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INTELLIGENT CONTROL SYSTEM FOR MINCED MEAT PRODUCTION

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ABSTRACT

This article presents the theoretical aspects of developing a control system for the processing of frozen raw meat by cutters in automatic mode. The method for analytical calculation of the productivity rate of meat cutting by a cutter with a screw tooth provides an accuracy for which relative error does not exceed 6%. The authors show automatic process control in minced meat production using a control system computer (CSC), with the aim of building an automatic control system (ACS) for chopping raw materials frozen in the form of blocks. The task of ACS synthesis was solved: the system structure and its elements were chosen, the topology of their cause-and-effect relationships and an algorithm of control devices were developed, and their parameters were determined. The ACS's control loop scheme for raw material cutting speed was realized, where an assembly of devices was chosen as the object of management (OM): the squirrel cage induction motor (SCIM) of the cutting mechanism drive; the frequency converter (FC) of the supply voltage, which changes the rotation speed of the SCIM (the rotation speed of the milling cutter); and the milling cutter of the chopper. The shaping filter method was used, to predict the size of the meat chips produced, to modulate the perturbation acting on the system from the load side. Based on the single-stage chopping of raw meat, an automatic line is created for producing meat products, with a minced meat quality management system based on artificial intelligence on the principle of 'unmanned technology'.

Keywords: automation of sausage production; innovative approach; minced meat production; machine control

INTRODUCTION

In the technology of meat and meat product processing **(Lisitsyn et al., 2004; Zajác et al., 2015; Herrero et al., 2008)**, it is noted that the structural and mechanical properties are determined largely by the particle size of the chopped raw material, i.e. the degree of chopping. It is also noted that with the help of structural and mechanical properties, it is possible to control the technological parameters of raw materials and minced meat, and the product quality at any stage of the technological process of minced meat preparation, as well as the texture of finished products.

To obtain ready meat products with specified characteristics, first of all, it is necessary to prepare minced meat under rational chopping modes. The duration of chopping (τ_k, s) depends on the type of chopping machine (its geometric and kinematic parameters) and is determined by the following equation **(Kosoj, Malyshev and Yudina, 2005)**:

$$\tau_\kappa = A_1 K_p \left[exp(0.326 K_{vd} + 0.35)\right] \Omega^{-1} \quad (1)$$

Where A_1 is a coefficient equal to 1×10^5 m^3.(kg.s)$^{-1}$; K_p is a coefficient that takes into account additional cutting of the product due to the pressure in the cutting chamber; K_{vd} is the ratio of protein and fat in the meat; and Ω is the generalizing kinematic characteristics of the chopping machine determined by the following dependence:

$$\Omega = f_0 \frac{W_n^2}{W_f}, \quad m^3/\left(kg \cdot s^2\right) \quad (2)$$

Where: f_0 is the cutting capacity of the machine equal to $f_0 = z n_n F_d / 60 m_f$ m^2/(kg·s) in which z is the number of knives in the cutting tool; n_n is the frequency of blade rotation; F_d is the cross-sectional area of the minced meat layer made with a knife in one revolution, m^2; and m_f is the weight of minced meat, kg. W_n is the circumferential rotation speed of knives at their greatest radius r_n, equal to $W_n = 2\pi r_n n_n / 60$ m.s^{-1}; and W_f is the feed rate of minced meat to the cutting mechanism along the axis of knife rotation, m.s^{-1}.

Machine control of the single-stage chopping mode of initial frozen meat raw materials will allow rational management of the entire technological process on an automatic line developed for sausage production. In this regard, the purpose of automatic control of chopping raw materials by the rotary cutting method can be formulated as follows: 1) it shall maintain a predetermined degree of chopping of the raw meat under the conditions of raw meat structural heterogeneity and textural features; 2) it shall calculate while chopping the forecast changes in meat particle (meat chip) size by means of an automatic control system (ACS) for the technological process. To achieve these goals, it is necessary to solve the task of ACS synthesis. For this purpose, it is necessary to choose the structure of the system, its elements, and the topology of cause-and-effect relations between them; and to develop algorithms for the control devices and values of their parameters, for example, regulator settings **(Pupkov et al., 2004b; Shaykhutdinov et al., 2016; Yao et al., 2010; Zhou and Wang, 2012; Balejko, Nowak and Balejko, 2012)**.

Frozen meat cut with cutters shows significant differences to that cut with some traditional materials (metals, wood, plastics) – significant heterogeneity of the structural and textural characteristics of frozen meat raw materials affects the quality of chopping **(Kapovsky et al., 2017; Lisitsyn et al., 2016, Lisitsyn et al., 2017; Kapovsky, Zakharov and Nikitina, 2019)**. Different amounts of ice (water) in frozen meat at different storage temperatures and the presence of fat and connective tissues are the structural signs of its heterogeneity. When cutting frozen meat blocks, the quality of chopping is affected by the different orientation of muscle fibres in the mass of the product block in relation to the cutter blades, which is a textural sign of the heterogeneity of the raw material.

