Theoretical background for a robotic device designed for suckling piglets nursing

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Abstract. The pig industry in Russia annually ramps up production through the improved intensity, high prolificacy of sows, high average daily weight gain, low conversion rate, and high slaughter yield. From 2005 to 2019, the pig production volume increased by above 2.6 times and, according to forecasts, this trend will continue. The greater domestic production contributes to a reduction in the share of imported products, which at the end of 2019 was 2.4% maximum. Complete self-sufficiency in pork, pork offal and pork fat increased the export capacity of these products to roughly 100 thousand tons, with a forecast of 270 thousand tons by 2024. To achieve this indicator, however, requires the more effective use of animal genetic potential with a simultaneous decrease in production costs. A promising direction for addressing this challenge is to increase the number of weaned piglets per sow per farrowing. The current solving tools are various devices for manual and automated supplementary feeding of piglets. Their application, however, results in many stressful situations, the spread of gastrointestinal diseases and a drop in the overall litter weight. A robotic device is under development to avoid these implications and replace a sow completely and not merely provide a supplementary feeding of suckling pigs from larger litters. The robotic device operates on a cyclic algorithm, which includes the following operations: the opening of valves for supplying the ingredients to prepare a feed mixture; its direct distribution to animals; the system rinsing; functioning of electric motors for mixing the feed components; functioning of servo drives to bring the locking devices and teats to a working position; operation of relay for giving sound and light signals; switching on and off the disinfection system. The article presents a mathematical model for determining the running time of each operation within the work cycle and assessing the device's energy consumption in general terms. The created model takes into account the change in the prepared feed mixture consumption depending on the age of the suckling pigs and allows selecting the required technological equipment for the manufacture of the robotic device’s prototype.

1. Introduction

Any branch of farming today mainly aims to create profitable, competitive, environmentally friendly production systems, which would provide the people in the country with all needed goods. Pig breeding plays an important role in this context as it features the improved production intensity, high prolificacy of sows, high average daily weight gains per herd, low feed conversion rate and high slaughter yield [1].
The emerging trend of the past five years in Russia is an increase in the consumption of all types of meat, with the general indicator being 75 kg/year/capita. The main part of this amount accounts for poultry meat and pork that in relative terms is 45% and 34% of the total consumption, respectively.

Since 2018, however, the poultry meat production has been going down due to such factors as the oversupply crisis, a growth of the production self-cost, the closure of several large poultry complexes, and the spread of diseases. The combination of these factors resulted in the rise of wholesale and retail prices for the poultry products, and, consequently, to a drop in consumer demand.

The overall pork production is, on the contrary, increasing every year owing to the growing consumer demand and delivery of the state programs. These support the reconstruction and technical re-equipment of functioning pig-breeding complexes and the construction of new pig farms introducing the most modern technical, technological and space-planning solutions. From 2005 to 2019, the pork production on a slaughter weight basis increased by above 2.6 times or by 2.4 million tons in physical terms (figure 1) [2].

Higher domestic pork production contributes to lower share of imported products, which in 2019 amounted to 2.4% of the total pork consumption. Since 2018, Russia is fully resourced with pork, pork offal and pork fat. This allowed to increase the export share of these products. In 2019, about 100 thousand tons of these products were exported or 15 thousand tons more than in 2018 [2].

As the domestic market demonstrates the saturation, the further development of the pig breeding industry directly depends on the increase in the exports, which is forecast to exceed 270 thousand tons by 2024. Two ways to achieve this indicator are more efficient use of the genetic potential of animals and lower production costs.

One promising solution in this context is to have more weaned piglets per sow per farrowing. Today, highly prolific sows can wean 19 or more piglets per litter. The limited sow teat number, however, allows only maximum 12 of them to receive the suitable nutrition, which leads to more severe competition for the teat access, animal stress and a decrease in the average daily weight gain of the entire litter.

Various types of manual and automated supplementary feeding of suckling piglets are used today to address this issue (figure 2) [3-7].
All the above methods have some disadvantages, such as causing many stressful situations, spreading of gastrointestinal diseases, and the high cost of equipment.

A robotic device under development at IEEP – branch of FSAC VIM is designed to avoid these implications and replace a sow completely and not merely provide a supplementary feeding of suckling pigs from larger litters [8].

The purpose of the study was to create a mathematical model for determining the running time of each operation within the work cycle of this device and assessing the device's energy consumption in general terms.

2. Materials and methods

The robotic device for suckling piglets nursing operates on a cyclic algorithm (figure 3), which includes the following operations: the opening of valves for supplying the ingredients to prepare a feed mixture, its direct distribution to animals, and the system rinsing; functioning of electric motors for mixing the feed components; functioning of servo drives to bring the locking devices and teats to a working position; operation of relay for giving sound and light signals; switching on and off the disinfection system.

