ADAPTIVE CYBER-PHYSICAL SYSTEM OF THE MILK PRODUCTION PROCESS / *АДАПТИВНА КІБЕР-ФІЗИЧНА СИСТЕМА ПРОЦЕСУ ВИРОБНИЦТВА МОЛОКА*

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ABSTRACT

The basic principles of adaptation of machine milking technical system to the physiology of milk ejection of cows are considered. Main adaptation parameters and conditions of the technical system are grounded, under these parameters and conditions the self-tuning of technical system is possible. The structure of modules of adaptive cyber-physical control system of machine milking is developed, its functionalities are revealed, the method of coordination between discreteness of measurement of information and the quantization period is developed to ensure maximum reliability of the information. The memory size of the operational information about the process parameters is justified, as well as their structure and functional content. Functional content and structure of information about the technological process of the database is formulated. The general view of the main elements of the adaptive cyber-physical system of cows milking is given, as well as the results of work of the experimental adaptive cyber-physical system of the milk production.

РЕЗЮМЕ

Розглянуто основні принципи адаптації технічної системи машинного доїння до фізіології молоковіддачі корови. Наведено основні параметри адаптації та умови за яких можливе самонастроювання параметрів технічної системи. Приведена структура модулів адаптивної кібер-фізичної системи керування технологічним процесом машинного доїння, розкриті функціональні можливості, наведено методику узгодження між дискретністю вимірювання інформації і періодом квантування для забезпечення максимуму достовірності інформації. Обгрунтовано розмір пам'яті оперативної інформації про параметри процесу, їх структуру та функціональний зміст. Наведено функціональний зміст та структуру інформації про технологічний процес бази даних. Наведено загальний вигляд основних елементів адаптивної кібер-фізичної системи доїння корів, результати роботи експериментальної адаптивної кібер-фізичної системи процесу виробництва молока.

INTRODUCTION

The adaptive milk production system of the "man-machine-animal" biotechnical system functionally ensures the realization of the genetic potential of cow productivity through interaction with the technical system. The effectiveness of the system's adaptation depends on the parameters that ensure the quality and efficiency of performing the technological functions.

The milking machine, as the main executor of the milking technological process, adapts the technical system to the physiology of the milk ejection of the cow due to the vacuum pressure of the given parameters and the possibility of their regulation, control at a given level during milking of the cow (*Pirlo G., Abeni F., Capelletti M., et al, 2005*; *Pařilova M., Stadnik L., Ježkova A., 2011*). Pneumatic electromagnetic pulsator, milk concentration meter, microprocessor control unit and other electronic elements are a feature of the milking machine configuration of modified configuration and functionality (*Jędruś A., Lipiński M., 2008; Czarnociński F., 2008*; *Jędruś A., 2010; Juszka H., Tomasik M., Lis S., et all, 2011; Juszka H., Lis S., Tomasik M., 2011*).

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One of the important factors is the vacuum gauge pressure that directly forms the adaptation parameters of the machine-cow system. To assess the adaptation of the parameters of the milking system, the influence of technological and structural parameters on the operating modes of the system was analysed (*Lis S., Juszka H., Mendyk M., 2016*). Study of vacuum gauge pressure stability, depending on the method of regulation in a vacuum tube or directly in the milking machine (*Pazzona A., Murgia L., Zanini L. et al., 2003*) found that vacuum stabilization by the gravitational type regulator was more dynamic and constant time was twice lower than in the case of the automated system. Such a conclusion was also obtained by the results of study of pulsating vacuum gauge pressure regulators (*Dmytriv V.T. et all, 2017*). Also, oscillations of vacuum pressure were investigated by (*Reinemann D.J., Schuring N., Bade1, R.D., 2007*; *Skalska D., Nejman M., Wiercioch M., et all, 2013*), depending on: a) the configuration of the vacuum and milk tube systems (length of the pipelines, its diameter and other parameters affecting the loss of pressure); b) the rate of milk flow in the milk pipeline; c) the velocity of air in the vacuum pipe. The results of these studies have shown that with a decrease in the intensity of milk ejection, the vacuum pressure increases both in the vacuum and milk tubes and in the under-teat space of teat cups.

The analysis of the research has shown that the parameters substantiation of effective functioning of cows milking biotechnological system requires the development of a concept and methodology for system parameters optimizing and also for its component of the technical system. This is relevant and actual for improving the efficiency of milking machines.

