Movement of crushed stem particles when they interact with hammers

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Abstract. The purpose of the paper is to study the movement of crushed stem particles when interacting with hammers inside the chopper. The basic principles and methods of classical mechanics, mathematical analysis and statistics were used in this study. An analytical expression is obtained for determining the speed of movement of crushed stem particles when they interact with hammers. It is established that the intensive splitting of the stalks of coarse feed by the rotor hammers is provided at their circumferential speed of 30-35 m/s. The particle velocity from the entrance to the exit from the working chamber gradually increases and is 15-16 m/s. The performance of the crusher depends on the angular velocity and radius of the rotor, as well as on the density and feed rate of the processed material.

1. Introduction

Animal products occupy a major place in food security. Therefore, Uzbekistan pays great attention to the development of animal husbandry. The development of animal husbandry is included in the Strategy for the Development of Agriculture of the Republic of Uzbekistan for 2020 - 2030. It provides for the development of animal husbandry in private subsidiary farms, dehkan farms and farms with a small number of animals.

The accelerated development of the livestock industry depends on the strengthening of the feed and technical base of the farms. Large amounts of wheat, corn, soybeans and oilseeds are grown in Uzbekistan. After they are harvested, a large amount of straw is obtained along with the grain and can be used as roughage for animals [1, 2, 3]. In animal husbandry in Uzbekistan, green and coarse feed, feed grains and grain waste obtained during post-harvest processing are used as feed [4-11]. However, before feeding the animals, green and coarse feed, feed grains and grain waste are crushed to the required size [1, 2, 8, 9, 10].

Currently, various machines and crushers-grinders are used [12, 13, 14, 15]. Most scientific research is devoted to the separate grinding or crushing of coarse feed stalks. There are separate works on grinding with simultaneous crushing, but they do not sufficiently justify the shape and parameters of the working bodies of the rotary type [16 - 23]. Some researchers, when developing shredders, take the physical and mechanical properties of the crushed material as the main indicator [24, 25, 26].

However, they do not provide the necessary quality of the technological process, especially when processing corn stalks and other crops [5, 13]. Of the known methods of processing the stems of coarse feed, the most promising for animal husbandry is grinding with simultaneous crushing, i.e.
splitting. For the processing of coarse feed, this method requires the creation of a new machine, since imported machines are expensive, and some of them have significant disadvantages.

2. Methods

According to the study and analysis of the previous work to eliminate the noted shortcomings of rotary crushers, we have developed a crusher-shredder. In this case, a certain part of the working elements of the rotor must carry out intensive processing of the crushed stems, and the other part of the movement of the crushed and split stems outwards. The crusher-chopper consists of a feeding tray 1, knives 3, hammers 4, a discharge window 5, a housing 6. The stems 2 are fed into the chopper at an angle (figure 1).

To reveal the essence of the technological process of the crusher-shredder, the process of movement of crushed stems under the influence of a hammer is studied by the method of theoretical modeling. In this case, the crushed stems are taken as a particle.

In this theoretical study, the motion of a particle from the center to the periphery of the drum along the hammers is considered.

![Diagram of the crusher-chopper](image)

**Figure 1.** Diagram of the crusher-chopper: 1 – feed tray; 2 – stem; 3 – knife; 4 – hammers; 5 – ejection window; 6 – housing

3. Results and Discussions

Representing the particles of the crushed mass as a material point, we will make a differential equation of the motion of the particles in interaction with the rotor hammer (figure 2):

\[ m\ddot{r} = F_s + G \cos \alpha - F_f \]  

(1)
Figure 2. Diagram of the forces acting on the particle when interacting with the hammer

Substituting the force values we get the differential equation of particle motion:

\[ m\ddot{r} = m\omega^2 r + mg \cos \alpha - f(2m\dot{r}\omega + mg \sin \alpha) \]  

where \( \ddot{r} \) – is the acceleration of the particle on the hammer, m/s\(^2\); \( \omega \) – the angular velocity of the particle, s\(^{-1}\); \( r \) – the movement of the particle on the hammer, m; \( g \) – the acceleration of gravity, m/s\(^2\); \( f \) – the coefficient of friction of the particle on the hammers; \( \dot{r} \) - the speed of the particle; m/s; \( t \) – the time of movement, s.

