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MATHEMATICAL MODELLING OF THE FRUIT-STONE CULTURE SEEDS CALIBRATION PROCESS USING FLAT SIEVES

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The paper provided describes a mathematical model of calibration process of fruit-stone culture seeds of cherry, sweet cherry, cherry-plum, apricot and almond using flat sieves with impact shock ball cleaners oscillating in the horizontal plane. It has been defined that the mathematical expectation of time of knocking out the fruit-stone from the sieve opening $\hat{T}$ is the minimum value of ratio of average time of complete ball motion cycle in space under sieve to the probability of knocking out the stone by a ball with the kinetic energy level of 2 Mj. The dependences of energy distribution density of ball on impact on the sieve have been obtained, based on which the intervals of ball cleaner parameters have been determined, i.e. the ball diameter *D* belongs to the interval 25–35 mm; the space height *H* under sorting sieve belongs to the interval 1.2*D*–1.4*D* mm; the value range for distance between rods *t* belongs to the interval 0.5*D*–0.7*D* mm. Using the method of golden section, the following parameters of ball cleaner were obtained: $D = 33$ mm, $t = 23$ mm, $H = 40$ mm. The parameters obtained provide mathematical expectation of time of knocking out the fruit-stone from the sieve opening $\hat{T} = 0.03$ s. Consequently, the average ball velocity $\hat{v}$ is = 0.4 m·s^{-1}, and the average ball path is $\hat{L} = 0.006$ m.

Keywords: sieve ball cleaners; distribution density; kinetic energy; mathematical expectation

In the process of sorting crop seeds using flat sieves, the sieve openings are clogged with stuck seeds. Currently, the most common means of cleaning the sieves are cleaners with random movement of the working bodies in sieve system. Rubber ball cleaners belong to these very working bodies (Butovchenko et al., 2019; Gras et al., 2001; Struchaiev et al., 2019).

Due to the fact that the fruit-stone culture seeds (hereinafter seeds) differ significantly in shape and size from the seeds of crops, the task arises to justify the parameters of the ball cleaners able to provide the quality of the sieve opening cleaning from the seeds stuck (Kocira et al., 2020; Piven, 2006; Dorokhov et al., 2018; Rouphael et al., 2018).

Analysis of recent research indicates that scientific data on the development of devices for cleaning the openings of sorting or calibration sieves are not sufficient. The results of researching the process of cleaning the sieves via the impact of the ball directly hitting the seeds stuck in the sieve opening are given in the works by Bajus et al. (2019) and Piven (2006).

In this case, it was believed that the probability of hitting stuck seeds by a ball is defined by a known value, moreover, a constant one (Zavhorodnii, 2001). This probability depends on the geometric parameters of cleaners and kinematic parameters of calibration unit (Bulgakov et al., 2018). Therefore, there is a need for developing a ball cleaner optimization model, which would minimize the mathematical expectation of the time of knocking the stones out of openings and provide the optimum parameters of ball cleaners that would result in a situation when the calibration unit can execute high-quality separation of seeds homogeneous in size and mass characteristics (Zavhorodnii, 2001; Tabor et al., 2019; Ridnyj, 1981).

As a working research hypothesis, it has been accepted that the average time of knocking out the seed by ball from the sieve opening is considered a factor significantly effecting the release stuck seeds from openings (Badretdinov et al., 2019; Craessaerts et al., 2007; Bondarenko and Tsymbal, 2008).

Material and methods

The research program provided is defined by theoretical methods of the optimum values of geometric parameters for calibration unit ball cleaner, based on which the ball energy is sufficient to knock out the stuck seed in a minimum time.

Consequently, the optimum values of following geometric parameters of ball cleaner were determined:

– the ball diameter (*D*);

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– distance between the bars of reflecting surface (*t*);
– the height of space under sorting sieve (*H*).

For the purpose function of optimization of specified ball cleaner parameters, the minimization of mathematical expectation of the knock-out time $\hat{T}$ of seeds stuck from sorting sieve openings was adopted.

The mathematical expressions for determining the optimum parameter values are obtained according to the scheme of ball motion in space under sorting sieve, which is shown in Fig. 1.

