ 2018 г.
SEPTEMBER – OCTOBER 2018

ЖУРНАЛ 1940 ЖЫЛДАН ШЫҒА БАСТАҒАН
ЖУРНАЛ ИЗДАЕТСЯ С 1940 г.
THE JOURNAL WAS FOUNDED IN 1940.

ЖЫЛЫНА 6 РЕТ ШЫҒАДЫ
ВЫХОДИТ 6 РАЗ В ГОД
PUBLISHED 6 TIMES A YEAR

АЛМАТЫ, ҚР ҰҒА
АЛМАТЫ, НАН РК
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Қазақстан Республикасы Ұлттық ғылым академиясы "ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы" ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

«ҚР ҰҒА Хабарлары. Геология мен техникалық ғылымдар сериясы».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Меншіктенуші: «Қазақстан Республикасының Ұлттық ғылым академиясы» РҚБ (Алматы қ.).
Қазақстан республикасының Мәдениет пен ақпарат министрлігінің Ақпарат және мұрағат комитетінде 30.04.2010 ж. берілген **№10892-Ж** мерзімдік басылым тіркеуіне қойылу туралы куәлік.

Мерзімділігі: жылына 6 рет.
Тиражы: 300 дана.

Редакцияның мекенжайы: 050010, Алматы қ., Шевченко көш., 28, 219 бөл., 220, тел.: 272-13-19, 272-13-18, http://nauka-nanrk.kz /geology-technical.kz

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Редакцияның Қазақстан, 050010, Алматы қ., Қабанбай батыра көш., 69а.
мекенжайы: Қ. И. Сәтбаев атындағы геология ғылымдар институты, 334 бөлме. Тел.: 291-59-38.

Типографияның мекенжайы: «Аруна» ЖК, Алматы қ., Муратбаева көш., 75.

«Известия НАН РК. Серия геологии и технических наук».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Собственник: Республиканское общественное объединение «Национальная академия наук Республики Казахстан (г. Алматы)
Свидетельство о постановке на учет периодического печатного издания в Комитете информации и архивов Министерства культуры и информации Республики Казахстан **№10892-Ж,** выданное 30.04.2010 г.

Периодичность: 6 раз в год
Тираж: 300 экземпляров

Адрес редакции: 050010, г. Алматы, ул. Шевченко, 28, ком. 219, 220, тел.: 272-13-19, 272-13-18,
http://nauka-nanrk.kz /geology-technical.kz

Адрес редакции: Казахстан, 050010, г. Алматы, ул. Кабанбай батыра, 69а.
Институт геологических наук им. К. И. Сатпаева, комната 334. Тел.: 291-59-38.

Адрес типографии: ИП «Аруна», г. Алматы, ул. Муратбаева, 75

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Owner: RPA "National Academy of Sciences of the Republic of Kazakhstan" (Almaty)
The certificate of registration of a periodic printed publication in the Committee of information and archives of the Ministry of culture and information of the Republic of Kazakhstan N 10892-Ж, issued 30.04.2010

Periodicity: 6 times a year
Circulation: 300 copies

Editorial address: 28, Shevchenko str., of. 219, 220, Almaty, 050010, tel. 272-13-19, 272-13-18,
http://nauka-nanrk.kz/geology-technical.kz

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Editorial address: Institute of Geological Sciences named after K.I. Satpayev
69a, Kabanbai batyr str., of. 334, Almaty, 050010, Kazakhstan, tel.: 291-59-38.

Address of printing house: ST "Aruna", 75, Muratbayev str, Almaty

N E W S
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN
SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224-5278 **https://doi.org/10.32014/2018.2518-170X.9**
Volume 5, Number 431 (2018), 48 – 65

UDC 004.94:637.5.031:637.5.037

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MATHEMATICAL SIMULATION OF ONE-STAGE GRINDING OF PRODUCTS FROZEN IN BLOCKS

Abstract. One-stage grinding by milling is energy- and resource-saving process. It allows to create the line for the production of finished meat products with automatic control system (ACS) for assessing quality of minced meat based on artificial intelligence within the "untended manufacturing" principle. To design the line, methods of mathematical simulation of both individual machines operation and the entire technological process were used. In the article, the problem is considered of mathematical simulation of the milling tool (milling shaft) speed control circuit to construct ACS for grinding process of raw materials frozen in blocks. The objectives of the ACS analysis are as follows: 1) establishing the covariance of the controlled variable with the driving signal, i.e. the exact correspondence of the milling tool rotational speed to the specified (optimal) value for a given type of grinded raw material; 2) construction of the transient process performance curve in the system for given parameters of adjustment (stabilization). The scheme for cutting speed control circuit of the ACS is shown, where the controlled object (CO) is a set of devices: asynchronous short-circuited electric motor (AM) of the cutting mechanism; frequency transformer (FT) of supply voltage that changes the frequency of AD rotation (the frequency of the milling tool rotation); the grinder milling tool. The parameters of the control circuit are calculated at rated AM power of 22 kW and 11 kW for two possible configurations of the grinder. The task for synthesis of the control circuit is to minimize the deviation from the setting of milling tool rotation speed under the influence of external disturbances, which leads to decrease in size (thickness) variance of the meat chips with the improvement of the meat product quality. A technique is proposed for calculating the degree of raw material grinding for prediction of its change under the influence of external factors using Monte Carlo computing experiment. This technique allows to increase the amount of statistical information (grinding of "virtual" meat blocks) about the change in the rotation speed of the grinder milling tool under the influence of external disturbances. These estimates determine the prediction for the degree of grinding to plan further processing of ground raw materials.

Keywords: mathematical simulation, degree of grinding, morphometry, automatic control system.

Introduction. Currently, in food technologies, products frozen in blocks are widely used as raw materials. Frozen meat (beef, pork, poultry), cottage cheese, fish fillets, etc. are used for processing. We will consider processing of such raw materials in meat industry.

In meat industry, the use of frozen meat blocks with preliminary defrosting results in losses of meat juice. In addition, special devices, additional labor, energy resources and time for carrying out the technological operation of preliminary defrosting are required [1, 2]. There is technology for processing frozen meat blocks without defrosting using several stages of grinding. The traditional technological chain includes medium grinding (block cutter), fine grinding (mincing machine) and ultra-fine grinding (cutter). However, in the multi-stage processing of frozen meat raw materials, the high quality of finished products is not always achieved [3]. Thus, prevention of losses and achievement of high quality of the finished product produced from frozen meat blocks, are actual tasks of modern meat-processing industry.

One-stage grinding is energy- and resource-saving process. It allows to provide high quality of finished meat products. In the grinder of frozen meat blocks, a cylindrical body of rotation (for example, in the form of milling tool or milling shaft) is chosen as the working part, on the flanges of which there are cutting edges along the screw lines. Such choice is due to the following circumstances: 1) when grinding raw materials with milling tool, the area of contact of cutting edges with meat is minimal in comparison with the area of the lateral surfaces of the cutter knives, so it is possible to reduce the energy consumption for friction; 2) by changing the parameters of the grinding process using the milling method with removable milling tools of different design and geometry, it is possible to influence the sizes of ground meat particle, providing the specified degree of raw material grinding while improving the quality of finished meat products; 3) when processing the blocks of frozen meat of industrial standard sizes by milling in one stage, it is possible to reduce the traditional technological chain of meat blocks processing (block cutter - mincing machine - cutter), which will ensure resource saving. Thus, the new grinding technology of frozen meat allows energy and resource saving, and also reduces the need for an industrial area to accommodate equipment due to a significant reduction in the technological chain [3].

On the basis of one-stage grinding of meat raw materials it is possible to create an automatic line for the production of sausages, semi-finished products, baby foods, etc. with a quality control system for minced meat based on artificial intelligence within the "untended manufacturing" principle. As a result of a significant reduction in the cost of finished products, energy saving and improvement of sanitary and hygienic parameters, meat products obtained by the proposed technology may be accessible for a wide range of buyers, including low-income population.

To design the line, it is reasonable to use methods of mathematical simulation of both individual machines operation and the entire technological process for meat products manufacturing. For computer simulation it is necessary to develop discrete numerical models realized by a complex of algorithms and programs. On the computer, in algorithmic form, it is possible to perform a digital simulation of the real technological equipment operating within the automatic line.

Structural and mechanical (rheological) properties of raw materials are considered to be the main ones in justifying the optimal technological and mechanical conditions for manufacturing of meat products. Instrumental control of these properties makes it possible to ensure stable quality of the products. In meat product technology, structural and mechanical properties are largely determined by the particle size of the ground raw materials, i.e. by the degree of grinding [1, 2]. With the help of structural and mechanical properties, it is possible to control the technological parameters of raw materials and minced meat, the quality of products at any stage of the technological process, as well as the texture of the finished products. Thus, machine control of the degree of grinding for frozen meat raw materials largely determines the control of the entire technological process for the production of sausages, semi-finished and finished products.