MATERIALS AND METHODS

Concept of adaptive cyber-physical system of milk production

A significant variety of technological schemes of milk production processes forms the appropriate units of control and governing parameters depending on the variant of the technological process.

We propose fundamentally new electronic-mechanical elements of the modular type with the use of microprocessor technology. These elements are developed and integrated into an adaptive cyber-physical system (ACPS) in dairy livestock, which allows for executive, informational, monitoring and diagnostic functions. During the development of such a system, new approaches to the synthesis of mechatronic modules are realized with the possibility of autonomous functioning (using single-chip microcontrollers of K1816BE48 and AT8335 type (by Atmel) at the level of introspection of both the technical system and the biological object which interacts with the machinery. Also, the system has operating mode by the boundary parameters set by the central computer.

ACPS contains software and hardware modules. Software modules include programs for technological objects controlling, the databases formation and management and also simulation of qualitative and quantitative parameters of the technological process of machine milking. The hardware modules include the following already researched and tested modules that are controlled by a central computer: an automated milking machine (with microprocessor control, a thermo-anemometric measurer of milk ejection intensity, the ability to control the pulsation frequency and the ratio of cycles and vacuum-metric pressure, the ability of temperature measurement and electrical conductivity of milk); automated vacuum unit; modular type interface with ACPS system bus, through which the code number forms and adaptive milking machines are connected; automated individual distributor-dispenser of mixed fodders; system of pressure sensors. The general structural scheme of the ACPS of the proposed functional and hardware solution is shown in fig. 1.

According to the needs of the user, the functions of the ACFS are the following: 1) technological information collection, coding, transmission, processing and storage; 2) the database forming and managing; 3) management by technical means and modules; 4) solving of optimization tasks in the system of milk production; 5) the technological information giving on functional request of system modules.

The information functions of the system are ensured in the automatic mode: 1) collecting the information about the dynamics of cow's milk ejection intensity and its maximum value; 2) the value of individual one-time milking; 3) physical time of milking start, machine milking up and milking finish of the cow; 4) time of maximum milk ejection; 5) the temperature of milk of quarters of the udder; 6) electric conductivity of milk; 7) the frequency of pulsation and the ratio of cycles; 8) vacuum pressure in the under-teat space of teat cups; 9) vacuum gage pressure at technological points of the vacuum line and control of the vacuum system; 10) control of the milk pump; 11) collecting information about the condition of the milk filter; 12) collecting the information about milk temperature at the outlet of the cooler and control of the cooler; 13) collecting the information about the washing process of the milking machine and washing process control; 14) transfer of data to the individual meter-dispenser of mixed fodder; 15) coding the processed information according to the cow number; 16) formation of a database and knowledge, supplementation of it with on-line information; 17) display of the information on the workplace of the machine milking operator.

Objects are surveyed in real time, according to the algorithm of the cyclic survey. Objects are not surveyed if they change the data with interruption (adaptive milking machine, signal of emergency state of the *n*-th object). To implement such an algorithm, the interface is created for receiving and transmitting the data from sensors, as functionally independent elements, and the structural chart of this interface is shown in fig. 2. A structural chart of an adaptive milking machine as to the ACPS is shown in fig. 3.