Reducing by weight and after several transformations we have:

\[ \ddot{r} + 2f \omega \omega - \omega^2 r = g \cos \alpha - fg \sin \alpha \]  

Equation (3) is solved by defining its general and particular solutions, i.e. as

\[ r = r_1 + r_2 \]  

where \( r_1 \) – is the general solution; \( r_2 \) – is the particular solution.

The general solution of the corresponding homogeneous equation is sought in the form

\[ Z^2 + 2f \omega Z - \omega^2 = 0 \]  

The roots of the characteristic equation of the additional function will have the form:

\[ Z_1 = \omega - f + \sqrt{f^2 + 1} \]
\[ Z_2 = \omega - f - \sqrt{f^2 + 1} \]

Therefore, the additional function itself is presented as follows:

\[ r_1 = C_1 e^{z_1t} + C_2 e^{z_2t} \]  

where \( C_1 \) and \( C_2 \) – are arbitrary constants

We are looking for a partial solution of equation (3) in the form:

\[ r_2 = A \cos \omega t + B \sin \omega t \]  

Differentiating equation (7), we define:

\[ \dot{r}_2 = -A \omega \sin \omega t + B \omega \cos \omega t \]  
\[ \ddot{r}_2 = -A \omega^2 \cos \omega t - B \omega^2 \sin \omega t \]  

Substituting the value in the left part of equation (3) and solving it with respect to \( A \) and \( B \), we determine the constants:

\[ A = -\frac{g(1 - f^2)}{2\omega^2(1 + f^2)} \]
\( B = \frac{fg}{\omega^2 \left( 1 + f^2 \right)} \)  

(11)

After replacing \( A \) and \( B \), we rewrite equation (7) as follows:

\[
\begin{align*}
\rho_2 &= \frac{fg}{\omega^2 \left( 1 + f^2 \right)} \sin \omega \theta - \frac{g \left( 1 - f^2 \right)}{2\omega^2 \left( 1 + f^2 \right)} \cos \omega \theta 
\end{align*}
\]

(12)

Taking into account (6), (11), the expression (4) will take the form:

\[
\begin{align*}
\rho &= C_1 e^{\omega \left( -f + \sqrt{1 + f^2} \right) t} + C_2 e^{\omega \left( -f - \sqrt{1 + f^2} \right) t} + \frac{fg}{\omega^2 \left( 1 + f^2 \right)} \sin \omega \theta - \frac{g \left( 1 - f^2 \right)}{2\omega^2 \left( 1 + f^2 \right)} \cos \omega \theta 
\end{align*}
\]

(13)

We find arbitrary constants under the condition

\[
\begin{align*}
t &= 0; \quad \rho(0) = \rho_0; \quad \dot{\rho}(0) = 0. \\
\rho_0 &= C_1 + C_2 - \frac{g \left( 1 - f^2 \right)}{2\omega^2 \left( 1 + f^2 \right)} 
\end{align*}
\]

where from

\[
\begin{align*}
C_1 &= \rho_0 + \frac{g \left( 1 - f^2 \right)}{2\omega^2 \left( 1 + f^2 \right)} - C_2 
\end{align*}
\]

(14)

Taking the derivative of equation (13) and taking into account the expression (14), we find:

\[
\begin{align*}
C_2 &= \frac{\left( \rho_0 + \frac{g \left( 1 - f^2 \right)}{2\omega^2 \left( 1 + f^2 \right)} \right) \omega \left( -f + \sqrt{1 + f^2} \right) + \frac{fg}{\omega \left( 1 + f^2 \right)}}{2\omega \sqrt{1 + f^2}} 
\end{align*}
\]

(15)

Given the expression (15), the constant \( C_1 \), will be equal to:

\[
\begin{align*}
C_1 &= \rho_0 + \frac{g \left( 1 - f^2 \right)}{2\omega^2 \left( 1 + f^2 \right)} - \frac{\left( \rho_0 + \frac{g \left( 1 - f^2 \right)}{2\omega^2 \left( 1 + f^2 \right)} \right) \omega \left( -f + \sqrt{1 + f^2} \right) + \frac{fg}{\omega \left( 1 + f^2 \right)}}{2\omega \sqrt{1 + f^2}} 
\end{align*}
\]

(16)