When cutting the frozen meat with milling tool, there is a significant difference from traditional materials (metals, wood, plastics, etc.), i.e. a significant heterogeneity of frozen meat raw materials in structural and textural characteristics affecting the quality of grinding [3]. Different amounts of ice (water) in frozen meat at different storage temperatures, the presence of fat and connective tissues are the main factors of structural heterogeneity. The quality of the grinding is affected by the different orientation of the muscle tissue fibers in block relative to the milling tool blades, which is the factor of textural heterogeneity in raw materials.

The influence of the above factors on the degree of grinding is of accidental nature, therefore, when establishing the process parameters, it is reasonable to carry out a statistical analysis of the sizes of meat chips obtained as a result of raw material cutting with the milling tool. In this regard, the mathematical simulation of the frozen meat grinding process by the milling method requires to develop discrete mathematical models for the factors of influence on the degree of raw material grinding, including the factors of the environmental influence on the grinder operation.

Materials and methods. The object of this study was the grinding process of frozen meat blocks by the milling method. From the theory of cutting the materials with milling tool it is known [4] that when cutting the workpiece (block of frozen meat) crosswise to the milling tool, the cutting mode is uniquely identified by the cutting speed and feed rate to the grinding zone at a constant milling width. We also assume that the longitudinal axes of symmetry of the meat block and the milling tool lie in the same plane, so this is the case of symmetrical milling.

Let's consider in general the problem of mathematical simulation for the work of the rotation speed control circuit for milling tool (milling shaft) of the grinder and determine the goal for constructing the automatic control system (ACS) for the grinding process of frozen meat raw materials.

The purpose of the ACS for raw material grinding using the milling method is to maintain the specified degree of grinding, which is optimal for certain technology of minced meat production, as well as the prediction of its deviation from the specified value due to disturbances in the system. Then, the tasks of analyzing the grinding process control system are: 1) establishing the covariance of the controlled variable with the driving signal, i.e. the exact correspondence of the milling tool rotational speed to the specified (optimal) value for a given type of grinded raw material; 2) construction of the transient process performance curve in the system for given parameters of adjustment (stabilization). Looped by a negative feedback, rotation speed control circuit of the grinder milling tool may be represented as shown in figure 1.

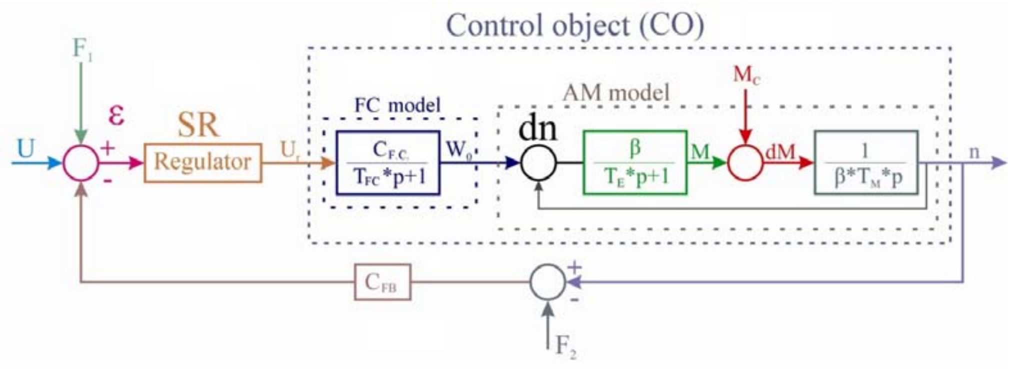

Figure 1 – ACS control circuit for cutting speed, where U is a signal corresponding to the setting of milling tool rotation speed; F_1 is disturbance influencing the input of control circuit; ε is adjustment error; U_r is signal at the output of controller; FT is frequency transformer; AM is asynchronous short-circuited electric motor of the cutting mechanism; K_{FT} is a transfer factor of FT; T_{FT} is a time constant of FT control circuit; β is the rigidity modulus of the linearized mechanical characteristic of AM; T_{eq} is the equivalent electromagnetic time constant of AM stator and rotor circuits; T_M is the electromechanical time constant of AM; M is the moment of AM; F_2 is the noise of milling tool rotation speed measuring; K_{FL} is a transfer factor of feedback loop; p is the Laplace operator

Hereafter controlled object (CO) means a set of devices: asynchronous short-circuited electric motor (AM) of the cutting mechanism; frequency transformer (FT) of supply voltage that changes the frequency of AD rotation (the frequency of the milling tool rotation); the grinder milling tool.

For the scalar law of adjustment of AM rotation speed, mathematical model for the electric motor ("Model AM") may be represented as shown in figure 1 [5, 6, 7].

Considering the process of electromechanical energy conversion in AM, it should be noted that the equations describing this conversion are nonlinear, since they contain products of various variables (current in AM windings, current linkages of phase windings, inductances and mutual inductances of stator and rotor windings). The analysis of transient processes in AM should be done using the full structural scheme of electromechanical energy conversion in motor. However, in the case of analyzing the transient (dynamic) processes in the ACS for grinding process, it should be taken into account that the system operates in the mode of AM speed stabilization, i.e. limited in motor angular speed variation. In addition, in the rotation speed adjustment, the control system maintains a constant magnetic flux in AM. In this case, it is possible to linearize the non-linear equations describing the electromechanical energy conversion in AM of the grinder. The equations obtained as a result of the linearization allow to use the simplified model of AM in the analysis of transient processes. This model takes into account the influence of the electromagnetic inertia of the motor on these processes with amplitude-limited oscillations of AM rotation frequency near the points of static characteristic [6]. This model has limitations for the application. There are two main limitations: 1) the considered structural diagram (model) is obtained by neglecting the active resistance of the stator chain in AM; 2) AM operates only in the working (linear) part of the motor mechanical characteristic within the absolute slip values $s_a \leq s_{cr}$, where s_{cr} is the critical slip of AM.

The first limitation determines the range of AM rotation speed adjustment, within which the application of the simplified model is correct. At AM rotation frequencies close to the rated ones, i.e. with a small adjustment range, the active resistance of the stator circuit may be neglected in comparison with the inductive resistance. Such speed can be applied when grinding raw materials in producing cooked sausages. For deeper speed adjustment, for example, when setting AM (milling tool) speed, which is optimal for making minced meat for summer sausages, more precise AM structural scheme should be applied, since in this case the inductance resistance of the stator circuit decreases with decreasing frequency of the supply voltage and becomes comparable to the active resistance of the stator chain. Consequently, neglecting the active resistance in this case is not correct.

Taking into account the considered limitations, the parameters of AM model are calculated as follows:

1. Rigidity modulus of the mechanical characteristic:

$$\beta = 2M_{cr}/(\omega_0 * s_{cr})$$

where M_{cr}, s_{cr} are the critical moment and the slip of AM; ω_0 – AM field velocity.

Since the adjustment of the AM rotation frequency occurs at a constant magnetic flux and, therefore, at the constant overload capability of the motor, M_{cr} and s_{cr} may be calculated from the specification of AM:

$$M_{cr} = \lambda_m \cdot M_{rated}$$

$$S_{cr} = S \cdot (\lambda_M + \sqrt{\lambda_M^2 - 1})$$

where M_{rated} – rated moment of AM; s – rated slip of AM; λ_M – maximum overload capability of AM.

2. The electromagnetic time constant is calculated by the equation:

$$T_{EQ} = \frac{1}{(\omega_{0el.rated} \cdot S_{cr})},$$

where $\omega_{0el.rated}$ is the angular velocity of the electromagnetic field of AM at its rated frequency f_{1rated} = 50 Hz.

$$\omega_{0el.rated} = 2\pi \cdot f_{1rated}$$

3. Electromechanical time constant is calculated by the equation:

$$T_M = \frac{J_{AM}}{\beta}$$

where J_{AM} is the moment of AM inertia (determined by specification).

For simulation of frequency transformer FT in dynamic processes, it can be represented by an inertial unit of the first order with a transfer function [6]:

$$W_{FT(P)} = {}^{K_{FT}}/_{(T_{FT} \cdot p + 1)}$$

where K_{FT} is a transfer factor of FT; T_{FT} is a time constant of FT control circuit; p is the Laplace operator.

Results and discussion. The calculation data for the AM model at P_{rated} = 22 kW and P_{rated} = 11 kW for the two possible configurations of the grinder are summarized in table 1.

For modern industrial FT, time constant T_{FT} does not exceed 0.001 s [6]. The speed sensor that outputs an information signal about AM rotation frequency to the negative feedback circuit is represented by a mathematical model in the form of proportional unit with the gain factor K_{FL} The open-circuited structural diagram of CO may be represented by the serial connection of the simplified structural circuit of cutting motor AM ("Model AM" in figure 1) to the dynamic model of FT ("Model FT" in figure 1) operating in this motor.