The impact of influence factors on the raw materials chopping degree by the rotary cutting method is random due to the above-noted heterogeneity of raw materials. For example, when the cutting blade of the milling cutter is positioned longitudinally to the bundle of fibers in the muscle tissue, the width of the cut layer of meat will be bigger in comparison with the transverse positioning of the same fibers. The orientation of the cutting edge of the chopper working blade during the chopping in reference to individual pieces of meat in the frozen block of raw materials is determined by their random arrangement after molding and freezing in a freezer mold. Taking into account the peculiarities of the meat block topology, it is advisable to analyze statistically the size of meat chips of minced meat obtained in result of chopping experimental blocks of frozen raw materials with cutters of different designs and geometry. The data of statistical analysis will allow defining the regularities of the meat chips size of as a random process, which numerical parameters are determined by the operating parameters of the raw materials chopping (speed of chopping and rate of feed of a block of frozen meat into the chopping zone) and the used chopper blade.

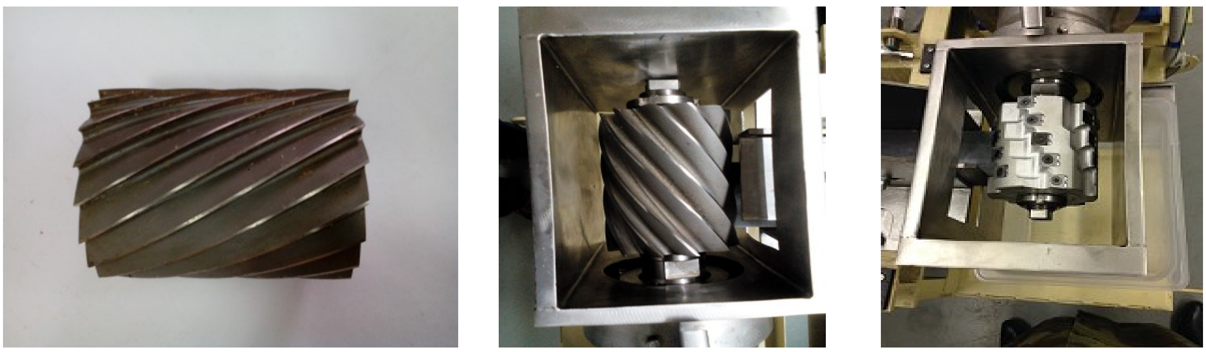
Scientific hypothesis

Let's assume the formation of the chip size as a random process, ACS shall be arranged to calculate the predicted values of the numerical parameters estimates (expected mean and variance) of the statistical distribution of the typical particle size of the chopped meat to determine the parameters of its further processing on an automated line. The specified forecast must correspond to the specified accuracy and reliability, determined by the requirements applied for the manufactured meat products. The calculation by ACS of the predicted value of the typical size of meat chips shall be based on imitating of the mathematical modeling of one-stage chopping of raw frozen meat with a multi-blade chopper tool.

MATERIAL AND METHODOLOGY

To study the single-stage process of frozen meat block cutting by cutters, the following experimental installation IBF-1 (meat block chopper with rotary cutting modification 1) was created. The unit was equipped with cutters of different designs and geometries (Figure 1).

The parameters of the cutting conditions (cutting speed of the rotary cutter and feed rate in the chopping zone) were set by the appropriate settings of the supply voltage frequency converters which work on the electric motor drives of the cutting and feeding systems of the IBF-1 installation. Experimental blocks of frozen meat preliminary cut from industrial-size blocks (second-grade beef and semi-fat pork) were chopped on the experimental installation. In accordance with **GOST R 54704 (2011)** 'Frozen blocks of trimmed meat', the mass fraction of connective and fat tissue in beef was 20% or less; in pork it ranged from 30% to 50%. The temperature of the meat in the centre of the experimental unit before chopping was -12 to -14 °C.



a b c

Figure 1 Rotary cutters, components of chopper IBF-1. Note: a – cylindrical rotary cutter according to **GOST 29092 (1991)**, type 1 (solid), version 1 (fine tooth), with an external diameter of 100 mm, inner diameter of 40 mm, length of 125 mm, and 18 teeth; b – cylindrical rotary cutter according to **GOST 29092-91**, type 1 (solid), version 2 (with large teeth), with an external diameter of 100 mm, inner diameter of 40 mm, length of 125 mm, and 12 teeth; c – rotary shaft-mounted cutting planer with TM21M EEC carbide inserts (Freud, Italy) with an external diameter of 100 mm, inner diameter of 30 mm, and length off 100 mm.