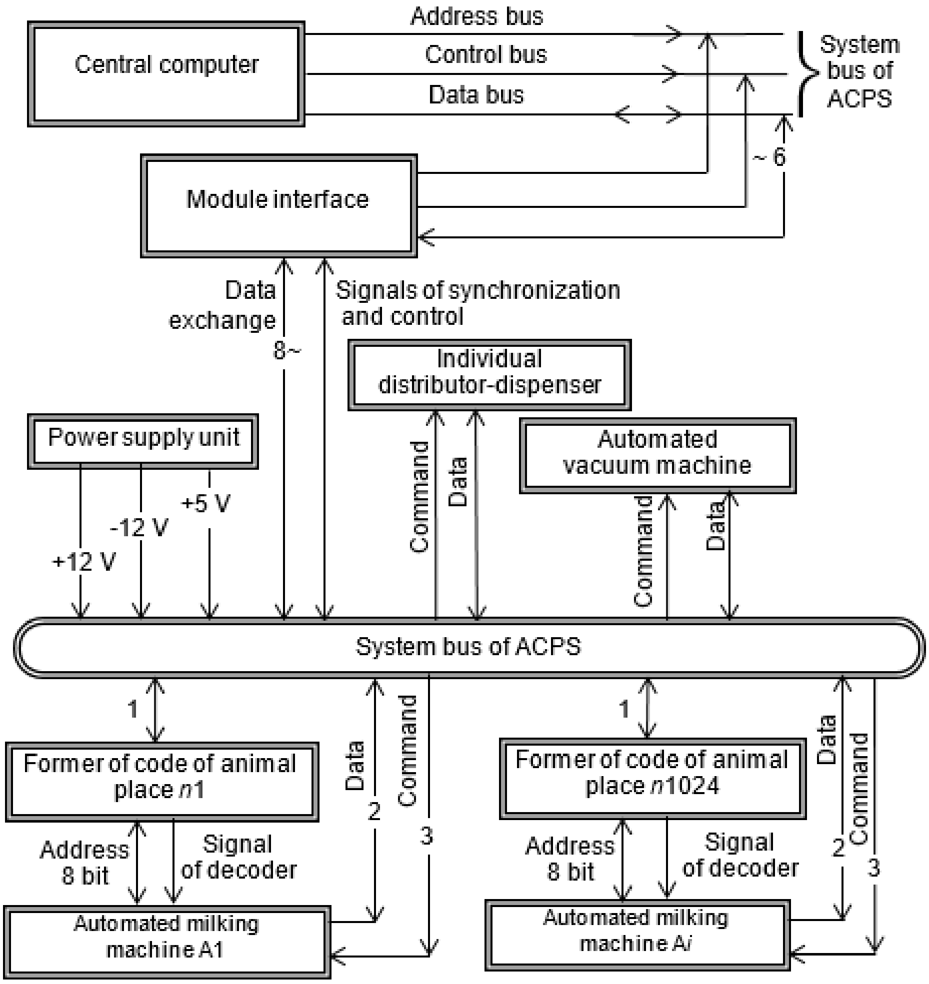

Fig. 1 – Structural scheme of adaptive cyber-physical system of milk production

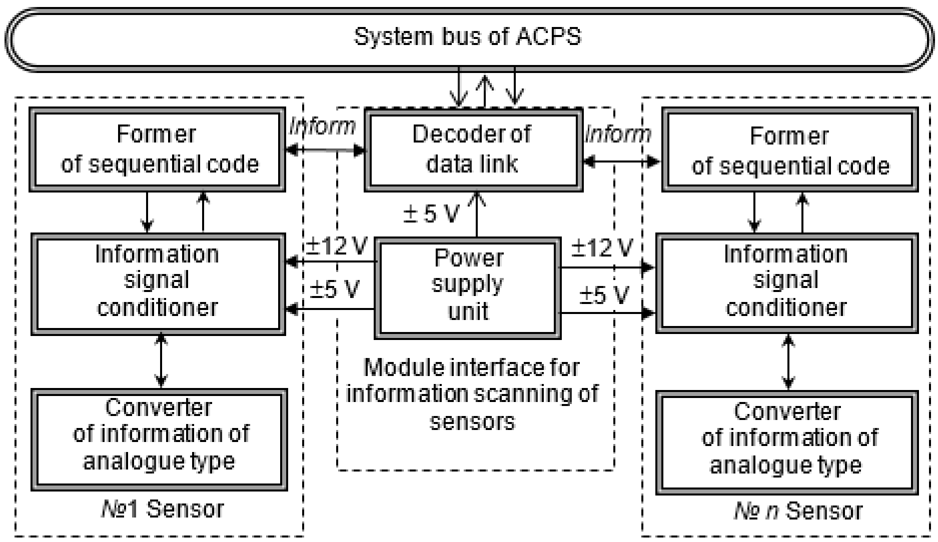

Fig. 2 – The structural chart of the interface for receiving and transmitting the data of ACPS sensors

To implement the operational control of integral characteristics of milk quality the single-frequency express analyser is designed on the principle of dielcometer measuring device of conductivity with modulation of the measuring resonant circuit parameters and the use of a layer-covered insulation of sensors-electrodes of the scattered field. The measuring converter provides important information during the operation of the milking machine. Functional scheme of the measuring converter is shown in fig. 4.