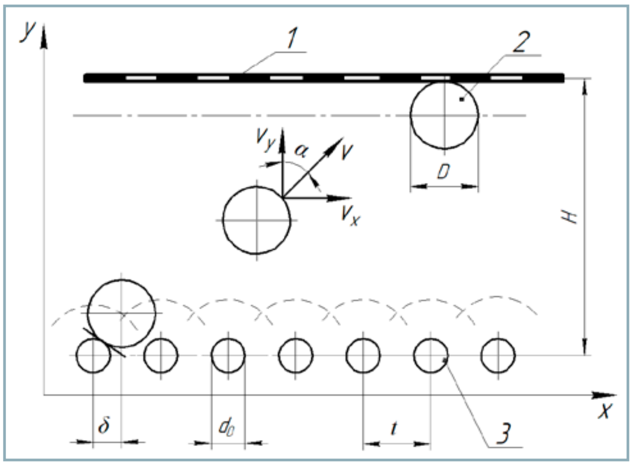

Fig. 1 Ball motion scheme in space under sieve
1 – sorting sieve; 2 – rubber ball; 3 – bar; *D* – ball diameter; *H* – height of space under sieve; *t* – distance between the reflecting surface bars; d_0 – bar diameter

The complete ball motion cycle in space under sorting sieve is represented by the following stages:
– a blow to the sieve or a seed stuck in sieve opening;
– free fall;
– impact on the reflecting surface rod;
– lifting to the sorting sieve.

The mathematical description of ball motion in space under sorting sieve at each stage is performed taking into account the following assumptions:

1. The displacement of ball relative to the rod δ is a stochastic value at the length (0; *t*/2).
2. The oscillation phase of ball when it collides with the reflecting surface rod (*t*) is a stochastic value for the length (0; 2 *p*/*w*).
3. The velocity modulus of ball just before hitting the sorting sieve (or stuck seed) (*v*) is a random variable with the distribution function *f*(*v*).
4. The deviation angle from vertical direction of the ball velocity before hitting the sorting sieve (or stuck seed) (α) is distributed approximately normally, with 3 *s* = *p*/2.

It is accepted that the ball movement speed has horizontal and vertical components after established process of lifting the ball to the sieve.

The ball motion speed at each stage was determined by the following equations.

The ball velocity at the beginning of movement just before hitting the sorting sieve (in a fixed reference system) v0 has the following components:

$$(v_{0x}, v_{0y}) = (v_0 \sin\alpha, v_0 \cos\alpha) \quad (1)$$

where:
α – velocity deviation angle before hitting the sieve

When hitting the sieve, the horizontal component of ball velocity is preserved on average, and the vertical one is transformed as in the case of a partially elastic impact.

Therefore, the ball velocity at the moment of impact on sorting sieve u_1 has the following components:

$$(u_{1x}, u_{1y}) = (v_{0x}, -k \cdot v_{0y}) \quad (2)$$

where:
k – ball recovery coefficient after impact

The ball velocity at the end of fall u_2 is equal to:

$$(u_{2x,}\, u_{2y}) = \Big(v_0 \sin\alpha - A\omega\cos\omega\tau - \quad (3)$$

$$-\sqrt{k^2 v_0^2 \cos^2\alpha + g\left(2H - D - \sqrt{(d_0 + D)^2 - 4\delta^2}\right)}\Big)$$

where:
A – oscillation amplitude of the unit sieves; ω – angular velocity of oscillation of the lattice part; τ – oscillation phase; *g* – gravity acceleration; *H* – height of space under the sieve; *D* – ball diameter; d_0 – rod diameter; δ – ball displacement relative to the rod

The ball velocity after hitting the rod u_3 is equal to:

$$(u_{3x,}\, u_{3y}) = \left(|u_3|\sin\theta, |u_3|\cos\theta\right) \quad (4)$$

where:
θ – angle between the direction of velocity after impact on the rod and the vertical direction

The ball lifting velocity to the sieve v_1 is:

$$(v_{1x,} v_{1y}) = u_{3x} + A\omega\cos\omega\tau \begin{cases} \sqrt{u_{3y}^2 - g\left(2H - D - \sqrt{(d_0+D)^2 - 4\delta^2}\right)} \\ u_{3y} > \sqrt{g\left(2H - D - \sqrt{(d_0+D)^2 - 4\delta^2}\right)} \\ 0, u_{3y} \le \sqrt{g\left(2H - D - \sqrt{(d_0+D)^2 - 4\delta^2}\right)} \end{cases} \quad (5)$$

After full completion of its motion, the ball lifting velocity v_1 is given as a stationary function of the parameters (v_0, α, δ):

$$v_1 = \sqrt{v_{1x}^2 + v_{1y}^2} = F(v_0, \alpha, \delta, \tau) \quad (6)$$

Based on assumption 3, the ball velocity modulus before hitting the sieve is a value that is described by a stationary function with a density distribution $f(v)$. Finding the distribution function $f(v)$ was carried out by numerical methods.