We simplify the task of analyzing the control circuit by setting $M_c \approx 0$, F_1=0, F_2=0. In production conditions, this situation may occur when ACS is output by the grinding process to the rotational speed of the grinder milling tool specified by the meat processing technology, without entering the grinding zone.

Table 1 – Calculation of AM and SC parameters

Parameter	Grinder configuration	
	Configuration with two bearing assemblies	Cantilever arrangement of milling tool
	Type of AM	
	AIR180S2	AIR132M2
Rated power, kW	22	11
Rated phase voltage, U_{frated}, V	220	220
Rated moment M_{rated}, N·m	71.98	36.10
Maximum overload capability $\lambda_{\text{м}}$	2.7	2.2
Rated rotation speed, rpm	2919	2910
Rated slip s	0.027	0.03
Rated angular velocity of field ω_{0rated}, s^{-1}	314	314
Critical slip, s_{cr}	0.14	0.13
Critical moment M_{cr}, N·m	194.34	79.42
Rigidity modulus of linearized mechanical characteristic β,	8.842	3.891
Equivalent electromagnetic time constant T_{eq}, s	0.023	0.025
Time constant of FT control circuit T_{FT}, s	0.001	0.001
Inertia moment of AM J_{AM}, kg·m²	0.057	0.023
Type of milling tool	Milling shaft	Milling tool with small tooth
Milling tool length, m	1.00	0.25
Milling tool diameter D, m	0.16	0.16
Inertia moment of milling tool J_{mil}, kg·m²	0.06	0.02
Electromechanical time constant of the controlled object $T_{\text{м}}$, s	0.013	0.006
Factor of proportional part of SC	6.500	3.000
Differentiation constant of SC , s	0.150	0.075
Integration constant of SC, s	0.002	0.002

Let's consider the transfer function of the open-circuited structural scheme of CO by the control action (speed setting signal):

$$W_{CO(p)} = \frac{y(p)}{r(p)} = [K_{FT}/(T_{FT} \cdot p + 1)] \cdot \left\{\frac{1}{[(T_{eq} \cdot p+1) \cdot \beta \cdot T_M \cdot p+1]}\right\} == \left[\frac{K_{FT}}{(T_{FT} \cdot p+1)}\right] \cdot \left[\frac{1}{(T_M \cdot T_{EQ} \cdot p^2+T_M \cdot p+1)}\right] \quad (1)$$

It is obvious that $W_{CO}(p)$ is the transfer function of two series-connected units: the inertial unit of the first order and the inertial unit of the second order. In automatic control theory (ACT) [5, 7], the method of sequential correction of transfer functions, such as (1), is considered to obtain the desired transfer function that provides the specified quality of transient processes in the transmission path of the control action, in accordance with the technological requirements for the equipment. In this case, speed controller must be included in the driving signal path. This controller is to have transfer function, which compensates for the inertia of the CO and provides the specified quality of transient processes in the rotation speed control circuit of the grinder milling tool.

Calculations show that the largest time constants in the control circuit are the time constants T_{eq} и $T_{\text{м}}$, which are more than an order of magnitude greater than the time constant T_{FT} (table 1). Thus, to achieve high performance of adjustment, speed controller (SC) must compensate for these time constants, since they mainly determine the inertia of the CO and, therefore, the nature of the transient processes in the control circuit. Then T_{FT} is assumed to be uncompensated time constant.

Qualitative indicators of transient processes in the system include performance, overadjustment and damping factor. Performance may be characterized by the adjustment time, during which the controlled variable reaches the specified value for the first time. Overadjustment is characterized by the maximum deviation (opposite to the initial value) referred to the specified (steady-state) value of the controlled parameter. The oscillation of the transient process may be characterized by a damping factor.

In ACT, various standard settings of the controller are considered, which provide the specified quality parameters of adjustment. Most often, in the control systems for industrial electric motors, the circuits are set up for a technical (modular) optimum [7]. In this case, a minimum time of adjustment $t_p = 4{,}7T_\mu$ is ensured, where T_μ is a small uncompensated time constant of the control circuit; overadjustment is less than 5% with a damping factor of $\sqrt{2}/2$.

We set up the speed controller SC of rotation speed control circuit of milling tool for the technical optimum.

For ACT it is proved [5, 7] that in this case, the optimal transfer function of the open-circuited control circuit with series-connected controller in the driving signal path, must be equal to:

$$W_{open.opt} = \frac{1}{[2T_M \cdot p \cdot (T_M \cdot p + 1)]} \tag{2}$$

where T_μ is a small uncompensated time constant of the control circuit.

We define the transfer function of the open-circuited control circuit for rotation speed (frequency) of milling tool with SC controller included as follows:

$$W_{\text{раз}} = W_{SC}(p) \cdot W_{CO}(p) = W_{SC}(p) \cdot [K_{FT}/(T_{FT} \cdot p + 1)] \cdot \left[\frac{1}{[2T_M \cdot p \cdot (T_M \cdot p + 1)]}\right] \tag{3}$$

By equating (2) and (3) and assuming a small uncompensated time constant of circuit T_{FT}, we obtain the desired transfer function of SC controller:

$$W_{SC}(p) = \frac{(T_M \cdot T_{EQ} \cdot p^2 + T_M \cdot p + 1)}{2T_{FT} \cdot K_{FT} \cdot K_{o.c.} \cdot p} = \frac{T_M}{2T_{FT} \cdot K_{FT} \cdot K_{o.c.}} + (T_M \cdot T_{EQ}) \cdot \frac{p}{(2T_{FT} \cdot K_{FT} \cdot K_{o.c.})} + \frac{1}{2T_{FT} \cdot K_{FT} \cdot K_{o.c.} \cdot p} \tag{4}$$

As it is seen from (4), the transfer function of the proportional-integral-differential controller (PID controller) is obtained. Using the PID controller, we compensate for the largest time constants (T_{eq} и $T_{м}$) by excluding them from the control circuit. By correcting the control circuit in this way, we get the resultant circuit with high performance due to the small uncompensated time constant $T_\mu = T_{FT}$, which determines the quality parameters of the rotation speed control for the grinder milling tool.

The presence of an integrating element in the resulting circuit results in a zero value of the static error of the adjustment by driving signal. With no disturbances from the load ($M_c \approx 0$) in the system and without taking into account other external disturbances ($F_1=0$, $F_2=0$), the total static error of the adjustment is also zero. Thus, when ACS is on the specified rotation speed of the grinder milling tool without feeding of raw materials into the grinding zone. So, when preparing the grinder for the operating mode, we get exactly the value of the milling tool rotation speed required by the certain technology of meat processing. It should be noted that in (4) $T_{м}$ is the electromechanical time constant of the entire CO, i.e. the moments of inertia for AM and the milling tool are summed up in its calculation. When calculating the inertia moment of a milling tool, its geometric shape is assumed to be cylindrical, which is a simplification. The structure of modern FT uses controllers with built-in system software tools that allow identifying CO parameters. Thus, the total inertia moment of AM and the milling tool can be determined more precisely in auto-adjustment mode. When selecting equipment, the transfer factors, K_{FT} (for a certain frequency transformer FT) and K_{FL} (for a specific AM speed sensor), are determined. In the calculations, the simplification was used in [6], in which K_{FT} and K_{FL} are assumed to be scale factors and to be equal to 1. Such an assumption will not affect the frequency characteristics of the circuit and the nature of the transient processes in it.

The results of calculating the parameters of the speed controller SC are summarized in table 1.

As a result of the adjustment of rotation speed control circuit of the grinder milling tool, we obtain a transient characteristic of the control circuit corresponding to the optimal setting. The transient characteristic of the circuit, i.e. the response of the system to the driving signal in the form of a "jump", is shown in the graph (figure 2). The graph is built in MATLAB for the grinder with electric motor of 22 kW.