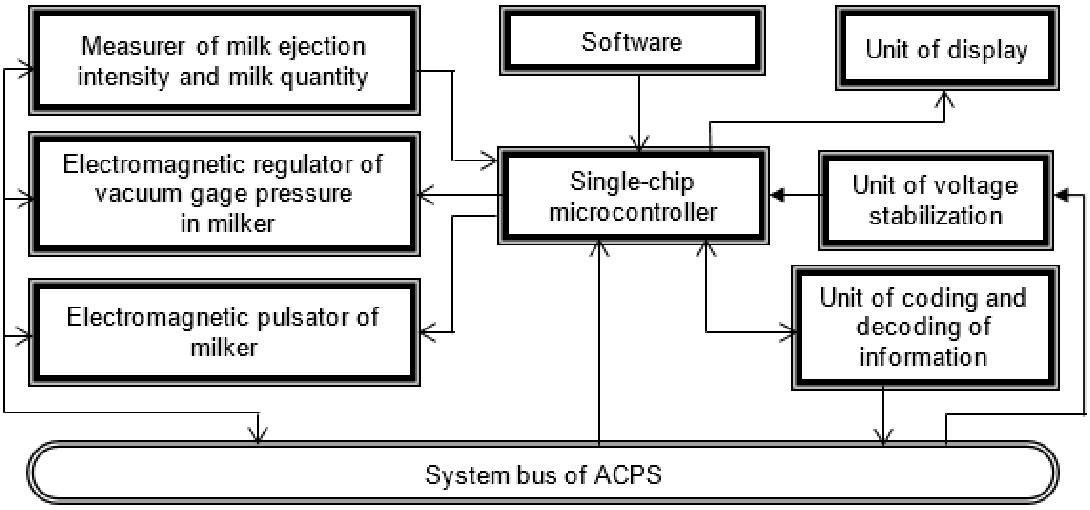

Fig. 3 – The structural chart of an adaptive milking machine as to the ACPS

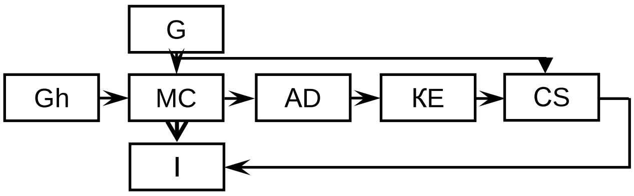

Fig. 4 – Functional scheme of the measuring converter of conductivity of ACPS

Gh – high frequency pulse generator; G – grid; MC – measuring circuit; AD – amplitude detector; KE – key; CS – coincidence scheme; I – integrator

The peculiarity of the circuit is that the elements are always in dynamic equilibrium mode, and the integrator output voltage is a measure of the actual capacitance of the sensor and, accordingly, the measured conductivity of the medium.

Algorithmization and firmware (soft hardware)

The adaptive cyber-physical system of the milking process provides control and management of the basic technological information about the milk ejection process as well as the state of the machine-animal system in the milking process. For research, an adaptive milking machine with feedback about the cow's milking process was used. According to the algorithm of operation of the pulsator, the feedback was carried out through a thermo-anemometric milk intensity measurer and a sensor of the vacuum gage pressure parameters in the inter wall and under-teat area of the teat cups. The electronic pulsator is controlled by a microcontroller that programmatically generates the f_p frequency and the digital pulse rate. Sensors were used to read the information as to vacuum gage pressure and ripple frequency. The pneumo-electromagnetic pulsator and the electromagnetic pressure regulator are controlled by the PID controller, which is implemented programmatically by the microcontroller.

Using an analog pressure sensor, the information as to vacuum gage pressure and ripple frequency was read. Data exchange was carried out using a bus shaper and an analog key. There is a galvanic isolation in the information lines of data changes with ACPS.

The card of functional distribution of memory cells of the RAM allocated area in the milking machine with microprocessor control is given in table 1.

Table 1

The card of functional distribution of memory cells for generating and storing operational information of the milking machine

16-th code of RAM cell number	Reference designation	PARAMETER
20	n	The cell of cow number forming
21	N	The physical counter
22	ΔM	Intensity of milk ejection
23	N_{start}	Physical time of milking start
24; 25	ΣM	Quantity of milk
26	M_{max}	Maximum intensity of milk ejection
16-th code of RAM cell number	**Reference designation**	**PARAMETER**
27	N_{max}	Physical time of occurrence of M_{max}
29	N_{finish}	Physical time of milking finish
2A	N_{1start}	Physical time of milking up start
2B; 2C	ΣM_i	Quantity of milk of the machine milking up
2D	M_{1max}	Maximum intensity of milk ejection of the machine milking up
2E	N_{1max}	Physical time of occurrence of M_{max1}
2F	$N_{1finish}$	Physical time of machine milking up finish
30	--	Complementary marker of the machine milking up
31	T_{finish}	Complementary marker of finish of the machine milking up
32	T_{max}	Maximum duration of milking
33; 34; 35; 36	t_i	Milk temperature by the quarters of the udder
37	$T_{aver.\ i}$	Average milk temperature
38	$T_{aver.-1}$	Average milk temperature of the pre measuring
39	δ	Electric conductivity of milk
3A	HELP	Indication of the existence of a mastitis
3B	f	Ripple frequency calculated
3C	F	Cycle ratio calculated
3D	P	Level of vacuum gage pressure