Assuming that the time of the full ball motion cycle fluctuates around certain average value, the following is determined:

– The average ball velocity \$\hat{v}$ near the sorting sieve surface at the beginning of the cycle:

$$\hat{v}=\int_0^{+\infty} vf(v)dv \tag{7}$$

– The average path of the ball L $\hat{L}$ when it falls:

$$\hat{L}=H-\frac{D}{2}-\left(\frac{1}{4}\sqrt{(d_0+D)^2-t^2}+\frac{(d_0+D)^2}{4t}arctg\frac{t}{\sqrt{(d_0+D)^2-t^2}}\right) \tag{8}$$

where:
t – distance between the reflective sieve rods

– The duration of ball passing half cycle t_0, provided that the vertical component of ball velocity at the beginning of cycle was v_y:

$$t_0=\frac{2}{g}\left(\sqrt{v_y^2+2g\hat{L}}-v_y\right) \tag{9}$$

Given the initial velocity is $\hat{v}$, the average ball motion time $\hat{t}_0$ in complete cycle was determined as follows:

$$\hat{t}_0=\frac{2}{g}\int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} f(\alpha)\left(\sqrt{(\hat{v}\cos\alpha)^2+2g\hat{L}}-\hat{v}\cos\alpha\right)d\alpha \tag{10}$$

where:
f(α) – distribution density of the velocity deviation angle before hitting the sieve

The probability of a stone being knocked out by a ball P for one complete cycle of its motion was determined as follows:

$$P=nS\left(1-\int_0^{\sqrt{\frac{12\tilde{E}}{\pi\rho D^3}}} f(v)dv\right) \tag{11}$$

where:
E – ball energy required for knocking out the stone from opening; ρ – material density of ball; n – sieve oscillation frequency; S – sieve opening area

The energy value of ball E, at which the knock-out of stuck seed is guaranteed, can be calculated as follows:

$$\tilde{E}=\frac{2F\cdot h}{3} \tag{12}$$

where:
F – adhesion force of stone and the edge of sieve openings;
h – value of the seed contact with sieve the opening

Taking into account Eqs 10 and 11, the mathematical expectation of time of knocking out the stone from sieve opening is as follows:

$$\hat{T}=\hat{t}_0\sum_{i=1}^{\infty}P_i(1-P)^{i-1}=\frac{\hat{t}_0}{P}=\frac{1}{nS}\frac{\hat{t}_0}{1-\int_0^{\sqrt{\frac{12\tilde{E}}{\pi\rho D^3}}} f(v)dv}\rightarrow\min \tag{13}$$

Considering the presented assumptions, this function (Eq. 13) is an unambiguous function of variables D, t and H.

Optimization of Eq. 13 was performed by the coordinate descent method. The search for optimum value was performed according to:

1. the search was carried out for the optimum value of ball diameter D with fixed values of t and H;
2. optimization was performed for the parameter t/D, and when calculating the value of function at each point, the procedure for item 1 is automatically performed;
3. H/D parameter optimization was performed with automatic execution of item 2 at each function calculation.

Therefore, the task of finding the minimum of a continuous, but undifferentiated, function of three variables is reduced to the superposition of tasks of finding the minimum of functions of one variable.

The gold section method was used for finding the minimum of a function of one variable. This method is slower than the gradient method, however, it does not require continuous differentiation of the function.

The determination of optimum values of parameters D and H was performed by setting the intervals of their optimum values based on the dependences of ball energy distribution density. To plot the dependencies, transition from distribution function $f(v)$ to function $f(E)$ was carried out.

