Modeling the dispensing process for chopped stalk fodder

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Abstract. Optimization of the parameters of mechanized processes of dosed delivery of crushed stalk fodder is given, which required the development of programs for modeling these technological processes with a quantitative assessment of the functional indicator of their quality. This made it possible to substantiate the solutions of technological processes that ensure their implementation within the specified requirements. The use of a KTU-10A fodder dispenser and a stalk fodder dispenser for dispensing stalk fodder in production lines allows reducing the unevenness of the dispensed fodder flow by 3.6 times compared to using the KTU-10A fodder dispenser. It is advisable to accept the following kinematic parameters of the working bodies of the batcher: rotation frequency of the conveyor drive drum $n = 120 \text{ min}^{-1}$; the circumferential speed of movement of the ends of the fingers of the scraping drum is $1.8 \text{ m/s}$ with a drum diameter $D = 0.68 \text{ m}$; the maximum installation height of the stripping drum above the conveyor belt $h = 0.3 \text{ m}$; conveyor belt width $b = 0.6 \text{ m}$; power for the batcher drive is $1.5 \text{ kW}$, which ensures uneven delivery of $\pm 5\%$. The dispenser provides a stable dosing of roughage (with a minimum mass flow rate of $0.2 \text{ kg/animal}$) in accordance with zootechnical requirements.

1. Introduction

To optimize the parameters of crushed stalk fodder mechanized batching the engineers should develop the programs for modeling these technological processes with a quantitative assessment of the functional indicator of their implementation efficiency. This will allow substantiating the solutions for technological processes that ensure their implementation within the specified requirements [1].

There are theoretical studies of dosing fodder dispensers and processes of fodder batching by stationary feeding dispensers [1–6, 10].

According to their data and the accepted requirements, the uneven distribution of stalk fodder should not exceed $\pm 15\%$. The KTU-10-01 fodder dispenser, which is most often used for dosing such fodder, ensures their delivery with an average unevenness, for example, $25.6\%$ for corn silage, with maximum deviations from the norm up to $50\%$, and minimum deviation up to $90\%$.

The performance of stationary batchers, for example, of the PZM-1.5 type, is almost the same.

In Russia and abroad, the industry produces few machines for dosing stalk fodder. However, such devices are increasingly used for uniform loading of various agricultural machines. Among the existing models of stalk fodder dispensers, the most typical ones are with a drum and conveyor working body [7–11].

In the course of the research, the main parameters of dispensers with a beater drum and conveyor stripping working body were determined. In particular, the following was determined: the optimal distance between the axis of rotation of the beater (the conditional center of rotation of the stripping conveyor) and the edge of the receiving hopper, the effect of the speed differential was studied:
\[ \Delta = \frac{V_{\text{mov}}}{V_{tr}} , \]  

(1)

where \( V_{\text{mov}} \) is the velocity of stripping stud movement; 
\( V_{tr} \) is the velocity of the batcher conveyor movement.

The angle of inclination of the stripping device studs was also determined.
During the tests, the irregularity of the fodder distribution \( \sigma \) was chosen as the device evaluation factor.

After determining the optimal values of the parameters \( c, \Delta, \alpha \) (Table 1), comparative tests of the drum and conveyor stripping organs were carried out.

**Table 1. Values of parameters during comparative tests of working bodies**

| Parameter name                      | Designation | Conveyor batcher-leveler | Drum dispenser-leveler |
|-------------------------------------|-------------|--------------------------|------------------------|
| Fodder delivery rate [kg/animal]    | \( q \)     | 14.3                     | 12.7                   |
| Distance between receiving hopper and working body [m] | \( c \)     | 0.8                      | 0.3                    |
| Differential of working body and conveyor speeds | \( \Delta \) | 3                        | 3.1                    |
| Working body tilt angle [deg]       | \( \alpha \) | 55                       | –                      |

Preference is given to the drum dispenser-leveler, which provides less uneven fodder delivery, consumes less (1.3–2.0 times) power in comparison with the conveyor-type metering unit and is simpler in design.

The dispenser of stalk fodder consists of a belt conveyor, a stripping needle drum and a receiving hopper. From the batcher, for example, from the KTU-10A fodder dispenser, the fodder is loaded into the receiving hopper of the dispenser and transported by a belt conveyor to a needle drum, which removes excess fodder, while a layer of fodder of a given thickness remains on the conveyor belt [1, 5].