The study used the standard indicators for the consumption of the prepared feed mixture depending on the piglets' age, the drinking water, and the water for rinsing the system after each feeding of animals. The study applied the method of mathematical modelling with a computational and constructive approach to determine the required parameters making use of PC tools.
3. Results
For the correct operation of the robotic device units and for assessing its power consumption the running time of each operation was determined.

The valve opening time, i.e. the time it stays open, for the supply of the required amount of dry feed mixture (milk replacer) into the dispenser was determined by the supply pipe cross section $S$, the number of suckling piglets in the litter $n$, the age of the suckling piglets $T$, and the standard consumption rate of dry feed mixture by the suckling piglets depending on their age $m_{\text{norm}}(T)$.

In our case, the opening time of the valve depended on the total amount of dry feed mixture required at any instant of suckling piglets nursing as well as on the pipe cross-section, at the end of which this valve was located.

The total amount of the dry feed mixture $M_{\text{dry}}$ was calculated from the following expression:

$$M_{\text{dry}} = n \cdot m_{\text{norm}}(T) \tag{1}$$

This dry feed mixture mass can be considered as a cylinder with the base area $S$ and height $h$. So it can be determined through the cylinder volume by expression (2):

$$M_{\text{dry}} = h \cdot S \cdot \rho \tag{2}$$

Where:
- $\rho$ – density of the dry feed mixture (milk replacer), kg/m$^3$.

We consider the cylinder formed by the dry feed mixture as an integral whole (material particle). The motion of this material particle is uniformly accelerated, and, therefore, the path it has travelled is equal to:

$$h = \frac{gt^2}{2} \tag{3}$$

Where:
- $t$ - travelling time of all the feed mixture through the valve, s.

Substituting expression (3) into expression (2), we obtain

$$M_{\text{dry}} = \frac{gt^2 S \rho}{2} \tag{4}$$

Equating the expressions (1) and (4) will produce:

$$n \cdot m_{\text{norm}}(T) = \frac{gt^2 S \rho}{2} \tag{5}$$

From the obtained equation, $t$ will be:

$$t = \sqrt{\frac{2nm_{\text{norm}}(T)}{S \rho g}} \tag{6}$$

The valve opening time corresponds to the time required for the entire volume of feed mixture to pass through the lower base of the pipe with a cross section $S$.

The valve opening time for the supply of the required amount of dry feed mixture (milk replacer) from the dispenser to the mixer was determined in the same way as the valve opening time for the supply of the required amount of dry feed mixture (milk replacer) into the dispenser. Besides, under the same cross-section of the supply pipes, the opening time of the dispenser valve is the same as the opening time of the valve on the dry feed mixture storing container.

The valve opening time for the supply of the required amount of water in the dispenser to prepare the mixture was determined by the water supply pipe section $S_{p,w}$, the number of suckling piglets in the litter $n$, the age of the suckling piglets $T$, and the standard consumption rate of water to prepare the ready feed mixture for suckling piglets depending on their age $m_{\text{norm},w}(T)$. 

In our case, the opening time of the valve depended on the total amount of water, i.e. its consumption, required at any instant of suckling piglets nursing, and on the cross section of the pipe, at the end of which this valve was located.

With the water flow being considered laminar, the water consumption $V$ for feed mixture preparing is determined by:

$$ V = S_{p,w} v_0 $$

Where:
- $v_0$ - water flow rate, m/s.

The water mass passing through the pipe cross-section $S_{p,w}$ is determined by:

$$ M_w = S_{p,w} v_0 t \rho $$

Where:
- $t$ - travelling time of all water mass through the valve, s;
- $\rho$ - water density, kg/m$^3$.

The total water consumption for the feed mixture preparing is determined knowing the relevant norms per each sucking piglet depending on its age:

$$ M_w = n \cdot m_{\text{norm} w}(T) $$

Where:
- $m_{\text{norm} w}(T)$ - the standard consumption rate of water to prepare the feed mixture for the suckling piglets depending on their age.

Equating the expressions (8) and (9) will produce:

$$ S_{p,w} v_0 t \rho = n \cdot m_{\text{norm} w}(T) $$

From the obtained equation, $t$ is determined as:

$$ t = \frac{n \cdot m_{\text{norm} w}(T)}{S_{p,w} v_0 \rho} $$

The valve opening time for the supply of required amount of water to prepare the feed mixture from the dispenser into the mixer was determined in the same way as that for the supply of the required amount of water to prepare the mixture into the dispenser. Besides, under the same cross-section of the supply pipes, the opening time of the dispenser valve is the same as the opening time of the valve on the tank with water for the feed mixture preparation.