Adaptive control module with using the single crystal microcontroller is the main functional module that implements the adapted technological mode of the milking machine. Functional scheme of the adaptive control module with search (expert) self-tuning system is shown in fig. 5. For such a control scheme, the action of disturbing factors F(*t*) and control signals M(*t*) = X(*t*) is characteristic. The system operates these factors with the least error.

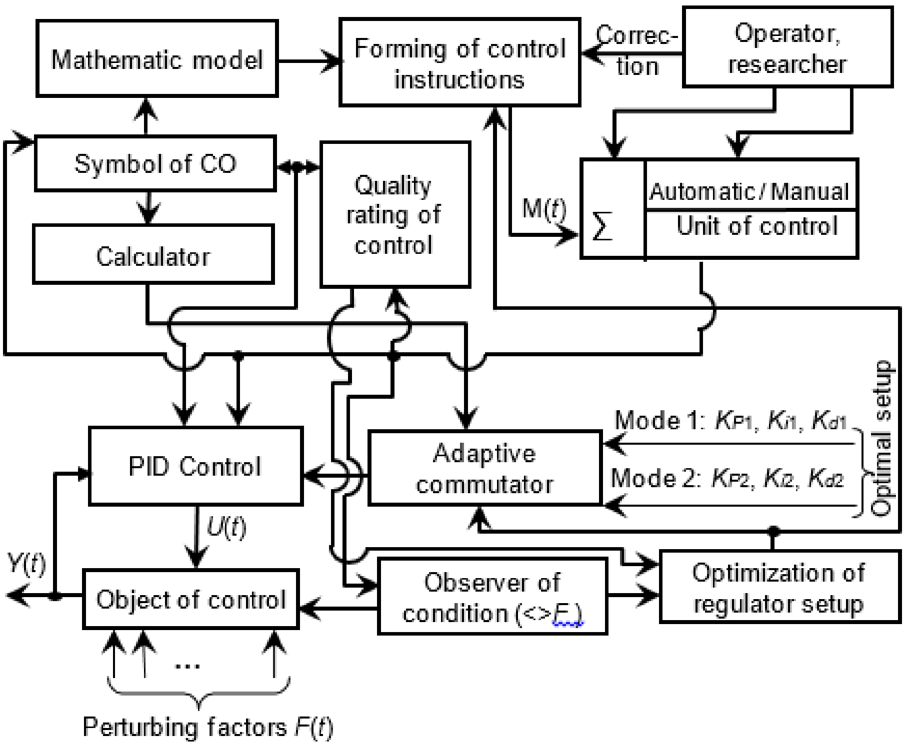

Fig. 5 – Functional scheme of the adaptive control module with search (expert) self-tuning system

The information about system status is collected in a cyclic survey mode. The sensors are interrogated periodically with a specified and clearly defined sequence that corresponds to real-time mode. Each survey cycle occurs at the same time intervals, which is limited by the ω_{max} cut-off frequency. The data of the *m* series of survey are processed according to a given algorithm. During the implementation of the data exchange algorithm, the procedure of algorithm-hardware correlation of external objects, the interface and the central computer was developed. This procedure enables to determine the duration of measurement and frequency of survey of external objects.

To improve the accuracy, the condition must be met:

$$m = 2^k ; \tag{1}$$

by the limitation of

$$m\Delta\tau_{meas.} \le T_0 ; \tag{2}$$

where T_0 – the period of quantization (measurement time); k = 0,1, 2, 3, … .