At steady-state operation of the dispenser, a roller of stripped fodder is formed in front of the drum, the cross section of which can be represented as an isosceles triangle with angles at the base equal to the angle of repose (Figure 1).

The transfer of fodder over the drum will be minimal if the height \( h \) of the triangle \( ABC \) is less than the radius \( R \) of the drum. Let us accept the limit value \( h = R \) for the calculation. Then the height of the triangle \( ABC \) will be

\[ h = \frac{q \sigma \rho \alpha}{\sqrt{1000 b u \rho}} , \]  

(2)

where \( q \) is a portion of fodder per animal, kg/animal; 
\( \sigma \) is uneven loading of the receiving hopper, %; 
\( \rho \) is the bulk density of feed, kg/m³; 
\( b \) is drum width, m; 
\( u \) is the flow velocity, m/s; 
\( \alpha \) is the angle of repose of the fodder, deg.

The vaulting of fodder over the drum can be reduced by setting the drum studs at an angle \( \beta \) to its radius (opposite to the direction of rotation) and choosing the optimal angular speed of the drum.

The limiting angle of stud inclination to the drum radius \( \beta \) is determined by the horizontal direction of the resulting force \( P \) (Figure 1) when the following condition is met:

\[ \beta - \tau \leq \varphi , \]  

(3)

where \( \tau \) is the rotation angle of the drum radius;
φ is the angle of friction against the finger.

**Figure 1.** Scheme for calculating the range of food particles vaulting over the drum

As per the sine theorem:

\[ \beta = \arctan \left( \frac{R \sin \phi}{R \cos \theta - l} \right), \]

where \( l \) is the stud length, m.

The stripped fodder will be removed from a stud when the stud is near the top of the formed roller.

The fodder particles must come off the studs at a speed that allows them to fly at least to point \( C \) (Figure 1). Arranging the coordinate axes as shown in the figure, we compose the equation of motion of a food particle with mass \( m \) thrown at an angle \( \alpha \) to the horizon (in the direction of the vector \( r_0 \ )):

\[
mx'' = \sum X_i = 0,
my'' = \sum Y_i = -mg.
\]

We define the initial conditions by setting \( t = 0 \), with \( x = 0 \), \( y = h = BM \), then:

\[
x_0' = V_{ox}, y_0' = V_{oy},
\]

where \( m \) is the mass of the fodder particle;

- \( x, x', x'' \) are the projections of the path, velocity and acceleration of the particle on the \( x \) axis;
- \( y, y', y'' \) are the projections of the path, velocity and acceleration of the particle onto the \( y \) axis;
- \( t \) is the duration.

By integrating (5) 2 times in time and substituting the values of the initial conditions (6), we determine the initial velocity that the particle must have in order to reach point \( C \):

\[
V_0 = \frac{gR}{\sqrt{2 \sin \alpha (1 + \sin \alpha)}}.
\]

To determine the value of the angular velocity of the drum, let us consider the system of forces acting on the particle in the zone of fodder removal (Figure 2).

In this zone, the particle under the action of the applied forces makes a relative motion, which, according to the basic equation of dynamics, can be considered as absolute if the force of moving space and the Coriolis force of inertia are added to the acting forces. In addition to these forces, the particle is affected by the force of gravity, \( G = mg \), the normal reaction force of the stud \( N \), and the friction force \( fN \).
Let us conditionally apply a centrifugal force to the particle and, having positioned the coordinate axes, as shown in the figure, compose a differential equation of motion of food particles along the x axis:

\[ m \ddot{x} = m \omega^2 r \cos \psi + mg \sin \beta - fN, \]  

(8)

where \( \psi = \omega t \) is the angle of the centrifugal force action, degrees;

\( \omega \) is the angular velocity of the drum, s\(^{-1}\);

\( t \) is the duration of stud cleaning, s;

\( f \) is the friction coefficient between the fodder and the stud;

\( r \) is the radius that determines the position of the fodder particle on the finger at the time of cleaning, m.