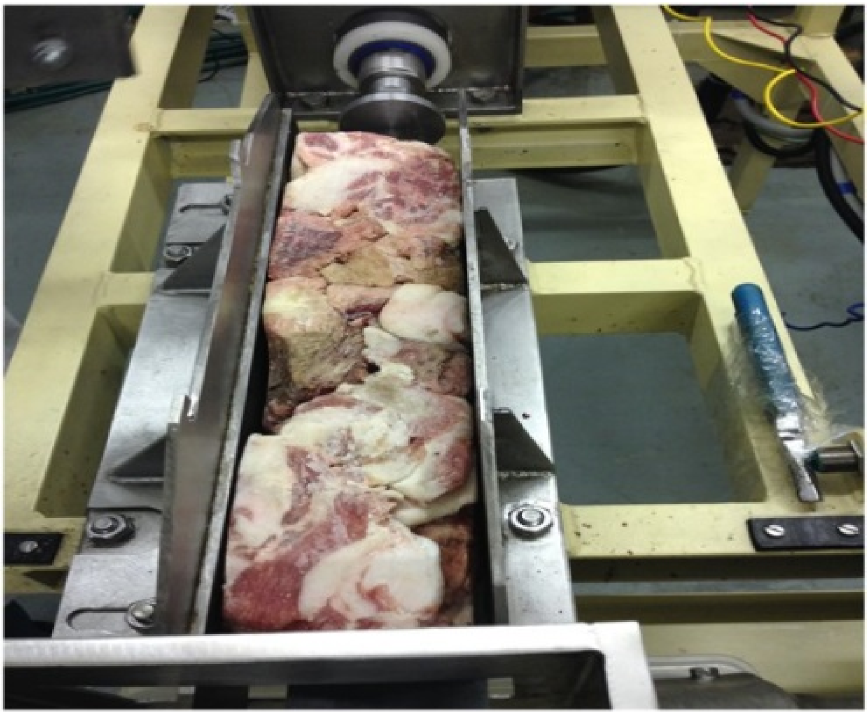


Figure 2 Experimental frozen meat block placed in the guide chute of the IBF–1 chopper.

The placement of the experimental frozen meat block in the guide chute of the IBF-1 chopper is shown below in Figure 2.

The blocks were moved to the rotary cutter by the action of the chopper feeding mechanism’s rod, with a preset feed rate along the guide planes. The guiding planes of the IBF-1 working chamber were installed and fixed in accordance with the dimensions of the experimental blocks of frozen meat. The chopped meat was extracted from the collection tank and subjected to microstructural studies carried out in accordance with **GOST 31479 (2012)** ‘Meat and meat products.

Method of histological identification of the composition’. Histological preparations were made on a MIKROM HM 525 freezing microtome. The plane sections were studied using an Axio Imager.A1 light microscope (Carl Zeiss, Germany) using computer software for image analysis. The active power consumed by the electric drive of the installation’s cutting mechanism in the operation mode was measured and recorded by an AFM-3192 industrial analyzer-recorder.

Statistical analysis

STATISTICA 10.0 software was used in this study for the statistical analyses. The results were calculated as "middle-value ±standard error" (M ±SE). The statistical distribution was equalized with the application of the theoretical (normal) distribution. The equalization was performed by Pearson's criterion **(Book, Velleman and Veaux, 2007; Greenwood and Nikulin, 1996)**. Differences with p-values less than 0.05 were considered as statistically significant.

RESULTS AND DISCUSSION

Figure 3 (a, b, c) shows the microstructure of minced meat chopped by obtained by the chopper IBF-1 with the rotary cutters in which technical characteristics are given above.

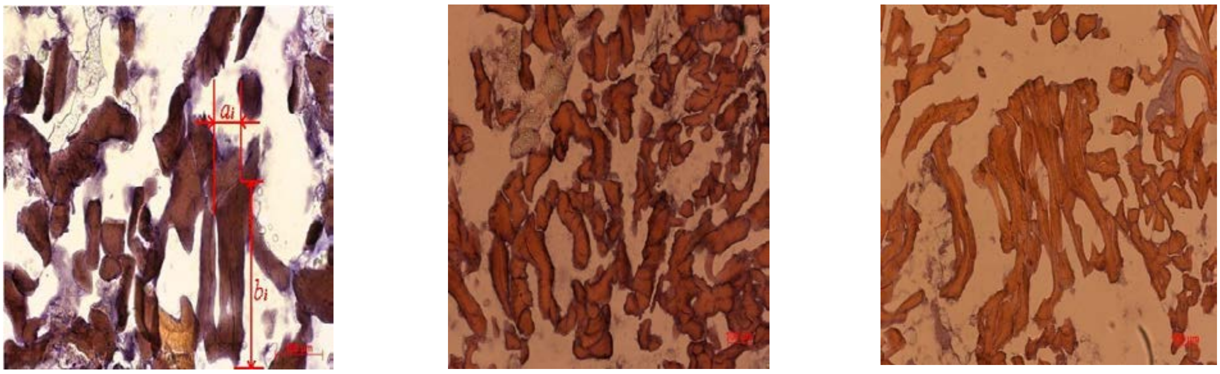
The meat chips size obtained from a certain type of rotary cutter and the applied cutting mode of raw materials were statistically analyzed in the following sequence:

1. The data of microstructural analysis of minced meat was grouped into statistical series (Table 1); **(Gaidyshev, 2001; Lagutin, 2007; Protasov, 2005)**.

If the thickness of the meat chips hits between two adjacent ranges, then the number of hits is divided equally between these ranges **(Gaidyshev, 2001)**. The frequency of hits in the range is defined as the quotient between the number of hits in this range and the total number of meat chip thickness measurements. The average value of the meat chips thickness in the range is determined as the arithmetic mean of the measured data for this range.