The ball kinetic energy is:

$$E=\frac{mv^2}{2}=\frac{\pi\rho D^3V^2}{12} \tag{14}$$

Since:

$$P(v_0<v<v_0+dv)=f(v)dv \tag{15}$$

Whereas:

$$F(E_0<E<E_0+dE)=\tilde{f}(E)dE \tag{16}$$

where:
$\tilde{f}(E)$ – energy distribution density probability over the parameters D, t, and H

The right parts of Eqs 15 and 16 were equated as:

$$f(v)dv=\tilde{f}(E)dE$$

Taking into account Eq. 14, there is:

$$f(v)dv=\tilde{f}(E)\frac{\pi\rho D^3V}{6}dV$$

As a result, the distribution density probability will have the following form:

$$\tilde{f}(E) = \frac{6f(v)}{\pi \rho D^3 V} \quad (17)$$

The distribution density *f*(*E*) was calculated using the Delphi software shell.

Results and discussion

The optimum values of ball cleaner geometric parameters (*D*, *t*, *H*), by which the ball acquires energy sufficient to knock out the stuck stone from sieve opening, were obtained as follows. Areas of optimum parameter values were determined by plotting the ball energy distribution density depending on the energy necessary for knocking out the seed (Figs 2–4).

Calculations were performed for the following parameter values:

- the coefficient of recovery of ball speed of after impact (determined experimentally for balls with a rubber mark of 1847), $k = 0.7$;
- the ball material density $\rho = 1050$ kg·m^{-3} (Bondarenko and Tsymbal, 2008);
- the angular velocity of electric motor shaft rotation $\omega = 48.2$ s^{-1} (Bondarenko, 2006);
- the amplitude of oscillations of sieve part $A = 0.01$ m (Bondarenko, 2006).

The vertical line graphs indicate the ball energy limit, at which the seed is knocked from opening on average.

This energy was calculated according to Eq. 12:

$$E = 1.867 \cdot 10^{-3} \text{ J} \approx 2 \text{ MJ}$$

When calculating it for other fruit crops, the following values were taken into account:

- the adhesion force of seed to the edge of sieve opening was determined in Newtons. The force value $F \approx 2H$ was obtained;
- the contact value of seed with sieve opening h = 2.8 mm (two sieve thicknesses).

Depending on obtained dependences, the intervals of optimum values of ball cleaner parameters were determined, namely:

1. the ball diameter *D* belongs to the interval 25–35 mm (calculations showed that ball with diameter less than 25 mm is too small);
2. range of values for the space height *H* under sorting sieve is dependent on the ball diameter of the ball and is 1.2D–1.4*D* mm;
3. range of values for the distance between rods *t* should not exceed 0.7*D* (otherwise it creates a significant phenomenon of repeated impact of ball on rods), however, it should not be less than 0.5*D*. It is accepted that $t \approx 0.5D$–$0.7D$ mm.

To obtain the target function (Eq. 13), which describes the ball velocity distribution function and depends on three variables, it is sufficient to apply algorithm (*a*) to find the function minimum via Delphi software shell.

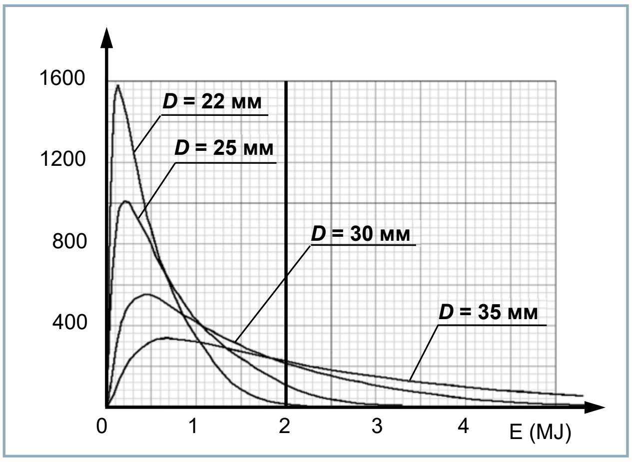

Fig. 2 Ball energy distribution density depending on its diameter *D*
Source: Ridnyj, 1981
t = 0.7*D*; *H* = 1.2*D*