Therefore, the measurement discretion must be appropriate:

$$\Delta\tau_{meas} = \frac{T_0}{2^k} . \tag{3}$$

The second condition is to minimize the distortion of information during the quantization process. The T_0 quantization period was chosen on the condition that the $N[nT_0]$ discrete function most accurately reflects the $N(\Delta\tau_{meas.})$ continuous function. The faster the $N(\Delta\tau_{meas.})$ continuous function are changed, the T_0 quantization period should be the smaller, i.e. the more often the data is read. Depending on the spectrum of continuous function, we chose the T_0 quantization period on the basis of Kotelnikov's fundamental theorem for the theory of impulse systems. According to the theorem, the $N(\Delta\tau_{meas.})$ time functions, which do not contain harmonic components above the ω_{max} frequency, are completely determined by their values at the $[n T_0]$ moments of time that are spaced apart from each other with the period of:

$$T_0 = \frac{\pi}{\omega_{\max}} . \tag{4}$$

The quantization frequency must be selected according to the condition:

$$\omega_0 = 2\omega_{\max} . \tag{5}$$

In this case, the $N[nT_0]$ discrete function will accurately reflect the $N(\Delta\tau_{meas.})$ continuous function and there will be no loss of quantization information, i.e.:

$$N(\Delta\tau_{meas.}) = N\left| n\frac{\pi}{\omega_{\max}} \right| ; \tag{6}$$

The task of optimizing the quantization period is one of the fundamental problems of machine time optimizing, which is directly defined for each digital control loop. As T_0 is decreased, the accuracy of measurement and the PCs utilization are increased, but machine time is not economically used The longer the time period T_0, the reliability of information is decreased. Therefore, the problem of finding a compromise solution occurs in order to satisfy the conflicting requirements. Accordingly, the quantization period should be within:

$$\frac{\pi}{\omega_{\max}} \ge T_0 \ge \omega_{tp} , \tag{7}$$

where ω_{tp} – the ripple frequency of technological process pulse system;

ω_{max} – the frequency of the functional element operation (control, primary information means, etc.).

The minimum quantization period is determined by the formula:

$$T_{0\min} \le \frac{\varepsilon}{\left| \frac{dy(\Delta\tau_{meas.})}{d\Delta\tau_{meas.}} \right|_{\max}} , \tag{8}$$

where ε – the constant that characterizes the measurement accuracy:

$$\varepsilon \ge N(\Delta\tau_{meas.}) - N[nT_0]; \tag{9}$$

$\left| \frac{dy(\Delta\tau_{meas.})}{d\Delta\tau_{meas.}} \right|_{\max}$ – the maximum speed of function change.

After assuming $\Delta\tau_{meas.} = 1/T_0 \approx T_0$ and taking into account (9) the $N\varepsilon \approx 0$ is obtained. Between the function rate of change and the frequency of functional element operation, there is the following functional dependence:

$$\left|\frac{dy(\Delta\tau_{meas.})}{d\Delta\tau_{meas.}}\right| \approx \omega_{\max} \tag{10}$$

For a specific milking process, the value of ω_{tp} = 1 [Hz] and ω_{max} depend on the type of milking machine. In two-cycle automated milking machines with a variable ratio of suction and compression cycle, depending on the intensity of milk ejection, the frequency of functional element operation will be of 1.5 Hz $\leq \omega_{max} \leq$ 3 Hz. The quantization period will be within $\pi/1.5$ Hz $\geq T_0 \geq$ 1 Hz.

Protection of software bit rate exceedance is implemented by including in the data processing algorithm the backup cells and intermediate control. Hardware overflow protection is ensured by software and measurement time limiting.

The developed control system allows to exchange the information between 1024 subscribers in one second. The ACPS database consists of operational information that is placed in modules and stores data only for the period of its operation and permanent information, which is stored in the central computer and is changed due to the data of the operational database and calculations.

The database area for the *i*-th cow is calculated by the formula:

$$N_i = N_{start} + K_i\ (i\ -1), \tag{11}$$

where N_i – the start number of the memory area cell for the *i*-th cow;

N_{start} – the start number of memory cell allowed by user for the central computer;

K_i – the number of information parameters that need to be formed and stored;

i – the number of cow identification (number of cow or animal location).

Card of the functional distribution of selected area memory cells for *i*-th cow in the central computer database is presented in table 2.

The last three signs of mismatch of the cow's condition (Table 2) are entered by the machine milking operator from the milking machine's keyboard.

The quantities of milk per milking, milk quality, the time of milking, the intensity of milk ejection, the electrical conductivity of milk are integral indicators that characterize following the rules of milk production technology, and especially milking. These indicators are used as the main diagnostic indicators of ACPS.