Having projected the forces on the y axis, we get:

\[ V m \sin r \cos mg \omega^2 \psi \beta = \omega^2 r \sin \beta - f \omega^2 r \sin \alpha - 2 f \omega V. \]

(9)

Substituting the value of \( N \) into eq. (8) and writing down \( \ddot{x} = \frac{dv}{dt} \), we have

\[ \frac{dV}{dt} = \omega^2 r \cos \alpha + g \sin \beta - f g \cos \beta + f \omega^2 r \sin \alpha - 2 f \omega V. \]

(10)

In formula (10), the value of \( r \) is assumed constant.

Equation (10) is a first-order differential equation which solution has the following form:

\[ y = e^{-\int_{t_A}^{t_B}} e^{\int_{t_A}^{t_B} B(t) dt}. \]

(11)

After solving (3.11), we have:

\( A(t) = 2 f \omega; \) \( B(t) = \omega^2 r \cos \alpha + g \sin \beta - f g \cos \beta + f \omega^2 r \sin \alpha, \)

then

\[ V = e^{-2 f \omega} y, \quad V' = y' e^{-2 f \omega} - 2 f \omega e^{-2 f \omega} y. \]

(12)

Substituting in eq. (10) the value of \( V \) and \( V' \) and replacing \( \sin \beta - f \cos = k \), we get the following equation

\[ y' e^{-2 f \omega} = \omega^2 r \left( \cos \alpha + k + f \sin \alpha \right) + gt, \]

(13)

which is a separable differential equation.
After integrating eq. (13) in the range from 0 to \( \frac{(\beta - \gamma)}{\omega} \), (where \( \frac{(\beta - \gamma)}{\omega} \) is the duration of stud cleaning from fodder), substituting the value of \( y \) into eq. (12) and solving the equation for \( \omega \), we obtain

\[
\omega = \frac{\left(1 + 4 f^2 \right)^{1/2}}{((2f - 1)\cos (\beta - \gamma) + (1 - 2f)\sin (\beta - \gamma) - (1 - 2f)r)_r}.
\] (14)

In eq. (14), \( V \) is the rate of descent of fodder particles from the studs, which, with small assumptions, can be determined by (7), \( (\beta - \gamma) \) is the angle of rotation of the drum radius at which there is a complete descent of fodder from the studs with the number of rows \( i = 8...12 \).

The location of the stripping drum relative to the loading hopper is determined from the conditions of joint operation of the batcher with the feeder (fodder dispenser KTU-10A). The distance from the end of the receiving hopper to the center of the drum will be

\[
C_o = \frac{D}{2} + \frac{2R}{tg\alpha} + L,
\]

where \( D \) is the drum diameter; \( \frac{R}{tg\alpha} \) is the flight range of food particles; \( L \) is flow formation zone, determined experimentally.

The drum during work strips off the excess fodder and throws it over the roller formed in front of the drum, which moves onto the drum at a speed \( V_{tr} \).

The force of the effect of the mass of the stripped fodder on the drum is determined from the following condition

\[
dFdt = V_{tr}M\cos\omega t,
\]

where \( dFdt \) is the impulse of force;
\( M \) is the mass of the fodder roll;
\( V_{tr} \) is the speed of the conveyor.

After integrating eq. (16) in the range from 0 to \( \frac{\pi}{2\omega} \), we obtain

\[
F = \left(\frac{\pi}{2\omega} \int dt \frac{M cos \omega t}{M cos \omega t}\right)^{-1} = V_{tr}M\omega.
\]

The power required to overcome the force \( F \) will be:

\[
N_1 = f'FV_{rot},
\]

where \( f' \) is the coefficient of internal friction of the fodder;
\( V_{rot} \) is the rotational speed of the drum.

Substituting the value of \( F \), \( M \) and \( V_{rot} \), into eq. (18) we get:

\[
N = \frac{\pi RSV_{tr}f'n\gamma}{30g\omega},
\]

where \( S \) is the cross-sectional area of the fodder roll, m\(^2\).

The power required to accelerate the batcher drum is determined by the following expression:

\[
N_2 = \frac{J\omega^2}{l},
\]

where \( J \) is the moment of inertia of the drum;
\( \omega \) is the angular velocity of the drum; 
\( t \) is the duration of the drum acceleration, \( t = 1 \ldots 1.5 \text{ s} \).