2. Using the data given in Table 1, the numerical distribution of the meat chips thickness was presented as a histogram according to the selected ranges of the values (Figure 4).

3. By dividing of every frequency of hit into the *i*-th range p_i^* on the stretch of every appropriate range $\Delta_i = a_{i+1} - a_i$, where a_{i+1} and a_i are the selected limits of the range, we get a table of frequency densities f_i^* (refer to the table 2), by which the histogram of the frequency density distribution f_i^* was built according to the range of values of the meat chips thickness (Figure 5); **(Gaidyshev, 2001; Lagutin, 2007; Protasov, 2005)**.



a b c

Figure 3 Microstructure of the minced meat. Note: a – chopping of beef with a fine teeth cutter, refer to the thickness of meat chips, width of meat chips; b – chopping of pork with a large teeth cutter; c – chopping of beef with hard metal rotary cutter.

Table 1 Grouped statistical series of the meat chips thickness measurements.

Range and its limits, um	The value of the meat chip thickness within the range	Frequency of getting within the range p_i^*	Average thickness of meat chips within the range a_{isr}, um
Range 1; 14 – 20	13	0.062	16.92
Range 2; 20 – 26	16.5	0.078	23.58
Range 3; 26 – 30	18.5	0.088	29.56
Range 4; 30 – 35	22	0.104	32.31
Range 5; 35 – 40	28	0.133	37.26
Range 6; 40 – 45	25	0.119	42.34
Range 7; 45 – 50	26	0.123	47.43
Range 8; 50 – 55	15	0.071	52.27
Range 9; 55 – 60	18	0.085	57.40
Range 10; 60 – 66	12	0.057	62.61
Range 11; 66 – 76	8	0.038	70.77
Range 12; 76 – 91	7	0.033	83.50

The presented statistical analysis refers to beef chopping with a fine-tooth rotary cutter at a rotation frequency of 2,289.14 min^{-1} and a rate of meat block feed per cutter = 0.0243 $m.s^{-1}$. The experimental data were used to calculate the estimates of the sample mean values of the thickness and width of meat chips $a^*_{average}$ and $b^*_{average}$, as well as estimates of the standard deviations of the thickness and width of meat chips σ_a^* and σ_b^*.

In the considered case the values of these parameters were as follows: $a^*_{average}$ = 42.28 um and $b^*_{average}$=166.64 um, σ_a^* = 15.86 um, σ_b^* = 90.48 um. In the same way we calculated the same parameters of the experimental distributions obtained when the rotary chopper IBF-1 was equipped with the other types of cutters and the certain cutting mode for raw materials was used. In particular, when equipping the chopper with a large-teeth cutter, the parameter values were: $a^*_{average}$ = 118.99 um and $b^*_{average}$=495.28 um, σ_a^* = 61.15 um, σ_b^* = 245.57 um; the rotary cutter speed = 2,289.14 min^{-1}; rate of the meat (pork) block feed per cutter = 0.0243 $m.s^{-1}$. When equipping the chopper with hard metal plates cutter, the values of the parameters were: speed of the cutter rotation = 2.033.50 min^{-1}; rate of the meat (beef) block feed per cutter = 0.0243 $m.s^{-1}$.

Calculations show that the experimentally obtained statistical distribution of the meat chips thickness is equalized with the help of the theoretical (normal) distribution. The equalization was performed according to Pearson's criterion **(Kobzar, 2006)**. It shall be noted that the mathematical expectation of the distribution of the specified values very well correlates with the supply of raw materials to the cutter tooth. At the same time, the statistical distribution of the meat chips width does not comply with the Gaussian law. This is explained by the prevailing influence of the cutting edge track on the chips width distribution when the rotary cutting edges of the cutter teeth slide on the surface of the meat block **(Book, Velleman and Veaux, 2007; Greenwood and Nikulin, 1996)**. The size of the track varies widely every moment of the chopping process for every tooth of the rotary cutter, while simultaneously taking part in the raw material chopping. This fact is proved by sweeping the lateral surface of a cylindrical rotary cutter with a helical tooth on the cutting surface of the meat block. Thus, to reduce the dispersion of the resulting width of the meat chips, it is necessary to use the rotary cutters with fragmentation of the rotary cutting edges into the equal sized segments (so called "corn-shaped" rotary cutters), which will equalize the width of the meat slices being cut off with all teeth of the rotary simultaneously during the operation.

The moment of resistance to chopping, i.e. the load on the cutter in the operating mode, varies significantly in magnitude. This is caused by the significant heterogeneity of the initial raw material as noted above. When changing the load on the milling cutter in the operating mode, the frequency of its rotation changes, which leads to additional dispersion of the linear dimensions of the meat chips due to changes in the parameters of the cutting mode (its feed into the rotary cutter tooth and cutting speed of the raw materials). This factor of influence on the degree of meat chopping reduces the homogeneity of the minced meat produced, which leads to a decrease in the quality of the meat products **(Thalhammer, 1998)**.