Above, we considered the optimal settings for the rotation speed control circuit of milling tool without taking into account the resistance moment ($M_c \approx 0$). However, for the synthesis of ACS by the

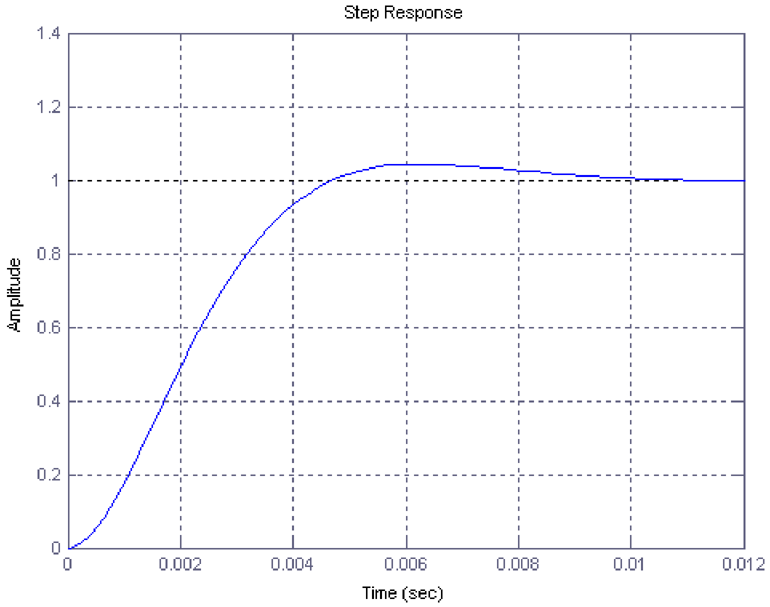

Figure 2 – Transient characteristic of the high-speed ACS circuit
(response to the "jump" of the load from zero to the relative "1")

grinding process, it is necessary to adjust the settings of speed controller (SC) taking into account the disturbances from the load, i.e. in the mode of raw material feeding to the grinding zone. To do this, we must develop a mathematical model of the load on the milling tool in the process of raw material grinding.

Let's consider the rotation speed control circuit of the grinder milling tool when applying one-step grinding technology with regard to external disturbances. In general, control circuit (i.e. rated control circuit or high-speed circuit) may be represented as shown in Figure 1. ACS for raw material grinding process operates by adjusting the deviation of the output coordinate of the system (rotation speed n of milling tool) with feedback on this coordinate. Controller SC based on the adjustment error ε, i.e. deviation of the controlled variable n from the target "u", performs the control action U_r on the control object CO. The task of ACS is to reproduce as accurately as possible the target "u" signal at the system output to minimize the adjustment error ε. From the point of view of managing the raw material grinding process, this means that the ACS must maintain the specified rotation speed of milling tool, which is optimal for certain type of grinding. In the ideal case (unattainable in practice), we need to get an exact reproduction of the ACS coordinate output at the system input, so the rotation speed of milling tool must exactly match the specified value. However, ideally precise reproduction is impossible for the following reasons: 1) the influence of the dynamic properties of the ACS, in particular the inertia caused by the presence in the control circuit of an uncompensated small time constant T_μ assumed in this case equal to the time constant of frequency transformer T_{FT} control circuit; 2) the influence of disturbances (F_1, F_2, M_c) on ACS (figure 1). Random influences on the ACS for grinding process affecting the nature of the grinding include the fluctuations F_1 of the supply voltage of meat processing facility not compensated by the network filter of frequency transformer FT, as well as possible random interferences F_2 in the information channel of ACS (feedback channels for the controlled coordinate), i.e. an inaccurate measurement of the milling tool rotation speed.

However, first of all, in synthesis of ACS for the grinding process (in this case, defining controller SC settings that provide covariance with the target), it is necessary to take into account that during the grinding, the control circuit is affected by the time-varying load M_c on the grinder milling tool. Since the structural diagram of rated control circuit shown in figure 1 represents the mathematical models of the dynamic ACS units connected in a certain way, then to take into account the effect of disturbances from the load on the milling tool during the grinding, when analyzing the transient processes in this circuit, it is necessary to develop a mathematical model of such influence, which fairly well fixes the essential properties of real influence of raw materials on the milling tool in the operating mode [8]. The essential properties of this influence include the random nature of load on the grinder milling tool during the grinding with the corresponding distribution of grinding resistance moment as a random function. As noted above, the load on the milling tool when grinding the blocks of frozen raw material of industrial sizes varies randomly under the influence of random factors: different spatial orientation of fibers in muscle tissue relative to the cutting edges of the milling tool; change in raw material temperature in the volume of raw material block; a multicomponent composition of raw materials, i.e. muscle, connective, fatty tissue with different mechanical characteristics of grinding [3]. As a result of the analysis by the methods of mathematical statistics it was established that the distribution of the active power consumed by the electric motor of the cutting mechanism of the plant equipped with a cylindrical milling tool with small tooth in accordance with GOST 29092-91 obeys the normal law (figure 3), as well as the dimensions of meat chips (thickness) in with this grinder configuration (figure 4):

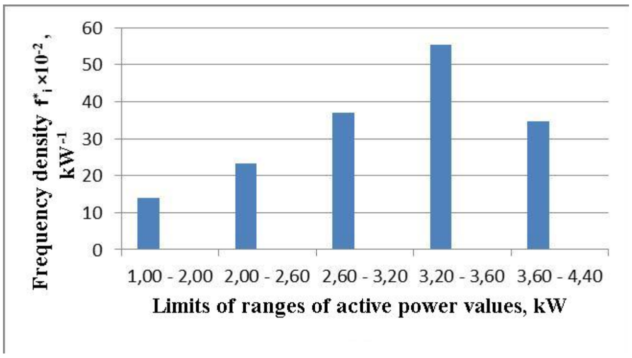

Figure 3 – Histogram of the frequency density distribution
for power consumed by the electric motor
of the cutting mechanism of the plant in the operating mode
over the ranges of its measured values

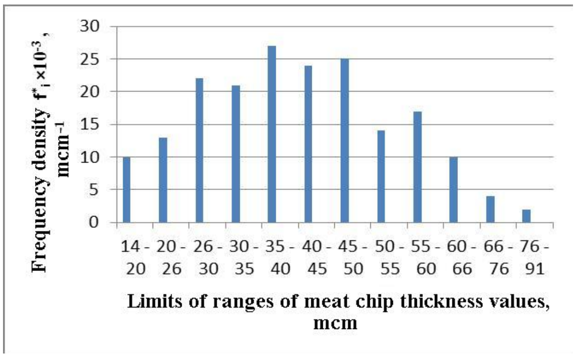

Figure 4 –
Histogram of the frequency fi* density
distribution for the thickness of meat chips falling
into the ranges of its values (beef)

In the first approximation, this suggests the normal law of distribution of the load on the milling tool when grinding the raw material blocks of industrial sizes. Thus, the factors influencing the anisotropy of the mechanical properties of raw material blocks, and having a random nature, do not prevail one above the other. This conclusion is based on the central limit theorem [9], whose meaning in the case under consideration can be defined as follows: whatever the laws of distribution of individual independent (or weakly dependent) factors of influence on the mechanical properties of frozen raw material blocks (for example, the law of distribution of temperature change in the volume of the block), the law of distribution of their sum of influence will be close to normal.

The ground product is shown in figure 5, and its microstructure is presented in figure 6:

Figure 5 –
The product of grinding (beef)

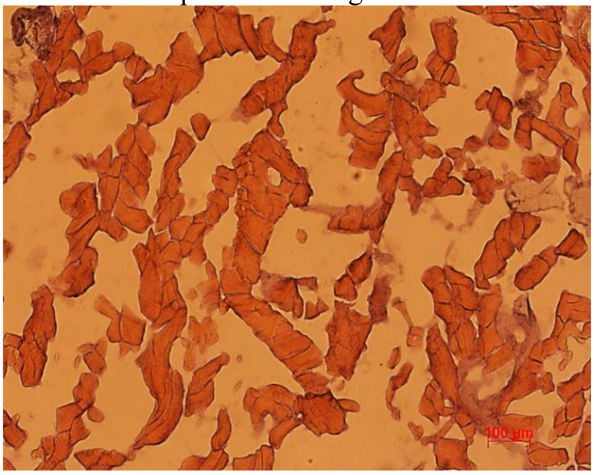

Figure 6 –
Microstructure of the ground product sample (beef) (20x)

Under the conditions of stabilization of the milling tool rotation speed and raw material feed rate to the grinding zone, it can be assumed that the random loading process of the grinder milling tool is a steady random process. In the random process theory (RPT), the process is called steady in the broad sense, if its mathematical expectation and variance are constant, and the correlation function is a function of the shift between the time arguments [10]. For the case under consideration, this means that the load on the milling tool during the grinding fluctuates near the unchanged mean value of the load (mathematical expectation of the load) at a constant variance near the mean value, regardless of the process section (from the moment of time).

Further, the random process of loading the milling tool will be considered as a centered process (with zero mathematical expectation), for which the value of the mean square is equal to the variance. The realization of a centered random process is the deviation of a random process from its mathematical expectation, while the variance characterizes the degree of realization range. In addition, we accept the hypothesis that the influence on the ACS from the load on the milling tool during the grinding is an ergodic random process. In this case, the parameters of the random process are estimated using time averaging. The accepted hypothesis seems to be valid because the time course of the grinding process in the conditions of stabilizing the cutting regime and supplying raw materials to the grinding zone is uniform, and ACS operates in a steady mode. Consequently, it may be assumed that any realization of a steady random process of a certain duration sufficiently fully represents whole array of realizations of the process under consideration, i.e. the process has the property of ergodicity.