The estimated parameters of the batcher: \( n = 40\ldots100 \text{ rpm}; \beta = 27\ldots30^\circ; \ C = 1.2 \text{ m}; \) with the following parameters per animal: \( R = 0.3\ldots0.35 \text{ m}; \ f = 0.3\ldots0.6; \ y = 350 \text{ kg/m}^3 \) (silage), \( \alpha = 55^\circ, \ q = 25 \text{ kg}, \) were specified further in the process of experimental research.

2. Materials and methods

To clarify the design parameters of the stalk fodder dispenser, experimental studies were carried out on a laboratory setup with a feeder (KTU-10A fodder dispenser with an electric drive), a stalk fodder batcher, a belt conveyor for determining the unevenness of the fodder flow and two belt conveyors for loading fodder back into the KTU-10A dispenser.

It is known that the uneven distribution of fodder in KTU-10A depends on the movement speed of the unit during distribution and those of the longitudinal and transverse conveyors.

A well-known method was used to determine the unevenness of the fodder flow by laying them out on the conveyor and weighing portions taken from its sections of a certain length. At the final stage, a VL-1058 belt weigher was used with a maximum capacity of 75 t/h and a distance between the drums of 1500 mm.

The power at the drive of the fodder dispenser and batcher was determined using a N-348 wattmeter.

The averaged indicator of irregularity was used as an estimated indicator of the delivery uniformity of a fodder portion:

\[
\delta_i = \frac{100(q_i - \bar{q})}{\bar{q}}, \% \tag{21}
\]

where \( q_i \) is the mass of the \( i \)-th portion of fodder, kg;
\( \bar{q} \) is the arithmetic mean of the mass of a portion of fodder for one animal, kg.

It was found that the average non-uniformity of silage delivery was 25.6%, while the maximum positive deviation of the delivery from the average was \( \delta_{\text{max}} = 48.8\% \), and the maximum negative deviation \( \delta_{\text{min}} = -91.1\% \).

The tests were carried out according to the plan of extreme planning of experiments.

During the tests, we varied the speed of the conveyor of the stalk fodder dispenser (0.3...1.0 m/s) and the installation height of the stripping drum within (80...196) \times 10^{-3} \text{ m}. The ratio of the rotational speed of the ends of the drum studs and the speed of the conveyor belt \( J = V_d/V_r = 3 \).

3. The study of base of data

The experiments we used fodder, the fractional composition of which is presented in Table 2.

| Fraction [mm] | Corn silage | Haylage | Green mass | Straw |
|--------------|-------------|---------|------------|-------|
| 0...20       | 6.83        | 33.0    | 68.14      | 24.6  |
| 20...40      | 27.2        | 26.7    | 22.02      | 14.8  |
| 40...60      | 22.9        | –       | 3.31       | 13.4  |
| 60...80      | 10.47       | 15.1    | 1.33       | 8.8   |
| 80...100     | 6.4         | –       | 1.0        | 7.4   |
| 100...120    | 6.0         | –       | 1.55       | 6.6   |
| 120...140    | 4.4         | 3.4     | 1.83       | 17.4  |
| ≥140         | 15.8        | 21.8    | 0.83       | 7.0   |

When testing the stalk fodder batcher on corn silage, the dependence of its performance on the installation height of the stripping drum at different speeds of the conveyor belt was established (Figure 3).

The regression equation determined in this case (correlation coefficient \( R = 0.978 \)) has the following form:
\[ Y_2 = -5.469 + 0.0528X_1 + 0.0857X_2 - 0.000351X_1X_2 + 0.0000928X_1^2 - 0.0000431X_2^2. \] (22)

The value of \( X_1 \) (the rotation rate of the conveyor drive drum) varies in the range of 80...150 min\(^{-1}\), while the value of \( X_2 \) (the height of the stripping drum) is from 70 to 200 mm. It follows from the regression equation that the installation height of the stripping drum has a greater effect on the dispenser performance. The power at the dispenser drive increases as shown in Figure 4.

\[ Y_1 = 0.052 + 0.009X_1 + 0.00038X_2 + 0.000026X_1X_2 - 0.00002X_1^2 - 0.00001X_2^2. \] (23)

As can be seen from this equation, an increase in the belt speed, and, consequently, in the rotational speed of the stripping drum have the main effect on the power consumption.

