Mathematical modelling of the dosing process of bulk materials on the example of the sowing apparatus of a seeder

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Abstract. A mathematical model of the dosing process of bulk materials has been developed, it allows to determine the optimal technological and design parameters of the metering device of the sowing apparatus of a seeder. A new type of a sowing apparatus of a seeder is proposed, allowing to seed small-seeded crops.

1. Introduction
Uniform and specified in certain values dosing of bulk materials [1], including the dosing of seeds during sowing, is a matter of current interest [2]. As a result of the analysis of technical solutions for sowing small-seeded crops, such as rapeseed, alfalfa, and tributary, it was found that the main disadvantages of the existing dosing systems are the uneven distribution of seeds (seeding pulsation) and increased seed injury. To eliminate these shortcomings, a metering device (sowing device) of bobbin-screw type [3] was developed, as is the synthesis of a bobbin sowing device and a screw dosing device.

2. Model
We consider a mathematical model of the process of dosing bulk materials on the example of a bobbin-screw type sowing apparatus [4]. Scheme of the bobbin-screw type sowing apparatus is presented in figure 1.

![Figure 1. Bobbin-screw type sowing apparatus](image)

1 – flute; 2 – groove; S – helix pitch, mm; h – depth of the rabbet, mm.
The volume of seeds $V_0 \text{ m}^3$ ejected by the bobbin in one turn consists of the volume of seeds trapped in the flutes $V_F$ and the volume of seeds ejected from the active layer $V_A$, i.e.:

$$V_0 = V_F + V_A,$$

(1)

where $V_F$ is the seed volume sown by the flutes in one turn of the bobbin, $\text{m}^3$; $V_A$ is the seed volume sown by the active layer one turn of the bobbin, $\text{m}^3$.

The determination of the volume of seeds sown by the active layer $V_A$ is complicated by a number of circumstances and primarily by the fact that the speed of the seeds movement is not constant in the thickness of layer $C$ (figure 2), and besides the type of function can only be determined by experiment.

\[ \text{Figure 2. Scheme of the bobbing type sowing apparatus operation.} \]

\[ C \text{ is the thickness of the layer; } C_{re} \text{ is the reduced thickness of the active layer; } n \text{ is the sowing machine bobbin rotation frequency.} \]

Experimental study of the operation of the bobbin-screw type sowing apparatus showed that the pattern of change of seed movement velocity $V_x$ in the active layer can (as a first approximation) be expressed by the following relationship [5]:

$$V_x = \pi \cdot D_B \cdot n \left(1 - \frac{x}{C}\right)^m,$$

(2)

where $m$ is an exponent, determined experimentally; $n$ is the sowing machine bobbin rotation frequency, $\text{c}^{-1}$.

We will conduct a simulation of the working process of the sowing apparatus, focusing on the reduced thickness of the center of the reduced layer $C_{re}$, which is easily determined experimentally. The given thickness of the active layer is the thickness $C_{re}$ of a certain layer of seeds moving with a constant velocity $V_{sa}$ (Figure 2).

If we use the expression 2, then the relationship between $C$ and $C_{re}$ can be determined from the following equality:

$$V_{sa} = \int_0^C \left(1 - \frac{x}{C}\right)^m \, dm = C_{re} \cdot V_{sa}$$

(3)

Whence:

$$C = C_{re}(m+1).$$

(4)
The values of $C_{re}$ vary slightly with the change in the length of the working length of the bobbin $I_B$ and the frequency of its rotation $n$, figure 2.

Thus, the volume of seeds sown by the active layer is determined by the formula:

$$V_A = \pi \cdot D_B \cdot C_{re} \cdot I_B,$$  \hspace{1cm} (5)

where $D_B$ is the diameter of the bobbin of the sowing apparatus, m;
$C_{re}$ is the reduced thickness of the active layer, m;
$I_B$ is the working length of the bobbin of the sowing apparatus, m;

The amount of seeds sown by the bobbin flutes can be determined by calculation, because the flute of the bobbin screw sowing apparatus is a helix with only one flute, and there is a single-thread screw, or with several flutes if there is a multiple-thread screw. Therefore, the volume of the flute is determined:

$$V_F = F_F \cdot L,$$ \hspace{1cm} (6)

where $F_F$ is the area of the section of the bobbin’s flutes
$L$ is the length of the flute of the bobbin, m.

The flute in cross section is a parabola, which can be represented as consisting of two elements: an inverted trapezium and a segment. Geometrical parameters of the flute are presented in figure 3.

![Figure 3. Geometrical parameters of the flute – area of a trapezium; – area of a segment; $a$ is the length of the smaller base of the trapezium; $b$ – the length of the bigger base, m; $e$ – the height of the trapezium; $r$ – radius of the segment; $a$ – tilt angle of the verge; $\Psi$ – central angle.](image)

The sectional area of the flute is determined as the sum of the trapezoid and segment areas (figure 3):

$$F_F = \left(b - h \cdot tg \frac{a}{2}\right)h + \frac{r^2}{2} \left(\frac{\pi}{180} \Psi - sin\Psi\right).$$ \hspace{1cm} (7)

We will find $L$ – the length of the flute of the screw bobbin of the sowing apparatus:
Figure 4. The main parameters of the helix $D_B$ is the diameter of the bobbin, m; $\beta$ is the elevation angle of the helix, degrees; $L$ is the length of the flute of the sowing apparatus’ screw bobbin, m; $S$ is the helix pitch, m.