Assuming a load on the milling tool in the process of grinding as a steady random process, we use the method of the forming filter (FF) for simulation of disturbance acting on the ACS by the load (M_c in Figure 1). The FF method is based on the fundamental property of passing a random steady process through a linear system, which can be expressed as follows [9, 10]:

$$S_{y(\omega)} = \left|W_{FF(j\omega)}\right|^2 \cdot S_{x(\omega)} \tag{5}$$

where $S_y(\omega)$ is the spectral density of the random process at the output of the system; $S_x(\omega)$ is the spectral density of a random process at the input of the system; $|W_{FF}(j\omega)|^2$ is square of the module of the transfer function of the system; ω is the frequency.

We assume that the random process at the input is white noise. The white noise in RPT is the limiting case of a sequence of very short pulses whose amplitude is an independent random variable with a very large variance, and the ratio of the variance of these pulses to their frequency is constant (finite) [10]. From the definition of white noise, the spectral density of the input random process is constant over the entire frequency range and is equal to:

$$S_{x(\omega)} = S_0 = const$$

If we assume that $S_o = 1$, then the equation (5) will be as follows:

$$S_{y(\omega)} = \left|W_{FF(j\omega)}\right|^2 \cdot S_{x(\omega)} = \left|W_{FF(j\omega)}\right|^2 \cdot 1 = \left|W_{FF(j\omega)}\right|^2 \tag{6}$$

Thus, in order to realize a random process with the specified statistical characteristic, i.e. the specified spectral density $S_y(\omega)$, we must pass white noise with a single spectral density through the linear system with the transfer function $W_{FF}(j\omega)$. Such a linear system in ACT is called a generating filter (figure 7).

Figure 7 – Method of generating filter

To apply the FF method, it is necessary to know the spectral density $S_y(\omega)$ of the random process being formed. In this case, this means requirement to measure the random process of load on the milling tool during the grinding. To obtain a consistent assessment of statistical information, it is necessary to grind frozen raw material blocks of industrial sizes, since only in this case the anisotropy of mechanical properties affecting grinding resistance can fully manifest itself.

It should be noted that the design features of the plant do not allow for significant distortion of the dynamic characteristic of the cutting mechanism motor during operation, since there are no long shafts resisting twisting force. Therefore, as a starting statistical information, we can use AM moment of the cutting mechanism M(t) during the grinding of raw material blocks of industrial sizes, or its stator current $I_c(t)$. When calculating $M_c(t)$, we should take into account the dynamic component of the moment $J_\sum(dn/dt)$, where $J_\sum$ is the total inertia moment of the transmission elements of the plant, which is applied to the motor shaft. Next, we can use the standard method for measuring random processes for engineering calculations [10]. In the case under consideration, this technique evaluates the correlation function of the random process M(t) or $I_c(t)$ on a limited time interval under the assumption that the random process is ergodic. Then the Fourier transformation of this estimate must be performed, which is the desired estimate of the spectral density of the random process being measured.

With estimate of the spectral density, it is possible to determine the transfer function of generating filter $W_{FF}(j\omega)$ by the equation (6) using the standard calculation algorithm [10]. Then the mathematical model of the random process of load on the grinder milling tool during the grinding is a random process at the output of the linear system (FF) with transfer function $W_{FF}(j\omega)$ after passing of white noise with a single spectral density through it. The FF determined is used in the statistical test method (Monte Carlo method) in the digital simulation of ACS.

In the synthesis of ACS, mathematical simulation on a computer allows to replace the field experiment with an equivalent one in terms of the accuracy of the information obtained by a calculative computer experiment [8]. Structural diagram of a calculative computer experiment using the statistical test method for the grinder is shown in Figure 8.

As can be seen from the structural diagram of the experiment, for digital simulation it is necessary to develop white noise generator program N(t). In the simulation of continuous white noise for the analysis and synthesis of ACS systems operating under random disturbances and interferences, a process close to continuous white noise is used, which is a sequence of independent random numbers, i.e. continuous white noise is approximates by discrete white noise [10].

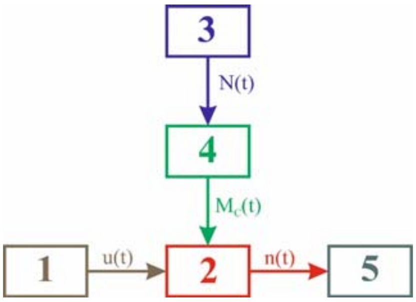

Figure 8 – Structural diagram of the experiment on the computer, where 1 is generator program of the signal of the target for milling tool rotation speed; 2 is linear model of high-speed circuit of ACS; 3 is white noise generator program; 4 is generating filter; 5 is statistical processing of experimental results

By analogy with continuous white noise, a random steady discrete function X[nT] with independent values for different argument values and zero mathematical expectation is called discrete white noise [10]. Here, n (number) takes the integer values 0, ± 1, ± 2, ...; T is period of discreteness. From the condition of steady state, the variance of the process does not depend on the number of the sequence term and is constant: $D_X[n] = D_X = \text{const}$.

In RPT, continuous white noise is defined as a random process whose mathematical expectation is zero, and the correlation function is proportional to the delta function [10]:

$$K_{(t_1,t_2)} = q(t) \cdot \delta(t_1 - t_2)$$

where q (t) is the intensity of white noise; δ is the sign of the delta function.

From the delta-function properties, $\delta(t_1 - t_2)$ is zero at the value of the argument $(t_1 - t_2)$ other than zero, so for white noise, the random variables corresponding to two arbitrarily close sections are uncorrelated. At a constant intensity, q(t) = q = const of continuous white noise, which we will consider below, its spectral density is equal to the intensity: $S(\omega) = q$. The spectral density of discrete white noise with variance D_X and the period of discreteness T is defined as follows [10]:

$$S^*(\omega) = T \cdot D_x$$

When the continuous white noise is approximated by a discrete one, the equation must be required:

$$q = T \cdot D_x$$

for a sufficiently small period of discreteness (T→0).

Then the variance of the discrete white noise and the standard deviation from the zero mathematical expectation are determined respectively as follows:

$$D_x = {}^{q}\!/_{T}$$

$$\sigma = \sqrt{D_x} = \sqrt{{}^{q}\!/_{T}}$$

To determine the period of discreteness T, the Kotelnikov-Shannon theorem on the quantization of continuous signals is used: if the continuous signal x(t) has a frequency spectrum bounded from above by the frequency w_x, then its time quantization with a doubled frequency $w_{\text{д}} \geq 2w_x$ does not lead to a loss of information, i.e. the signal is uniquely and completely represented by its discrete values with the quantization period $T \leq \pi/w_x$. Then the period of discreteness T for discrete white noise in the white noise generator program in the calculative experiment of the digital simulation of the grinding process will be determined as follows [10]:

$$T = {}^{\pi}\!/_{(\text{晧} \cdot w_{xup})} ,$$

where w_{xup} is the frequency that limits the frequency spectrum of the random process under consideration; r is factor chosen depending on the features of the internal structure of the random process.

The ranges of w_{xup} and r values for different technical systems are as follows [10]: w_{xup} = 20-60 [rad/s]; r = 1,5 to 3. Thus, it is possible to determine the upper limit of the values for the period of discreteness: T ≤ 0.018 to 0.105 s. For this case, let us take a period of discreteness T = 0.01 s.

When measuring the active power consumed by the electric motor of the cutting mechanism of the plant in the operating mode, the industrial analyzer ACM-3192 was used. The minimum time of discretization, i.e. the time interval between two adjacent measurements, is 2 seconds for this device. This is much longer than the accepted period of discreteness (0.01 s). Thus, to determine the parameters of the generator program of the random load signal for the milling tool during the grinding for the digital simulation of the ACS, the torque of the motor must be measured by another device with a smaller allowable time of discretization.

Having no statistical information on the grinding of raw material blocks of industrial sizes (the dimensions of the experimental blocks ground in the experimental plant are much lower than the industrial prototypes) and not enough information on the measurement of the cutting power (moment), we illustrate the method by simulating test signals for operation of the grinder in the operating mode. The Gaussian (normal) discrete noise N(t) with zero mathematical expectation and a standard deviation equal to 1 passed through the generation filter in the form of an aperiodic unit with a time constant $T_{\text{ф}} = 0.25$ s is used as a test signal of the influence of the raw material on the milling tool during the grinding [11]. At the output of FF we get a random process $M_c(t)$ simulating the load on the milling tool distributed according to the normal law. The simulation of the random load on the grinder milling tool (teas load) in the operating mode is shown in figure 9.