Adding the value of \( C_1 \) and \( C_2 \) to equation (13), we get the desired equation for determining the displacement

\[
\begin{align*}
\rho &= \left[ \rho_0 + \frac{g \left( 1 - f^2 \right)}{2\omega^2 \left( 1 + f^2 \right)} - \frac{\left( \rho_0 + \frac{g \left( 1 - f^2 \right)}{2\omega^2 \left( 1 + f^2 \right)} \right) \omega \left( -f + \sqrt{1 + f^2} \right) + \frac{fg}{\omega \left( 1 + f^2 \right)}}{2\omega \sqrt{1 + f^2}} \right] \times \\
&\times e^{\omega \left( -f + \sqrt{1 + f^2} \right) t} + \frac{\left( \rho_0 + \frac{g \left( 1 - f^2 \right)}{2\omega^2 \left( 1 + f^2 \right)} \right) \omega \left( -f + \sqrt{1 + f^2} \right) + \frac{fg}{\omega \left( 1 + f^2 \right)}}{2\omega \sqrt{1 + f^2}} e^{\omega \left( -f - \sqrt{1 + f^2} \right) t} + \\
&+ \frac{fg}{\omega^2 \left( 1 + f^2 \right)} \sin \omega \theta - \frac{g \left( 1 - f^2 \right)}{2\omega^2 \left( 1 + f^2 \right)} \cos \omega \theta 
\end{align*}
\]
Thus, we have derived the equation of the change in the movement of the particles of the crushed mass by the rotor over time.

Using equation (16), it is possible to determine the speed and acceleration of the movement of the articles of the crushed mass when it interacts with the rotor hammers.

The speed of movement is determined from the equation:

\[
\dot{r} = \left[ r_0 + g\left(1 - f^2\right) \right] \left( r_0 + \frac{g\left(1 - f^2\right)}{2\omega^2\left(1 + f^2\right)} \alpha\left(f + \sqrt{1 + f^2}\right) + \frac{fg}{\alpha(1 + f^2)} \right) (-f + \sqrt{1 + f^2}) \times \\
\times e^{\left(-f + \sqrt{1 + f^2}\right)/R} + \left( r_0 + \frac{g\left(1 - f^2\right)}{2\omega^2\left(1 + f^2\right)} \alpha\left(f + \sqrt{1 + f^2}\right) + \frac{fg}{\alpha(1 + f^2)} \right) (-f - \sqrt{1 + f^2}) \times \\
\times e^{\left(f - \sqrt{1 + f^2}\right)/R} + \frac{fg}{\alpha(1 + f^2)} \cos \alpha + \frac{g\left(1 - f^2\right)}{2\alpha(1 + f^2)} \sin \alpha.
\]

Equations (16) and (17) establish the relationship between all the parameters that determine the movement of the crushed mass along the rotor of the crusher-shredder when the hammers interact with the particles of the processed mass.

From the analysis of equations (16) and (17), it follows that for given operating conditions, the distance and velocity of the particles moving in the working chamber mainly depends on the speed of the rotor and its radius $R$.

Using expressions (16) and (17), figure 3 plot the changes in the velocity of the particles as a function of time $t$ for different values of $R$ and the following data: $f = 0.5$; $=110 \text{ s}^{-1}$ and $g = 9.81 \text{ m/s}^2$.

From Figure 3, it can be seen that the stem particles move along the length of the hammer for a short time, but it takes a certain amount of time to move through the package of hammers.

![Figure 3](chart.png)

**Figure 3.** The nature of the movement of the stump articles at different values of the radius $R$:

1 – $r_0=0.1$ m; 2 – $r_0=0.125$ m; 3 – $r_0=0.15$ m; 4 – $r_0=0.175$ m

The study of the nature of the velocity of the particles inside the working chamber during the interaction of the particles with the hammers shows (Fig. 3) that their velocity from the entrance to the exit from the working chamber gradually increases.

4. **Conclusion**

1. It is found that the intensive splitting of the stalks of coarse feed by the rotor hammers is provided at their circumferential speed of 30-35 m/s.
2. Theoretical studies have established that the particle velocity from the entrance to the exit from the working chamber gradually increases and is 15-16 m/s.

3. It is established that the productivity of the crusher-shredder depends on the angular velocity and radius of the rotor, as well as on the density and feed rate of the processed material.

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