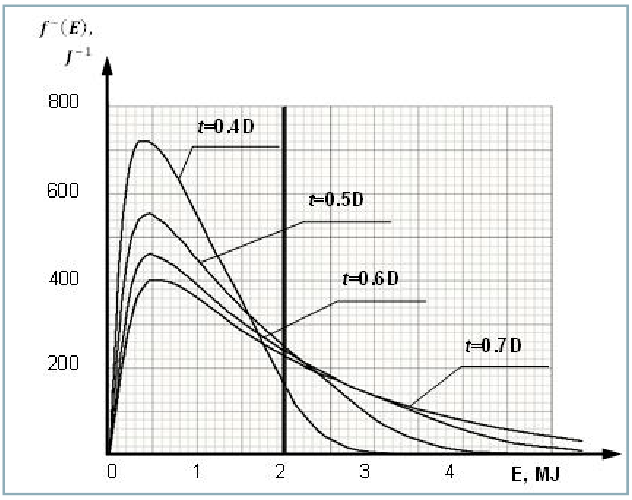

Fig. 3 Ball energy distribution density depending on the distance between rods *t*
D = 33 mm; *H* = 1.2*D*

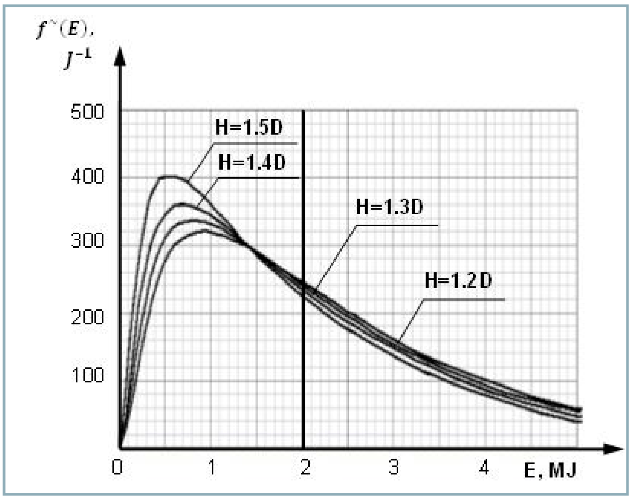

Fig. 4 Ball energy density distribution as a function of the height of space under sieve
H (*D* = 33 mm; *t* = 0.7*D*

As a result of calculations, the following optimum values of ball cleaner parameters were obtained:

– the ball diameter $D = 33$ mm;

– the distance between the rods $t = 23$ mm;

– the space height under sieve $H = 40$ mm.

Ridnyj (1981) and Zavhorodnii (2001) determined a value range of the space height under sieve H depending on the ball diameter D, namely: $1.2D$–$1.4D$ mm. According to developed mathematical model, $D = 33$ mm, $H = 40$ mm belong to the given range of values, indicating the adequacy of proposed model.

The obtained parameters provide the minimum value of the mathematical expectation of the time necessary for knocking out the stone from sieve opening $\hat{T} = 0.03$ s. The average ball velocity is $\hat{v} = 0.4$ m·s^{-1}, the average ball path is $\hat{L} = 0.006$ m.

Conclusion

1. In terms of units for calibration of fruit seeds, the ball cleaners with shock impact proved to be the most efficient tool for cleaning the stuck stones from openings of sorting sieves.
2. It has been defined that the mathematical expectation of time of knocking out the seed from sieve opening is the minimum ratio value of average time of complete ball motion cycle in space under sieve to the probability of knocking out the stone by a ball with sufficient kinetic energy.
3. It has been noted that the magnitude of ball kinetic energy and, therefore, the ball diameter (D), the space height under sieve (H), and the distance between rods of reflecting surface (t) have a significant effect on cleaner quality. It has been proposed to determine the optimum values of these parameters by adjusting the intervals of their optimum values using the dependences of the energy distribution density of ball, minimizing thus the function of knock-out time of stuck stone from opening.

   Using the golden section method, the following parameters of ball cleaner were obtained:

   – the ball diameter $D = 3$ mm;

   – the distance between rods $t = 2$ mm;

   – the space height under sieve $H = 4$ mm.
4. Calculated values of the ball cleaner geometric parameters can serve for development of experimental device and experimental research aimed at determination of the optimum values of sieve unit parameters, namely: oscillation frequency; amplitude of oscillations; and inclination angle between sieves and ball cleaners.

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