At the input of the high-speed circuit, the signal u(t) is generated corresponding to the target of the rotation speed of the grinder milling tool, in the form of rectangular pulses (figure 10). The horizontal "parts" of this signal correspond to the constant value of the target (relative "1"). This signal can be considered a test signal.

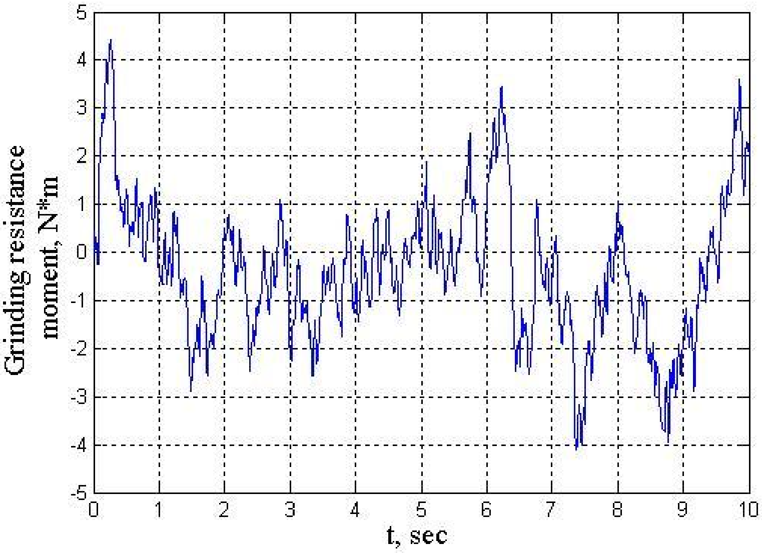

Figure 9 – Simulation of the random load on milling tool during the grinding

The systems of differential equations describing the operation of the dynamic units of the circuit model (figure 1) are represented in the simulation program in the normal form of the state space (the standardized vector-matrix Cauchy form):

$$dx/_{dt} = A \cdot x + B \cdot u$$

$$y = C \cdot x + D \cdot u$$

where x is the parameter of unit state; y is output unit; u is input influence; A is state matrix; B is input matrix; C is output matrix; D is bypass matrix.

It is noted in the literature [11] that exactly this representation of the dynamics of the model units' work provides the most accurate calculations for simulation. The model (rotation speed control circuit of milling tool) has two inputs and one output. The matrix of input influences on the system is: U = [u v], where u is input influence, v is disturbance from the load. The output coordinate of the system is n (rotation speed of the grinder milling tool). The result of simulation, i.e. the change in the milling tool rotation speed under the influence of the raw material grinding resistance moment (test signal) is shown in figure 11.

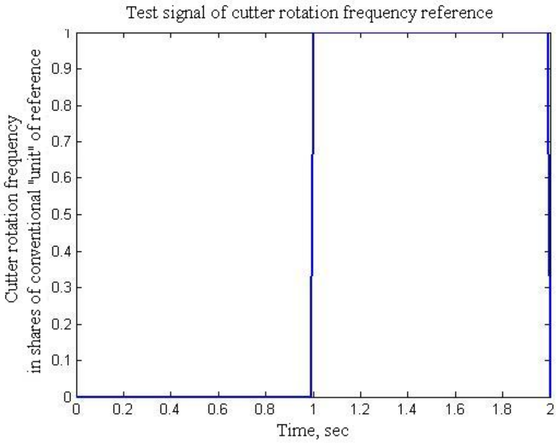

Figure 10 – Test signal of the target of rotation speed of the grinder milling tool

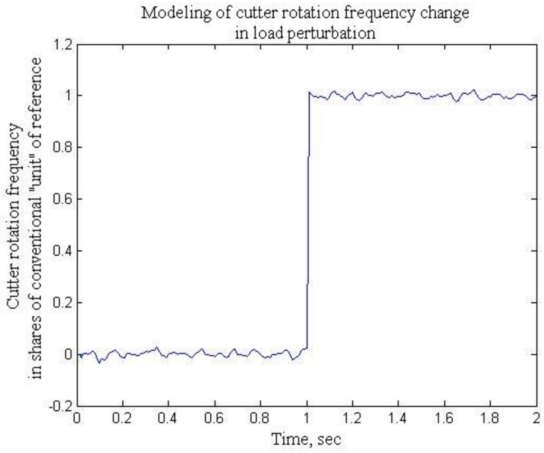

Figure 11 –
Change in the milling tool rotation speed

The complete scheme for synthesizing the linear high-speed circuit of raw material cutting of ACS for the grinding of frozen meat blocks using the milling method is shown in figure 12.

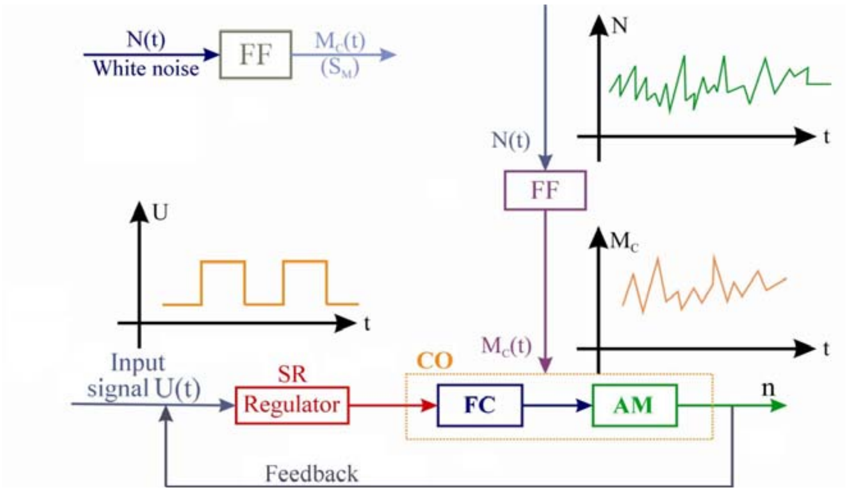

Figure 12 – Scheme for the linear high-speed circuit of raw material cutting of ACS

In the mathematical simulation of stochastic systems, the realization of random processes obtained as a result of a calculative experiment on a computer is used to determine the probability characteristics. The analysis of the results of the calculative experiment consists in obtaining statistical estimates of the probability characteristics of the system output parameters characterizing the quality and efficiency of its operation and determining the compliance with the technical requirements for these parameters [9]. In this case, the controlled output parameter is the rotation speed of the grinder milling tool. Therefore, to analyze the results of mathematical simulation of meat block milling, it is necessary to obtain a set of graphs n(t) corresponding to the implementation of the random influence $M_c(t)$ on grinder in the operating mode for different values of the optimized parameter

$$a = {}^{T_0}\!/_{T_\mu}$$

where T_0 is the integration time constant of SC controller; T_μ is an uncompensated time constant.

To optimize the grinding process, at least two random environmental influences on the grinder in the operating mode must be considered. In addition, the effect of these influences on the rotation speed control circuit of milling tool should be different. This means that with increasing (decreasing) the optimized parameter of SC controller setting, the components of the variance of the adjustment (stabilization) error of the milling tool rotation speed caused by the action of these influences should not simultaneously increase or decrease. Then the optimization task is to determine the value of the optimized parameter, at which the variance of the adjustment error is minimal and the synthesis scheme of linear high-speed circuit of raw material cutting of ACS will make sense.

In addition to the randomly changing load $M_c(t)$ on the milling tool during the grinding, random fluctuations of the supply voltage and interference in the measuring path (F_1 and F_2 in figure 1) affect the operation of the grinder. Fluctuations in the supply voltage of the power supply network in the meat-processing facility may be caused by the switching-on (switching off) of powerful electrical receivers, for example, large cutters, etc. In addition, the power supply networks can be prone to frequent fluctuations in the supply voltage with respect to the rated value. In particular, this is possible in the facilities that were designed and built in the past years (the "old" power supply schemes). As noted in the literature [12], random fluctuations of the supply voltage usually obey the normal distribution law. We have reviewed only the effect of $M_c(t)$ on the change of rotation speed of the grinder milling tool in the operating mode. Statistical analysis of the results of the calculative experiment may be implemented by taking into account the other accidental environmental influences on the work of the grinder, which specified above. Mathematical models of these influences are constructed in the same way as described above, while the matrix of external influences "U" on ACS for the grinding process will be accordingly of greater dimension.

As noted above, the graphs n(t) derived from the calculative experiment are realizations of random process. All the values of the milling tool rotation speed in the implementation will be assumed as the population in the statistical observation. Then a part of the values chosen from the population in a random way will be assumed to be a sample of statistical observation. The ultimate goal of statistical analysis is to estimate the variance of the milling tool rotation speed under the influence of random load, i.e. resistance moment of raw material grinding, which is variable in time $M_c(t)$. Then it will be possible to determine the variance in the linear size of the meat chips.