Mixing the feed components in a robotic device for the suckling piglets nursing implies the use of a mixer. The operating time of the mixer to achieve a homogeneous medium needs to be determined.

The phenomenological theory considers each moving volume as a single physical body with the following physical and mechanical characteristics – mass, momentum, energy [9].

The area consisting of the same particles for all $t$ is called the moving volume, sometimes the material volume.

The energy of the set feed mixture volume is assessed by:

$$ E = \frac{1}{2} \sum_{i=1}^{J} m_i |v_i|^2 $$

Where
- $J$- all the particles with mass $m_i$ of the set feed mixture volume

Based on this expression the kinetic energy of the rotating mixture is determined as:

$$ E = \frac{1}{2} M_{f,m} \iiint_V |v|^2 dV $$

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Since the volume is cylindrical, this integral is taken over the height and over the cross sectional area:

\[ E = \frac{1}{2} M_{\text{f.m.}} \int_0^H \int_S |v|^2 \, dS \, dz \]  

(14)

Next we pass to polar coordinates. We consider that the rotation has become stable and the mixture rotates at the speed of the mixer. Then \( v = \omega r \). The Jacobian transformation takes place from the area integral to angle and radius integrals:

\[ E = \frac{1}{2} M_{\text{f.m.}} H \int_0^{2\pi} \left( \int_0^R (\omega r)^2 \, rdr \right) \, d\phi \]  

(15)

Upon integrating Eq. 15 with respect to \( R \) we obtain

\[ E = \frac{1}{2} M_{\text{f.m.}} H \cdot 2\pi \omega^2 \cdot \frac{1}{4} R^4 = \frac{1}{4} MH \cdot \pi \omega^2 R^4 \]  

(16)

Where:

- \( M_{\text{f.m.}} \) - total feed mixture mass.

On the other hand, the kinetic energy of the feed mixture is the energy of the mixer.

\[ E = Nt \]  

(17)

Where

- \( N \) - power capacity of the mixer

From which

\[ t = \frac{1}{4} M_{\text{f.m.}} H \pi \omega^2 R^4 \]  

(18)

Time was determined in an ascending order (minimum time).

The turn-on time of the tubular electric heating element for warming the prepared feed mixture was determined using the formula of the specific heat capacity of a substance \( c \); in other words, how much heat must be transferred to a substance weighing one kilogram so that its temperature would increase by one degree Celsius:

\[ c = \frac{Q}{m (t_f - t_i)} \]  

(19)

Where:

- \( Q \) - heat quantity; \( m \) – substance mass, kg; \( t_f \) – final temperature of the substance, \( ^\circ \text{C} \); \( t_i \) – initial temperature of the substance, \( ^\circ \text{C} \).

The heat quantity \( Q \) is determined by an expression that takes into account the power capacity of the heating element (tubular electric heating element) and its operating time:

\[ Q = W \cdot t \]  

(20)

Where:

- \( W \) - power capacity of the heating element, W; \( t \) - operating time of the heating element, s.

The operating time of the heating element is determined from expressions (19) and (20):

\[ t = \frac{c \cdot m (t_f - t_i)}{W} \]  

(21)

The valve opening time for the required amount of prepared feed mixture to enter the collector was determined from its dependence on the total amount of the prepared feed mixture, i.e. its consumption, required at any instant of suckling piglets nursing, as well as on the cross section of the pipe, at the end of which this valve was located.
The Poiseuille equation was applied to determine the feed mixture consumption $V_{f.m.}$ [10]:

$$V_{f.m.} = \frac{1}{2} S \cdot v_0$$  \hspace{1cm} (22)

Where:

$v_0$ – feed mixture flow rate, m/s.

From which the mass of the feed mixture passing through the pipe cross-section $S$ is:

$$M_{f.m.} = \frac{1}{2} S \cdot v_0 \cdot t \cdot \rho_{f.m.}$$  \hspace{1cm} (23)

Where:

$t$ – travel time of all the feed mixture mass through the valve, s; $ho_{f.m.}$ – feed mixture density, kg/m$^3$.

The total mass of the feed mixture was determined in the same way as the amount of dry milk replacer and water needed for its preparation, knowing the standard consumption rates of the prepared feed mixture by every suckling piglet depending on its age:

$$M_{f.m.} = n \cdot m_{n.r.f.m.}(T)$$  \hspace{1cm} (24)

Where:

$m_{n.r.f.m.}(T)$ - the standard consumption rate of prepared feed mixture by the suckling piglets depending on their age.