Given this, it is necessary to ensure the stabilization of the parameters of the meat-cutting mode by means of an ACS for the chopping process in the operating mode of the cutter. The use of automatic control of a single-stage technological process of minced meat production is shown in the example of a line developed for the production of sausages (Figure 6).

When implementing this project, we set the task not only to improve the technological process of cutting frozen meat raw materials through the use of a new method of chopping by the milling method, but also to ensure the production of minced meat of a preset quality on an automatic line.

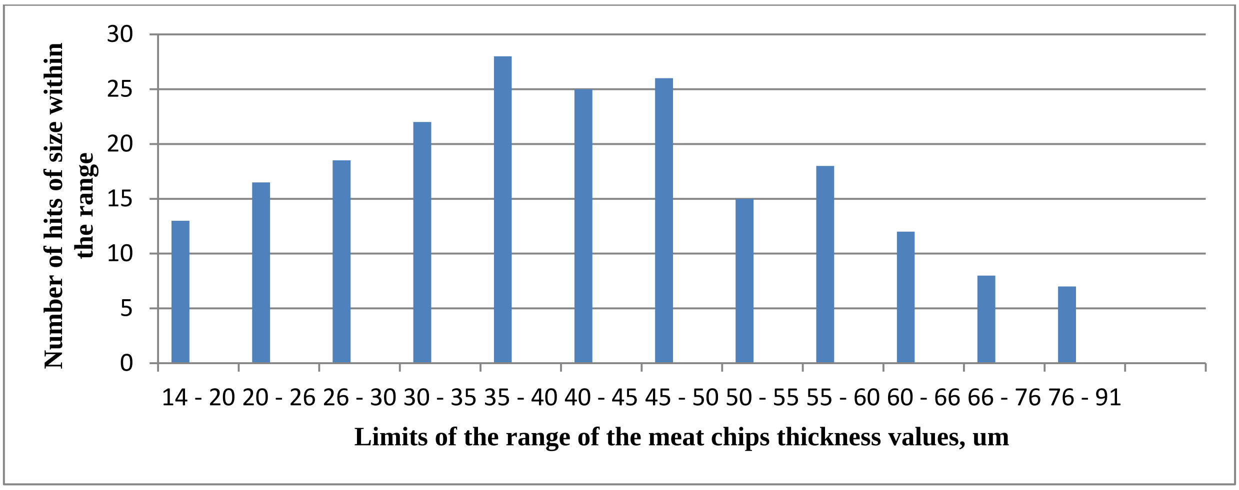


Figure 4 Histogram of the numerical distribution of hits of the meat chips thickness in the selected range of its values.

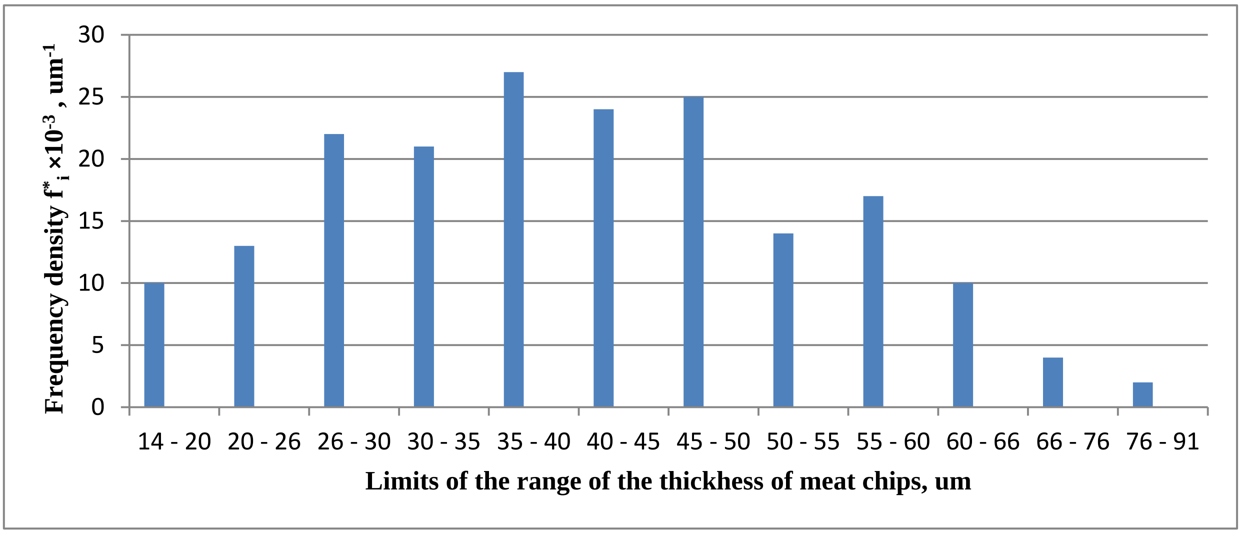


Figure 5 Histogram of the frequency density distribution fi * of the meat chips thickness hitting into the range of its values.

Table 2 Frequency densities f_i^* by range of values of the meat chips thickness.