To solve this problem, we use point estimates of the mathematical expectation and variance of the milling tool rotation speed for the sample under consideration, based on the law of large numbers [9]:

$$M_W^* = (1/\mathrm{N}) \cdot \sum_{k=1}^{N} W_k \cdot (t)$$

$$D_W^* = \left[{}^{1}\!/_{(N-1)}\right] \cdot \textstyle\sum_{k=1}^{N} [W_K(t) - M_W^*] \tag{7}$$

Here, N is the number of measurements of the milling tool rotation speed on the graph n(t) for each sample. Since the measurement points may be chosen in random manner, the estimates (7) are random variables. Then the problem arises to supplement the point estimates with information about its possible error and reliability, i.e. to estimate the sampling error $\delta = D_W - D^*_W$ (for the variance of the rotation speed of the grinder milling tool) [9].

To determine the dependence of the size of the resulting meat chips (thickness) on the rotation speed of the grinder milling tool, we consider the formation of the cutting surface of the meat block (figure 13) and the corresponding milling scheme (figure 14).

Figure 13 –
Forming the cutting surface
of frozen meat block

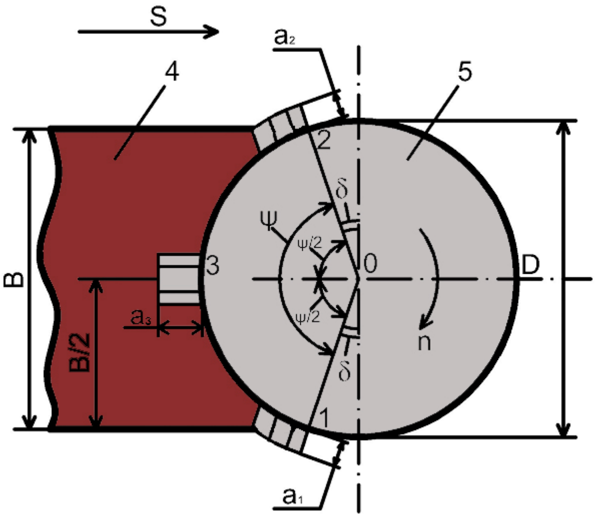

Figure 14 – Scheme for milling of the frozen meat block, where: S is feeding the block to the milling tool; n is rotation speed of milling tool; a_1, a_2, a_3 is thickness of meat chips at points 1, 2, 3; B is width of the meat block; D is diameter of the milling tool; ψ is angle of contact; δ is angle on the cutting path at points 1, 2; 4 is frozen meat block; 5 is milling tool

If we consider the average chip thickness along the length of the contact of the milling tool and the meat block as the arithmetic mean of the maximum (at point 3) and the minimum value (at points 1 and 2), then [3]:

$$a_{cp} = \frac{a_{max}+a_{min}}{2} = S_z \cdot \frac{D+\sqrt{D^2-B^2}}{2D} \tag{8}$$

where B is width of the meat block; D is diameter of the milling tool; S_z is supply of raw material to the tooth of milling tool.

The supply (8) of raw material to the tooth of the milling tool S_z is defined as:

$$S_Z = \frac{1000 \cdot S}{n \cdot Z},$$

where S is the raw material feed rate for the milling tool; n is rotation speed of milling tool; Z is number of milling tool teeth.

Conclusions. From the presented dependencies, the change (deviation from the target) of milling tool rotation speed under the influence of external disturbances leads to a variance in the size (thickness) of the meat chips. It should be noted that it is possible to limit the change in the second dimension of the meat chips, i.e. width, by the choice of the geometry of the milling tools used, in particular by fragmenting the segments of the cutting edges of the multi-blade tool of the grinder.

Thus, it is possible to propose the following methodology for calculating the degree of raw material grinding when predicting its change under the influence of external factors using the mathematical simulation of the grinding process:

1. The task of ACS for the process of frozen meat block grinding is to ensure the covariance of the controlled coordinates of the system with the target. The target is determined by the chosen technology of meat products [13]. The specified task is solved by the corresponding settings of ACS controllers.

2. Calculation of parameters for mathematical models of equipment types that compose the object controlled by the ACS is performed taking into account the non-linear nature of the electromechanical energy conversion in the system, or by linearizing the models under the specified conditions for the correctness of the simplifications used.

3. The work of ACS is considered with the influence of the resistance moment of raw material variable in time, which is applied to the motor of the milling grinder. It is assumed that the random process of loading the milling tool of the grinder in the operating mode is a steady random process with the property of ergodicity. The numerical characteristics of this process (mathematical expectation and variance) are determined by the control computer (CPC), an ACS component, during the calculative experiment by the Monte Carlo method. Digital simulation of ACS operation is simulating the operating conditions of a real system using calculation algorithms that are implemented in the form of programs on the CPC.

4. The method of generating filter (FF) is used for simulation of disturbances in load acting on the ACS. It is assumed that the random process at the FF input is white noise with a spectral density that is constant over the entire frequency range and equal to: $S_{x(\omega)} = S_0 = const = 1$. Then at the FF output we have a random process with spectral density as follows:

$$S_{y(\omega)} = \left|W_{FF(j\omega)}\right|^2 \cdot S_{x(\omega)} = \left|W_{FF(j\omega)}\right|^2 \cdot 1 = \left|W_{FF(j\omega)}\right|^2$$

To apply the FF method, it is necessary to know the spectral density $S_y(\omega)$ of the random process being formed. In this case, this requires to measure the random load process on the grinder milling tool during the grinding. To obtain a consistent assessment of statistical information, it is necessary to grind frozen raw material blocks of industrial sizes, since only in this case the anisotropy of mechanical properties affecting grinding resistance can fully manifest itself.

5. Measurements of the electric motor moment M(t) during the grinding of raw material blocks of industrial sizes may be used as the initial statistical information. Measurements should be conducted at time of discretization not exceeding 0.01 s. When calculating the resistance moment of grinding $M_c(t)$, the dynamic equation of electric motor motion should take into account the dynamic component of the moment $J_\Sigma(dn/dt)$, where J_Σ is the total inertia moment of the rotating masses; n is the rotation speed of the rotor. Next, the standard method for measuring random processes for engineering calculations can be used. In this case, this technique evaluates the correlation function of the random process M(t) on a limited time interval under the assumption that the random process is ergodic. Then the Fourier transformation of this estimate must be performed, which is the desired estimate of the spectral density of the random process being measured. With estimate of the spectral density, it is possible to determine the transfer function of generating filter $W_{FF}(j\omega)$ using the standard calculation algorithm. Then the mathematical model of the

random process of load on the grinder milling tool during the grinding is a random process at the output of the linear system (FF) with transfer function $W_{FF}(j\omega)$ after passing of white noise with a single spectral density through it. The FF determined is used in the statistical test method (Monte Carlo method) in the digital simulation of ACS.

6. The statistical information about the random process $M_c(t)$ obtained with the help of the calculative experiment allows the CPC to calculate the variance of the population of the process data n(t) and determine the required number of measurements of milling tool rotation speed n (sample size N) by means of ACS in real time to calculate the point and interval estimation of the average process value n(t) with the specified statistical accuracy and reliability. According to the established functional relationship between the speed of the milling tool n and the typical particle size of the ground meat, the CPC calculates a point and interval evaluation of the specified size of the meat chips. According to the laws of mathematical statistics, one can also determine the variances of these estimates themselves, i.e. to determine the degree of "blurring" of the range boundaries. Using the statistic estimates for the size of meat chips established in this way, it is possible to specify the technological parameters of further processing the ground raw materials in order to produce high-quality ground meat.

The scheme of the suggested calculation procedure is shown in figure 15. It should be noted that the calculative experiment by the Monte Carlo method allows to increase the amount of statistical information (grinding of "virtual" meat blocks) about the change in the rotation speed of the grinder milling tool under the influence of external disturbances on the ACS, while the CPC determines the necessary amount of this information to obtain statistical estimates with the specified accuracy and reliability. These estimates determine the prediction for the degree of grinding to plan further processing of ground raw materials.