The travel time of all the feed mixture through the valve is expressed by equating expressions (23) and (24):

$$t = \frac{2n \cdot m_{n.r.f.m.}(T)}{S \cdot v_0 \cdot \rho_{f.m.}}$$  \hspace{1cm} (25)

The density of the prepared feed mixture is determined by linking the volumetric and mass characteristics of the ingredients.

The feed mixture is considered as a two-phase one. The expression to determine its mass $M_{f,m.}$ will look as follows:

$$M_{f.m.} = m_l + m_{m.r.}$$  \hspace{1cm} (26)

Where:

$m_l$ – mass of water to prepare the feed mixture, kg; $m_{m.r.}$ – mass of dry milk replacer, kg.

Mass concentration of liquid in the feed mixture is denoted as $\beta$ and the expression for its determining will be written as follows:

$$\beta = \frac{m_l}{M_{f.m.}}$$  \hspace{1cm} (27)

Consequently, the mass concentration of the dry milk replacer in the feed mixture will be determined as:

$$1 - \beta = \frac{m_{m.r.}}{M_{f.m.}}$$  \hspace{1cm} (28)

The total volume of the prepared feed mixture $V_{f.m.}$ is:

$$V_{f.m.} = v_l + v_{m.r.}$$  \hspace{1cm} (29)

Where:

$v_l$ – volume of water to prepare the feed mixture, m$^3$; $v_{m.r.}$ – volume of dry milk replacer, m$^3$.

We shall call the volumetric concentration of the dry milk replacer $\alpha$; then the volumetric concentration of the liquid will be $(1-\alpha)$.

The expressions for determining the volume of water for preparing the feed mixture and the volume of dry milk replacer are:
\[ v_l = (1-\alpha)V_{f.m.} \]  
\[ v_{m.r.} = \alpha V_{f.m.} \]  

We express the total mass of the prepared feed mixture through its total volume:

\[ M_{f.m.} = \beta = v_l \rho_{l} = \rho_l (1-\alpha)V_{f.m.} \]  

From which:

\[ \beta = \frac{\rho_l (1-\alpha)V_{f.m.}}{M_{f.m.}} \]  

On the other hand:

\[ M_{f.m.} = \rho_{f.m.} V_{f.m.} \]  
\[ \beta = \frac{\rho_l (1-\alpha)}{\rho_{f.m.}} \]  

This way:

\[ 1-\beta = \frac{\rho_{m.r.}}{\rho_{f.m.}} \alpha \]  

We shall express the density of the prepared feed mixture as follows:

\[ \rho_{f.m.} = \rho_l (1-\alpha) + \rho_{m.r.} \alpha \]  

Substituting expression (37) into expression (25), we obtain:

\[ t = \frac{2n m_{n.r.} (T)}{S \cdot v_0 \left( \rho_l (1-\alpha) + \rho_{m.r.} \alpha \right)} \]  

The opening time of the collector valves coincides with the opening time of the valve for the supply of required amount of the prepared feed mixture from the mixer into the collector.

The teat holes in the robotic device are opened by the servo drives.

The time for the valve to turn 180 degrees from the start position needs to be determined.

The time for the servo drive to open the teat holes is written as follows:

\[ t_{open} = \frac{\pi R}{v} \]  

Where:

- \( R \) - radius of a circle centered on the servo drive shaft, m;
- \( v \) - rotation velocity of the servo drive. Скорость вращения сервопривода.

Given that the radius of the circle \( R \) coincides with the diameter of the teat hole valve, expression (39) will take the form:

\[ t_{open} = \frac{\pi D}{v} \]  

Where:

- \( D \) - diameter of the teat hole valve, m.

The engine operation time to close the teat holes is the same as the opening time of the teat holes.

In the robotic device for the suckling piglets nursing, the teats slide out for every feeding cycle and slide in to their original location at the end of feeding to prevent the piglets to damage them and for their disinfection with ultraviolet lamps.

The teat moves along the guides with the help of a stud, which passes through a rigidly locked nut; the stud end is found on the motor shaft.

The time for the teat to move to the distance \( L \) and take the position for piglet feeding under the known thread pitch \( \Delta l \) and the number of engine revolutions per minute needs to be determined.
The engine operation time when the teat slides out is determined by:

\[ t_{\text{slide out}} = \frac{L}{\Delta a} \]  

(41)

Where:

\( a \) – engine revolutions per minute, rpm.