Range $\boldsymbol{a_i}$, um	14 – 20	20 – 26	26 – 30	30 – 35
Frequency densities $\boldsymbol{f_i^*}\times10^{-3}$, um^{-1}	10	13	22	21
Range $\boldsymbol{a_i}$, um	35 – 40	40 – 45	45 – 50	50 – 55
Frequency densities $\boldsymbol{f_i^*}\times10^{-3}$, um^{-1}	27	24	25	14
Range $\boldsymbol{a_i}$, um	55 – 60	60 – 66	66 – 76	76 – 91
Frequency densities $\boldsymbol{f_i^*}\times10^{-3}$, um^{-1}	17	10	4	2

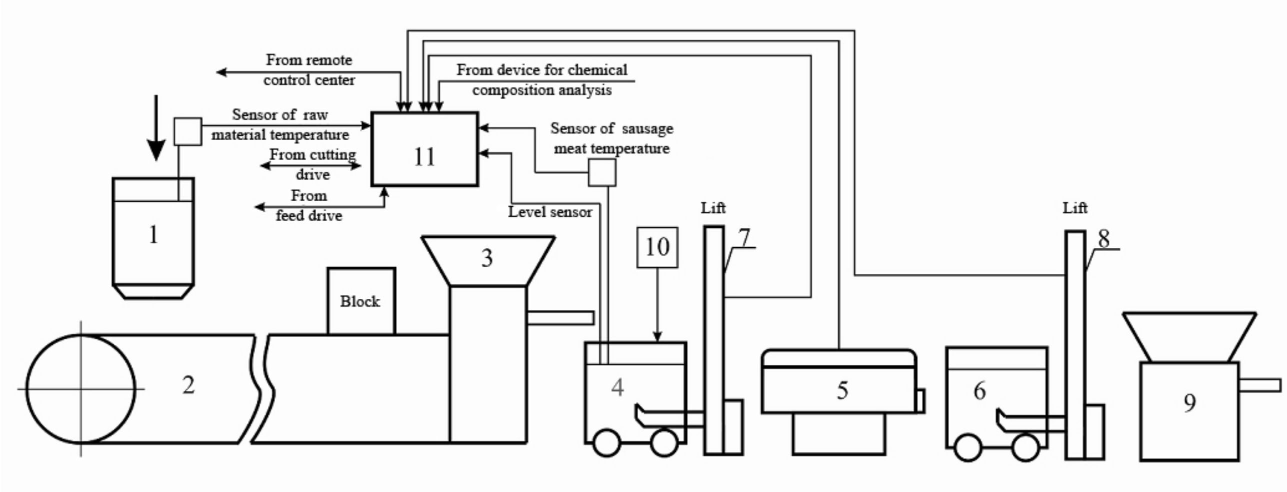


Figure 6 Automatic line for sausage production. 1 – instrument for input control of raw materials; 2 – conveyor belt; 3 – rotary cutter for meat chopping; 4 – storage and dispenser tank; 5 – minced meat mixer; 6 – trolley; 7, 8 – elevators; 9 – filling machine (syringe); 10 – device for analysis of the chemical composition of the chopped meat; 11 – control system computer (CSC).

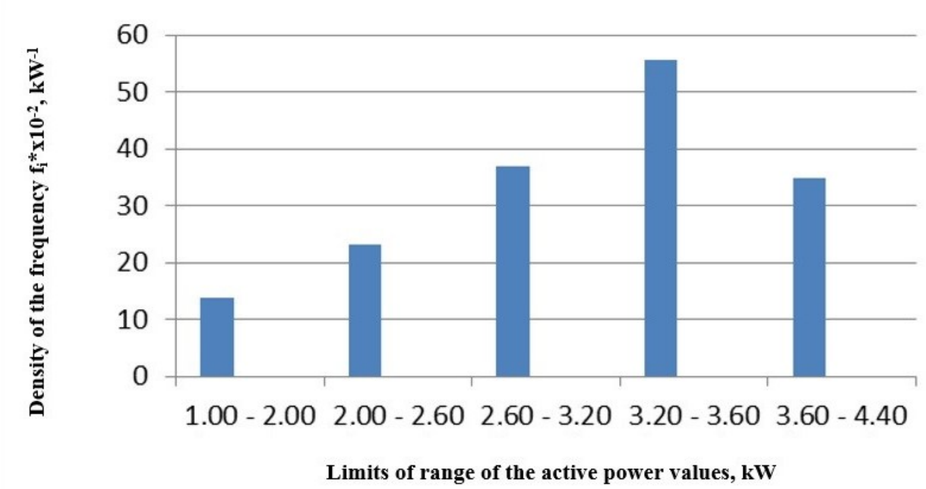


Figure 7 Histogram of the frequency density of the power distribution consumed by the electric motor of the rotary cutting mechanism drive in IBF-1 installation, operating mode, according to the range of its measured values.