Table 2

The card of cells functional distribution of database memory area per 1 cow, for generating and storing operational information of the machine milking ACPS

16-th code of cell number	Reference designation	PARAMETER
xx00	n	The cell of cow number
xx01; xx02	∑M	Milk quantity
xx03; xx04	∑Mi	Milk quantity of the machine milking up
xx05	T_{max}	Maximum duration of milking
xx06	$t_{aver.-1}$	Average milk temperature
xx07	δ	Electric conductivity of milk
xx08	HELP	Indication of the existence of a mastitis
xx09	Gcalc.	Calculated quantity of disposable mixed fodder
xx0A	---	Indication of the cow heat period
xx0B	---	Indication of the blood in the cow milk
xx0C	---	Other indication of the cow disparity

The reasons of deviations are analysed according to the algorithm with the output on the screen of the remarks to the administrator. Information row is entered by the milking operator from the console of the automated milking control unit or from the simplified console on the milking machine.

RESULTS

The proposed adaptive cyber-physical system of milk production process and in particular machine milking, is capable to implement the adaptive interaction between the animal and the machine, where milk ejection is a functional parameter. ACPS of milk production process consists of the following subsystems - information, analytical, control, visualization. Let us consider the functioning peculiarities of the developed system main components, as independent elements that can operate both autonomously and within the ACPS.

The experimental laboratory installation of the ACPS (Fig. 6) and individual equipment elements were developed. The nature of the cow milk ejection during the milking process was reproduced by a simulator (2) of milk ejection intensity (Fig. 6). The simulator allows creating a characteristic of milk ejection of different types of cows.

The milk ejection curve is described by the empirical dependence of milk yield on the milking time:

$$q = \frac{a \cdot t^b}{e^{ct}}, \quad (12)$$

where a, b, c – research coefficients for a given character of milk ejection curve; t – the time of milking, min.

The *c* coefficient characterizes the maximum milk ejection, *a* coefficient – the milk ejection and the time of milking. As *a* coefficient is increased, the milk ejection and milking time are increased as well. The b coefficient characterizes the rate of maximum milk ejection start. As the b coefficient is decreased (b = 1.2), the maximum milk ejection is simulated at the beginning of the first minute, as b = 2, the maximum milk ejection is simulated for the second minute from the beginning of milking. The results of the milk ejection curve simulation are shown in Fig. 7.

Fig. 6 – General view of the experimental laboratory complex of ACPS

1 – the reservoir of the milk simulator; 2 – the simulator of milk ejection intensity; 3 – teat cups; 4 – sensors of the pressure in the inter wall and under-teat area of the teat cups; 5 – sensor of the pressure in the milk hose; 6 – measuring device; 7 – the electronic module of milk ejection gauge; 8 – DAC-ADC; 9 – the control system (main computer); 10 – the system of data processing of the pressure sensors; 11 – the electronic module of data-measuring parameters visualization; 12 – blocks of regulated voltage; 13 – the pneumo-electromagnetic pulsator; 14 – the milk tap; 15 – the vacuum hose; 16 – the imitation of udder; 17 – the collector; 18 – the milk hose

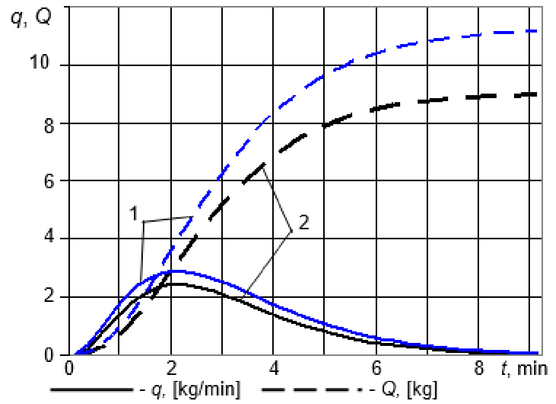

Fig. 7 – Graphs of simulation of *q* milk ejection intensity and *Q* milk quantity by simulator of milk ejection intensity during the cow milking period

1 – *a* = 5; *b* = 1.8; *c* = 0.9; 2 – *a* = 4.5; *b* = 2; *c* = 1

Vacuum pressure fluctuations, and in particular the vacuum pressure regulator, were studied using a sensor developed on the basis of the BMP180 sensor (*Dmytriv V.T., Dmytriv I.V., Lavryk Y.M. et all, 2017*). The general view of the sensor with the microprocessor control unit is shown in fig. 8.