The engine operation time for the teat to slide out is the same as that for the teat to return to its original location, only the travel direction changes. Whence the total engine operation time for the teat travel is

\[ t_{\text{tot}} = 2t_{\text{slide out}} \]  

(42)

The operation time of the engine for the teats to slide in to their original location is the same as that for the teats to slide out.

The turn-on time of the tubular electric heating element for warming the water for rinsing the system was determined in the same way as the turn-on time of the heating element for warming the prepared feed mixture.

To rinse the system of the robotic device for the suckling piglets nursing a pressure boosting pump and nozzles are suggested.

The required volume of water \( V_{\text{rinse}} \) for the system rinsing is defined as:

\[ V_{\text{rinse}} = N \cdot \gamma \cdot T \cdot n \]  

(43)

Where:

\( N \) – number of nozzles; \( \gamma \) – throughput of each nozzle, l/s; \( T \) – working time of nozzles, s; \( n \) – number of feedings per day.

To determine the operation time of the pressure boosting pump, it is necessary to know its power capacity \( W \). This factory indicator is found in the product certificate.

The expression for determining the operation time of the pressure boosting pump for rinsing the system is written as:

\[ t_{\text{pump}} = \frac{V_{\text{rinse}}}{W} \]  

(44)

The opening time of the valves on the mixer, collector and teats for the rinsing water discharge is determined in the same way as the valve opening time for the supply of the required amount of water to prepare the mixture into the dispenser.

The time of the light and sound signal, as well as the switch-on time of the ultraviolet lamp need not be calculated and is set manually when writing the programme code.

The energy consumption during the operation of the robotic device was determined for the period of artificial nursing of suckling piglets of 28 days – from the moment of birth and the receipt of a portion of colostrum from the sow [11].

The robotic device can feed 14 suckling piglets maximum. The feed mixture for suckling piglets is prepared in the following proportion: one kilogram of dry feed mixture and five liters of drinking water. Table 1 presents the average daily standard consumption of the prepared feed mixture by a suckling piglet at different time intervals of its nursing [12].

| Number of the day | Total amount of consumed prepared feed mixture by one piglet per day, ml | Number of feedings per day |
|------------------|---------------------------------|-----------------------------|
| 1–4              | 360                             | 12                          |
| 5–10             | 500                             | 6                           |
| 11–20            | 800                             | 5                           |
| 21–28            | 1000                            | 4                           |
To estimate the energy consumption of the robotic device, we use the previously determined operation time of its every unit. The expression for determining the energy consumption of the robotic device depending on the feeding day of piglets is written as:

$$E = \sum_{i=1}^{4} \left( \sum_{j=1}^{m} N_i t_{ij} \right)$$

Where:
- $j$ – number of period;
- $i$ – number of units

4. Discussion
Today, foreign companies such as Schauer, Big Dutchman, MS Schippers, HOLM & LAUE are world leaders in the field of artificial feeding of piglets from large nests. But the technical and technological solutions presented by these companies have a number of disadvantages, such as a high percentage of stressful situations due to the struggle of piglets for nipples, high labor costs for servicing animals and equipment, the risk of spreading diseases of the gastrointestinal tract of piglets, and, consequently, a high percentage their mortality.

The technical and technological solutions presented in the article for the mechanization and automation of the suckling period of suckling pigs and a description of their shortcomings allow us to determine the directions for further research to maximize the use of the genetic potential of animals, reduce stress situations, as well as labor costs for servicing piglets during the sucking period.

Achieving a competitive price for the export of pork is possible with the use of technical and technological solutions that ensure the elimination of stressful situations due to the struggle of suckling piglets for the nipples, which allows to reduce their mortality by 18%, improve the sanitary and hygienic conditions for automated feeding of piglets, as well as increase the culling period for highly productive sows up to 3 years old.

The main direction of further developments for the process of feeding suckling pigs is robotic means of artificial feeding of animals that can completely replace the sow, eliminate conflict situations due to competition, and also exclude the possibility of the spread of diseases of the digestive tract of suckling piglets.

5. Conclusion
The study outcome is a mathematical model which allows determining the time of each operation in the feeding cycle of suckling piglets in general terms. It also estimates the total energy consumption of the robotic device under development.

This mathematical model takes into account the change in the consumption of the prepared feed mixture depending on the age of the suckling piglets.

Application of the created mathematical model allows selecting the required technological equipment to manufacture a prototype of the robotic device for suckling piglets nursing.

As part of the work, the robotic device for suckling piglets nursing was granted a patent of invention of the Russian Federation (RU 2706204 C1), which confirms the practical novelty of the device under development.

The follow-up study will include writing a programme code for the device functioning, selecting the necessary components, assembling an experimental prototype, and its testing at a pig breeding enterprise.

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