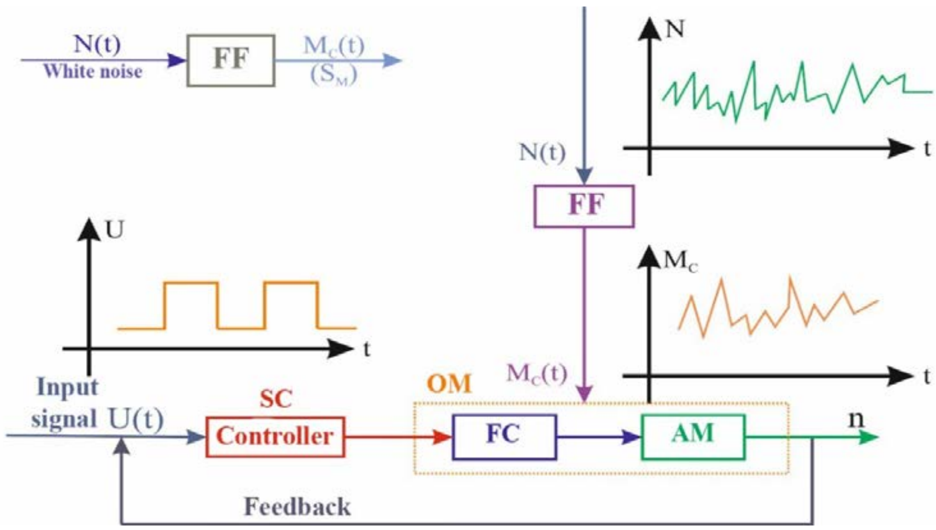


Figure 8 Automatic control system synthesis. OM – the object of management; FC – frequency converter, changing the rotation of the rotary cutter; AM – asynchronous electric motor of the drive on the cutting unit of the chopper; N(t) – white noise; U(t) – input signal (cutting speed setting of the raw material); FF – forming filter; SC – speed controller (frequency) of rotary cutter rotation; Σ – summarizer; n – frequency of the rotary cutter rotation.

To solve this problem, the line is equipped with a storage and dispenser tank, in which the required amount of chopped raw materials of each type (beef, pork, fat) is measured in accordance with the recipe of the finished product. The line also has equipment for monitoring the chemical composition of chopped meat (protein, fat and moisture content) in the production flow in real-time mode. In the process of mixing minced meat in the mixer, its viscosity is controlled by the appropriate sensor and the pH of the minced meat is also measured; water and other components provided by the recipe are dosed and added. The measurement data are sent to the control system computer (CSC – industrial computer), which controls the technological process of producing sausages on the automatic line.

The presented statistical analysis (Figure 7) refers to a beef chopping with a fine teeth rotary cutter at rate of 2.289.14 min^{-1} and a feed rate of a meat block per cutter = 0.0243 $m.s^{-1}$. When constructing the ACS as technological process with the function of stabilization of the operating parameters of one-stage chopping, we can assume that the random process of loading on the cutter is a stationary process with the ergodicity property. This means that any realization of a stationary random process of certain duration represents to a sufficient degree the entire set (ensemble) of realizations of the process considered.

Taking into consideration the normal law of load distribution on the rotary cutter during the chopping process, for mathematical modelling of this disturbance (M_c in Figure 8) it is expedient to use the forming filter (FF) method **(Pupkov et al., 2004c)**.

The FF method is based on the fundamental property of a random stationary process passing through a linear system, which can be expressed as follows **(Gaidyshev, 2001; Kobzar, 2006)**:

$$S_{y(\omega)} = \left|W_{ff(j\omega)}\right|^2 \cdot S_{x(\omega)} \quad (3)$$

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

We will consider white noise as a random process at the input. White noise in the theory of stochastic processes (TSP) is understood as the limiting case of a sequence of very short pulses, the amplitude of which is an independent random variable value with a very large dispersion, and the ratio of the dispersion of these pulses to the frequency of their appearance is a constant (finite) value **(Gaidyshev, 2001; Ivashov et al., 2018)**. From the definition of white noise, it follows that the spectral density of the input random process is constant through the entire frequency range and is equal to:

$$S_x(\omega) = S_0 = const$$

If we assume S_0 = 1, then formula (3) will have the following form:

For synthesis of the ACS technological process on the proposed line (in particular solving the task of predicting the size of meat chips in the chopping process), it is necessary to take into account the impact on the rotary cutter from the load side. To do this, it is necessary to develop a mathematical model of the load on the rotary cutter in the process of chopping raw materials. The data obtained during the experiment and processed by methods of mathematical statistics give reason to assume, in the first approximation, the normal law of load distribution on the rotary cutter when chopping industrial-size blocks of raw materials. The experimental statistical distribution of consumption of active power of the cutting mechanism IBF-1 in the chopper drive (Figure 7) is equalized with the help of the theoretical distribution according to the Gaussian law.

$$S_y(\omega) = \left|W_{ff}(j\omega)\right|^2 \cdot S_x(\omega) = \left|W_{ff}(j\omega)\right|^2 \cdot 1 = \left|W_{ff}(j\omega)\right|^2 \quad (4)$$

Thus, in order to realize a random process with a given statistical characteristic, i.e. a given spectral density $S_y(\omega)$, we must send the white noise with a unit spectral density through a linear system with a transfer function $W_{ff}(j\omega)$. Such a linear system in the theory of automatic control is called a shaping filter.