Average irregularities in the distribution of fodder portions under various modes are shown in Figure 5 and described by the following equation:

\[ \text{Table 3. Moisture content and bulk density of fodder} \]

| Fodder name | Moisture content [%] | Bulk density [kg/m}^3\]
|-------------|---------------------|------------------|
| Corn silage | 79.51               | 370              |
| Haylage     | 58.72               | 250              |
| Straw       | 22.02               | 50               |
| Green mass  | 71.0                | 260              |

In this case, the regression equation (correlation coefficient \( R = 0.99 \)) is as follows:

\[ Y_1 = 0.052 + 0.009X_1 + 0.00038X_2 + 0.000026X_1X_2 - 0.00002X_1^2 - 0.00001X_2^2. \] (23)

\[ \text{Figure 3. Dependence of the dosed delivery of corn silage } Q \text{ on the installation height of the drum } h \text{ at different rotation rates of the conveyor drive drum} \]

\[ \text{Figure 4. Dependence of power at the dispenser drive } N \text{ when dosing corn silage on the height of the beater } h \text{ at different rotation speeds of the conveyor drive drum } n \]

Moisture content and bulk density of fodder are given in Table 3.
The regression equation for fodder delivery in this case will be as follows:

\[ Y_2 = -0.739 + 0.0222X_1 + 0.0260X_2 + 0.000101X_1X_2 - 0.0000424X_1^2 - 0.0000272X_2^2. \] (25)

Correlation coefficient \( R = 0.97 \). The energy consumption for the green mass dosing process is slightly higher in comparison with the silage (Figure 7), which is represented by the following regression equation:

\[ Y_1 = -0.0142 - 0.0160X_1 + 0.0194X_2 - 0.0000114X_1X_2 + 0.000129X_1^2 - 0.0000678X_2^2. \] (26)

The increase in power at the dispenser drive is explained by an increase in the thickness of the fodder layer on the conveyor, and, consequently, the area of contact of the material with the skirting
board. At the same time, green fodder has a higher friction coefficient against steel ($\mu = 0.87...0.95$) than that of silage ($\mu = 0.48...0.52$).

![Figure 7. Dependence of the power at the dispenser drive $N$, when dosing green mass, on the installation height of the stripping drum $h$ at different rotation speeds of the conveyor drive drum $n$](image)

The average unevenness of the dispensing of green fodder does not exceed 5.5% (Figure 8) and can be represented by the following regression equation:

$$Y_3 = 8.202 + 0.00293X_1 - 0.0503X_2 + 0.000215X_1X_2 - 0.000198X_1^2 + 0.000116X_2^2. \quad (27)$$

The average delivery unevenness when leveling the fodder layer in the KTU-10A bunker was 16.2%. At the same time, the use of a stalk fodder dispenser allows reducing the average unevenness of the fodder delivery by more than 3 times.

![Figure 8. Dependence of the delivery unevenness of green mass $\delta$ on the drum installation height $h$ at various rates of the conveyor drive drum $n$](image)

4. Conclusion

The use of a KTU-10A fodder dispenser and a stalk fodder batcher in production lines allows reducing the unevenness of the dispensed fodder flow by 3.6 times compared to using the KTU-10A fodder dispenser as a batcher.

When developing the design of the stalk fodder dispenser, it is advisable to take the following kinematic parameters of its working bodies:

- conveyor drive drum rotation rate $n = 120 \text{ min}^{-1}$, which corresponds to the speed of the conveyor belt 0.6 m/s;
- rotational speed of movement of the ends of the stripping drum studs 1.8 m/s with a drum diameter $D = 0.68 \text{ m}$;
- maximum installation height of the stripping drum above the conveyor belt $h = 0.3 \text{ m}$;
- the number of rows of drum studs $i = 12$, the distance between the studs in a row is 0.07 m;
- the working length of the studs $l = 0.150 \text{ m}$, the angle of stud back deflection in relation to the direction of rotation of the drum $\beta = 27^\circ$.
the ratio of the rotational rate of the ends of the drum studs to the conveyor belt movement speed $\Delta = 3$;
width of the conveyor belt $b = 0.6$ m.
In this case, the power per drive of the dispenser does not exceed 1.5 kW, and the uneven delivery is $\pm 5\%$.

The dispenser provides stable dosing of roughage (with a minimum mass flow rate of 0.2 kg/animal) in accordance with zootechnical requirements.

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