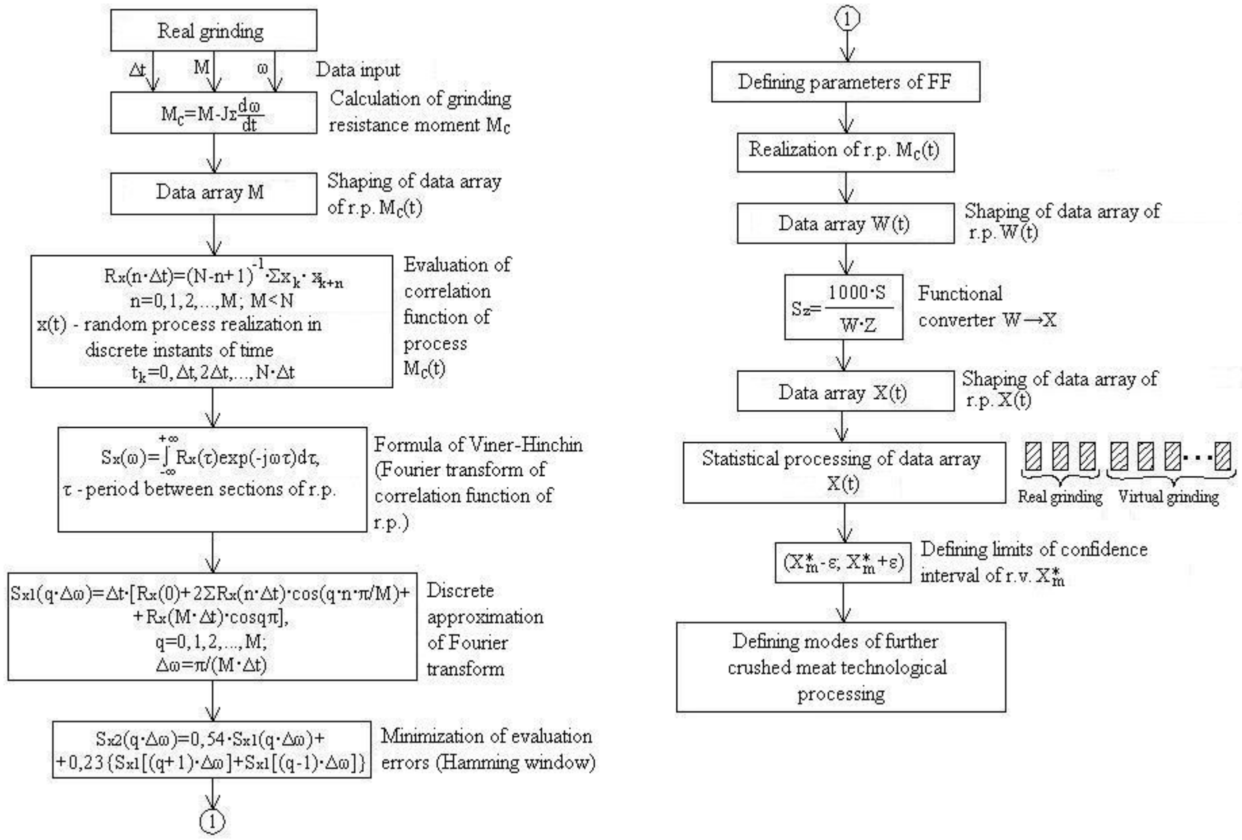

Figure 15 – Scheme of the methodology for calculating (predicting) the typical particle size of ground meat, where X is the typical particle size; W is rotation speed of the grinder milling tool

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БЛОК ТҮРІНДЕ МҰЗДАТЫЛҒАН ӨНІМДЕРДІҢ БІРСАТЫЛЫ ҰСАҚТАУ МАТЕМАТИКАЛЫҚ МОДЕЛЬДЕУІ

Аннотация. Бір сатылық фрезерлік ұсату – энергия және ресурс үнемдеу технологиясы болып табылады, жасанды интеллект базасында «иесіз технологиялар» қағидасы бойынша тартылған ет сапасын, сонымен қатар, автоматты басқару жүйесін (АБЖ) қамтитын дайын ет өнімдердің желісін құруға мүмкіндік береді. Желіні жобалау үшін математикалық модельдеу әдістері болып жекелеген машиналардың (аппараттардың) жұмысы, сондай-ақ бүкіл технологиялық процессті дайындау жұмысы қолданылды. Мақалада математикалық модельдеудің міндеттері ретінде шикізатты блок түрінде ұсақтап қатыратын процессі бар АБЖ құрастыру мақсатында контурдың айналу жиілігін реттейтін ұсақтағыш фрезінің (фрезер білігі) жұмысы қарастырылған. АБЖ талдау міндеттері: 1) айнымалы беретін әсер ету басқарылымды ковариантты фактісінің анықталуы, яғни фрез айналыс жиілігінің шикізатты ұсақтау түріне байланысты оның оптималды мәніне дәлме-дәл сәйкестігі; 2) өтпелі процесс жүйесінде берілген сапа көрсеткіштерін реттеу (тұрақтандыру) сипаттамаларын құру. АБЖ шикізатының кесу жылдамдығын реттейтін контурдың схемасы көрсетілген, басқару объектісі (БО) ретінде келесі құрылғылар жиынтығы алынған: асинхронды қысқа тұйықталған электр қозғалтқыш (АҚ) жетегінің тетігін кесу; АҚ (фрездің айналу жиілігін) айналу жиілігін өзгертетін қуат кернеуінің жиілік түрлендіргіші (ЖТ); ұсақтағыш фрезі. АД 22 кВт және 11 кВт номиналды қуаты бар ұсақтағыштың екі ықтимал құрастыруына реттеуіш контурының параметрлері есептелген. Реттеу контурының синтез міндеті болып сыртқы қозғалыс әсерінен фрездің айналу жиілігі тапсырмаларынан ауытқулардың азаюы табылады, бұл өнімнің сапасын арттыру барысында ет жоңқасының дисперсия мөлшерінің (қалыңдығының) төмендеуіне әкеледі. Монте-Карло әдісі бойынша есептеу экспериментін қолдана отырып, сыртқы факторлар әсерінен оның өзгеруін болжайтын, шикізаттын ұсақтау деңгейіне есептеу әдістемесі ұсынылды, бұл статистикалық ақпараттың ("виртуалды" ет блоктарын ұсақтау) көлемін арттыруға сонын ішінде сыртқы қозғалыс әсерінен ұсақтағыш фрезінің айнылу жиілігінің өзгеруіне мүмкіндік береді. Ұсақталған шикізатты әрі технологиялық өңдеуге жоспарлау үшін бұл бағалау ұсақтау деңгейін болжап анықтайды.

Түйін сөздер: математикалық модельдеу, ұсату дәрежесі, морфометрия, автоматты басқару жүйесі.

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ОДНОСТАДИЙНОГО ИЗМЕЛЬЧЕНИЯ ПРОДУКТОВ, ЗАМОРОЖЕННЫХ В ВИДЕ БЛОКОВ

Аннотация. Одностадийное измельчение фрезерованием является энерго- и ресурсосберегающими позволяет создать линию по выработке готовых мясных продуктов с системой автоматического управления (САУ) качеством мясных фаршей на базе искусственного интеллекта по принципу «безлюдной технологии». Для проектирования линии использованы методы математического моделирования работы как отдельных машин (аппаратов), так и всего технологического процесса выработки. В статье рассмотрена задача математического моделирования работы контура регулирования частоты вращения фрезы (фрезерного вала) измельчителя с целью построения САУ процессом измельчения замороженного в виде блоков сырья. Задачами анализа САУ выделены: 1) установление факта ковариантности управляемой переменной с задающим воздействием, то есть точное соответствие частоты вращения фрезы заданному (оптимальному) значению для данного вида измельчения сырья; 2) построение характеристики переходного процесса в системе при заданных показателях качества регулирования (стабилизации). Приведена схема контура регулирования скорости резания сырья САУ, где объектом управления (ОУ) выделена совокупность устройств: асинхронный короткозамкнутый электродвигатель (АД) привода механизма резания; преобразователь частоты (ПЧ) питающего напряжения, изменяющий частоту вращения АД (частоту вращения фрезы); фреза измельчителя. Рассчитаны параметры регулятора контура при номинальной мощности АД 22 кВт и 11 кВт для двух возможных компоновок измельчителя. Задачей синтеза контура регулирования выбрана минимизация отклонения от задания частоты вращения фрезы под воздействием внешних возмущений, что приводит к снижению дисперсии размера (толщины) мясной стружки при повышении качества мясного продукта. Предложена методика расчета степени измельчения сырья при прогнозировании ее изменения под влиянием внешних факторов воздействия с применением вычислительного эксперимента по методу Монте-Карло, которая позволяет увеличить объем статистической информации (измельчение «виртуальных» блоков мяса) об изменении частоты вращения фрезы измельчителя под влиянием внешних возмущений. Эти оценки определяют прогноз степени измельчения для планирования дальнейшей технологической обработки измельченного сырья.

Ключевые слова: математическое моделирование, степень измельчения, морфометрия, система автоматического управления

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ISSN 2518-170X (Online), ISSN 2224-5278 (Print)

http://geolog-technical.kz/index.php/kz/

Верстка *Д. Н. Калкабековой*

Подписано в печать 08.10.2018.
Формат 70х881/8. Бумага офсетная. Печать – ризограф.
15,0 п.л. Тираж 300. Заказ 5.

Национальная академия наук РК
050010, Алматы, ул. Шевченко 28, т. 272-13-19, 272-13-18