As can be seen from figure 4, the arc length of one pitch $l$, is determined by:

$$l = \frac{\pi D_B}{\cos \beta}, \quad (8)$$

where $D_B$ is the diameter of the bobbin, m; $\beta$ is the elevation angle of the helix, degrees.

The helix pitch is determined by:

$$S = \pi \cdot D_B \cdot \tan \beta \quad (9)$$

At an angle of $0^\circ < \beta < 90^\circ$, the flute is located along the helix with the parameters shown in figure 4, the number of turns is determined by:

$$z = \frac{l_B}{p \cdot \cos \beta}, \quad (10)$$

Therefore, the length of the helix is equal to:

$$L_F = l \cdot z. \quad (11)$$

To determine the length of the flute of the bobbin, we substitute in equation 11 equations 8, 9 and 10:

$$L_F = \frac{2l_B}{\sin 2\beta}. \quad (12)$$

Due to a number of factors: the shape and size of the seeds, the profile of the flute of the bobbin, etc., it is necessary to enter the fill factor of the flute $\xi$, which is determined by the ratio of the volume of the flute filled with seeds to the total volume of the flute, and this is how we get the volume of seeds sown by the flute for one turn of the bobbin:

$$L_F = \xi \left( b - h \cdot \tan \frac{\alpha}{2} \right) h + \frac{r^2}{2} \left( \frac{\pi}{180} \Psi - \sin \Psi \right) \frac{2l_B}{\sin 2\beta}. \quad (13)$$
Then the volume of seeds sown by the bobbin per turn (the working volume of the bobbin or the sowing capacity), based on formulas 1, 12 and 20, expresses in:

\[ V_0 = \xi \left( b - h \cdot \tan \frac{\alpha}{2} \right) h + \frac{r^2}{2} \left( \frac{\pi}{180} \psi - \sin \psi \right) \frac{2l_k \xi}{\sin \frac{2\beta}{\pi}} + \pi \cdot D_B \cdot C_{re} \cdot l_B. \]  

(14)

Knowing that the number of seeds is determined by: where \( \gamma \) is the volumetric weight of seeds, kg/m\(^3\), and \( \delta \) is the weight of 1000 seeds, kg, we determine the number of seeds sown per one turn of the bobbin, while introducing the correction speed coefficient \( k_n \), which shows how much the number of sown seeds varies from the frequency of rotation of the bobbin. Formula 14 takes the final look:

\[ N = \left( \left( b - h \cdot \tan \frac{\alpha}{2} \right) h + \frac{r^2}{2} \left( \frac{\pi}{180} \psi - \sin \psi \right) \frac{2l_k \xi}{\sin \frac{2\beta}{\pi}} + \pi \cdot D_B \cdot C_{re} \cdot l_B \right) \cdot \delta^{-1} \cdot \gamma - k_n. \]  

(15)

This expression shows how many seeds are sown in one turn of the bobbin of the sowing apparatus.

3. Results and discussion

Using the method of substituting the constant values of the parameters of the most common seeder into expression 15, we model the seed dosing process, i.e. the dependence of the metering capacity of the metering device on the technological and constructive parameters of the bobbin screw sowing apparatus. Using the data obtained, we construct two-dimensional sections of response surfaces (figure 5) and analyze them.

![Figure 5](image)

**Figure 5.** Two-dimensional section of response surface: \( a - N = f(n, S), \% \), if \( h = 3 \) mm; \( b - N = f(n, h), \% \), if \( S = 8 \) mm; \( c - N = f(S, h), \% \), if \( n = 0,10 \) c\(^{-1}\).

From figure 5 (a) it can be seen that the dependence of the seeding capacity \( N \) on the frequency of rotation of the bobbin \( n \) is inverse linear, that is, if there is an increase in the frequency of rotation of the bobbin \( n \), the seeding capacity \( N \) decreases. The dependence of the seeding capacity \( N \) on the helix pitch \( S \) is a power-law.

Figure 5 (b) shows that the dependence of the seeding capacity \( N \) on the depth of the flute \( h \) is straight linear; the deeper the flute, the greater the number of seeds sown.

Figure 5 (c) shows the combined effect of the parameters: the depth of the flute \( h \) and the helix pitch \( S \) on the seeding capacity \( N \).

We will conduct a comparative analysis of the sowing capacity of the designed sowing apparatus. For one turn of the sowing apparatus of a seeder, it is necessary to sow 830 pieces of rapeseed at a seeding rate of 3.0 million pieces/ha of seeds, consequently this condition is met by the parameters: flute...
depth \( h = 4 \text{ mm} \), helix pitch \( S = 8 \text{ mm} \) with the frequency of rotation of the bobbin \( n = 0.07 \text{–} 0.13 \text{ c}^{-1} \).

With these parameters, 800 – 1200 pieces of seeds are sown, which allows both to increase and decrease the seeding rate.

4. Conclusion
   As a result of mathematical modeling of the seed dosing process, namely the dependence of the metering capacity of the dosing device on the technological and design parameters of the bobbin screw sowing apparatus, the technological and constructive parameters of the dosing device of the sowing apparatus that are optimal for the sowing of small seed crops are determined. Constructive parameters: depth of the flute \( h = 4 \text{ mm} \), helix pitch \( S = 8 \text{ mm} \). Technological parameters: bobbin rotation frequency \( n = 0.07 \ldots 0.13 \text{ c}^{-1} \).

The developed model is recommended to be used for development of new types of dosing devices for dosing of various bulk materials.

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