Single-stage chopping control provides automatic maintenance of the set degree of chopping of raw materials while stabilizing the parameters of the cutting mode in real time. The ACS of the technological process on the developed automatic sausage production line has the features of an intelligent control system **(Pupkov et al., 2004a)**: 1) close interaction of the intelligent system's information with the environment when using information communication channels – in the case of control over the single-stage chopping of meat blocks, their temperature, the presence of foreign particles, and the weight of the units are controlled; 2) the availability of forecasts of changes in the external environment and their own behaviour – in this case, the system calculates the forecast amount of meat chips obtained by cutting of the raw materials with a multiblade tool; 3) improving intelligence and improving one's own behaviour – the system is trained in real time, updating the forecast amount of meat chips in the process.

The ACS algorithm (Figure 9) is characterized by the fact that, in addition to the statistical information obtained during chopping of a real block of meat about the change in cutting shaft speed under the influence of the chopping resistance moment, the CSC will have an additional volume of similar statistical information while computer modelling of chopping of 'virtual' blocks of meat.

This allows the CSC to calculate the point and interval estimates of the process under changing rotation speed of the chopper cutting shaft in the chopping process, and on their basis, according to the established analytical dependence, it can determine the same estimates for changing the characteristic size of the resulting meat chips with a preset statistical accuracy and reliability.

The CSC also calculates the variance of these estimates themselves, i.e. determines the degree of 'blurring' of the range limits which include the size of meat chips, which is important in the production of baby food.

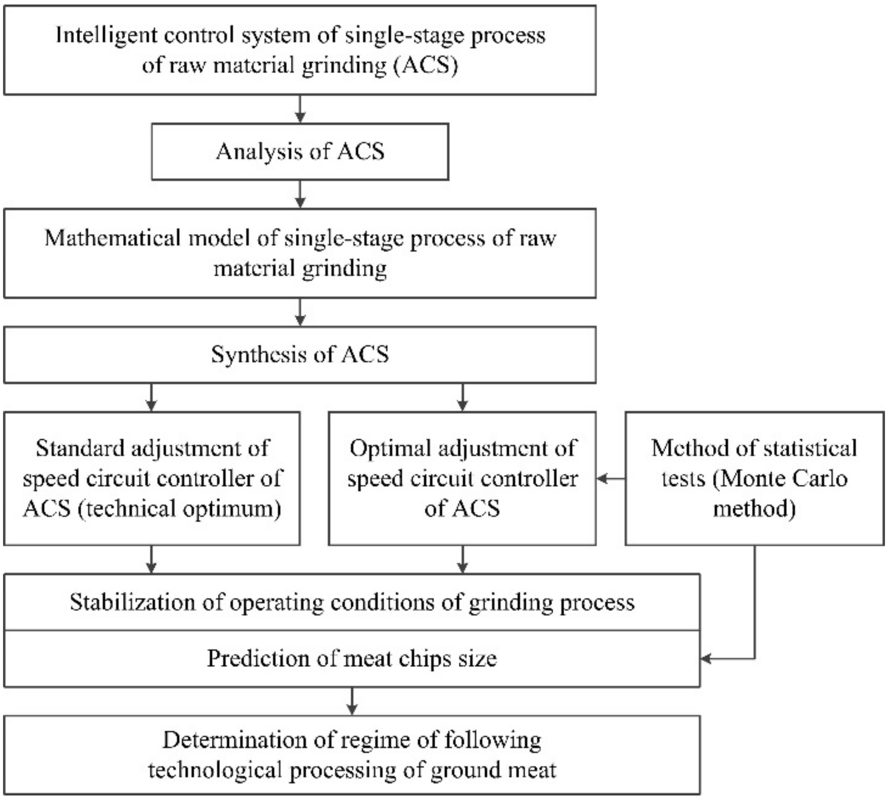


Figure 9 Block diagram of the development of an automatic control system (ACS) for a single-stage process of chopping of frozen meat raw materials.

In the process of real chopping of a block meat, the CSC accumulates and processes statistical information about the chopping process, i.e. the system is trained in the operating mode, improving its prediction of the degree of the raw material chopping. As a result of implementing the above algorithm, the control system will have statistical information about the degree of raw material chopping in an explicit (digital) form. The composition of the ACS may include equipment for rapid analysis of the chemical composition of chopped meat, as well as its temperature after chopping. Then, the further process of minced meat production can be controlled strictly as a function of time, excluding the subjective factor of assessing the degree of the final product readiness. This will allow acquisition of a finished product with a preset high quality.

CONCLUSION

In the proposed project for automatic sausage production lines, the technological chain is reduced in comparison with the traditional solution: instead of three meat-cutting machines: block cutting machine → the top → the cutter, only one is used – the rotary cutter for meat chopping. This significantly reduces the cost of operating meat processing plants engaged in the production of mass market products. Machine control of the minced meat produced for sausages at all stages of its production ensures high quality of the final product. Full automation of the technological process of minced meat production using the proposed control system opens the way to the design of automatic meat processing plants in the future.

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