Pneumo-electromagnetic pulsators of two types are developed and tested: micro pulsator for each milking cup and pairwise action (Fig. 9) with low power consumption, up to 6 W, variable pulsation frequency (shift between the cycles of pairs of milking cup is 0.2 sec.). The microprocessor unit (Fig. 10) with using of single-chip Atmel microcontroller ensures working algorithm of the central computer. The designed microprocessor unit realizes the following parameters - the step of changing the pulse rate of 0.1 [Hz], the ratio between the cycles of 0.25%, the step of phase shift of 0.1 sec.

General view of the rapid analyser of milk qualitative adjectives is shown in fig. 11.

Functional dependence of the differential sensitivity of the rapid analyser converter as to its execution variant is shown in fig. 12.

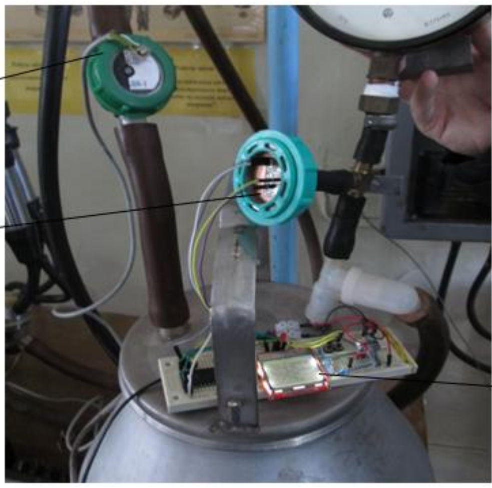

Fig. 8 – General view of the measurement system of vacuum gage pressure fluctuation

1 – the sensor vacuum gage pressure of the line type; 2 – the one-port vacuum gage pressure sensor; 3 – the microprocessor measurement unit

Fig. 9 – General view of the experimental pneumo-electromagnetic pulsator of pairwise interaction

Fig. 10 – General view of the microprocessor unit of the adaptive milking machine

Fig. 11 – General view of rapid analyser of milk qualitative adjectives

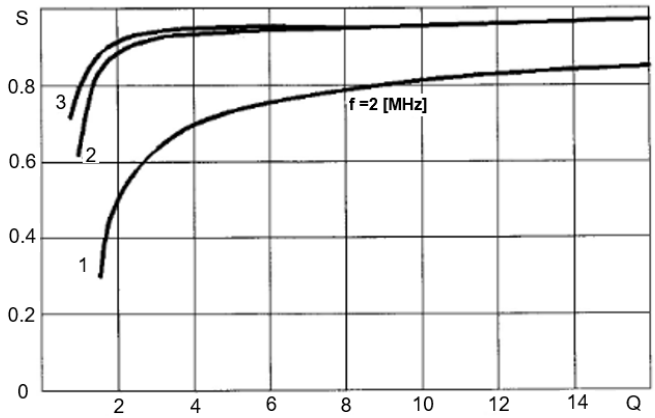

Fig. 12 – Dependence of the differential sensitivity of the converter on its Q-factor

1 – sensor with one-side electrodes (C_M = 32 [pF]); 2, 3 – sensor with electrodes of interspersed field at frequency of 2 and 5 [MHz] (C_M = 144 [pF] i C_M = 112 [pF])

The range of measurement of the Q-factor in the milk by sensors with isolated electrodes is in the range of 1-2, the differential sensitivity varying from 0.5 to 0.9.

CONCLUSIONS

The tried-and-tested adaptive cyber-physical milk production system with an adaptive milking machine with microprocessor control provides regulation of the pulsation frequency depending on the intensity of milk ejection, measures the conductivity of milk, regulates vacuum pressure and displays technological information. Studies of the time characteristics of the transient processes of adaptive milking machine operation with pneumo-electromagnetic pulsators and digital control have shown high efficiency, adaptation of the milking machine to the physiology of milk ejection of cows, stability of technological parameters and indices independence from fluctuations of vacuum pressure.

The use of digital control systems based on single-chip microcontrollers enables the implementation of digital controllers by programming microprocesses, which greatly simplifies the hardware. The optimal parameters for adjusting the regulators are determined in advance by mathematical dependence, which reduces the number of additional adjustments to the parameters of the regulators.

The quantization period of information parameters is chosen based on the frequency characteristics of the machine milking process and it is within 100 [Hz] $\geq T_0 \geq$ 10 [Hz].

Protection against software overflow is realized by entering into the data processing algorithm of backup cells and intermediate control. Hardware overflow protection is provided by software, limiting the duration of measurement.

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