815. Investigation of straw layer movement over the walker surface

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Abstract. Straw layer movement over the walker surface has been examined by measuring characteristics of elasticity and viscosity of the straw layer. For this purpose a visco-elastic model has been introduced. The examined process is represented by two stages: the first one is associated with the elastic deformation of the straw while the walker section moves upwards, and the straw layer laying on its surface is subjected to compression. Whereas the second stage involves a free throw of straw after the takeoff from the walker surface, and after the free throw, their contact onto the walker surface. The method of successive steps was used for the analysis of the movement process. The proposed model can be applied for modeling complex nonlinear characteristics of the straw layer movement by employing linear elastic and viscous elements through selection of their equivalent coefficients. Measurement of the elastic and viscous characteristics of the straw layer by their equivalent coefficients enabled to calculate rational rotation angles of the walker crankshaft at the takeoff ωt_1 of the layer from the walker surface and contact ωt_3 to the surface provided that during each period of crankshaft rotation a straw layer undergoes an impact. It was determined that straw movement is mainly dependent on the thickness, moisture content and viscosity of the straw layer. The takeoff of the thicker straw layer from the walker surface is delayed, since after the impact duration of its deformation is longer, resulting in a shorter time of free throw. Wet straw layer is less elastic, resulting in its longer movement jointly with the walker section, and the height of the free throw is smaller resulting in less favorable conditions for grain penetration when compared to the dry straw.

Keywords: straw walker, grain separation, straw properties, crankshafts rotation.

Introduction

Grain combine harvesters use straw walkers where two separate processes occur simultaneously: straw is transported and separated from the grains at the same time (grain separation through the straw layer and walker screens takes place). Modern combine harvesters are commonly equipped with the straw walkers having a length of 3 to 5 m. If during the period of straw transportation over the walker surface some grains remain un-separated, they are passed from the combine harvester onto the crops field surface resulting in a grain loss. Separation efficiency of straw walkers depends on the supplied amount of straw, characteristics of the straw layer, and structural and technological parameters of straw walkers. To improve separation efficiency of straw walkers, a range of walker auxiliaries are in use. Two hypotheses are presented of decisive factor of grain separation from the straw. The first hypothesis states that the greatest influence on the separation process has the impact of the walker surface to the straw layer. The second hypothesis states that grain separation is related with the duration of the straw free movement and the increase of the porosity after the takeoff of straw from the walker surface [1-3]. The interaction of the free movement duration of the straw layer and the walker stroke impulse influencing the separation process has to be coordinated [4].

In theoretical studies of the operation of straw walkers, the straw layer is usually identified with a material point [2, 5]. Irrespectively of the elasticity of the straw, moments of their takeoff ωt_1 from and impact ωt_3 to the walker are calculated from the following equations [2]:

$$\sin \omega t_1 = \frac{\cos\alpha}{k}, \tag{1}$$

where: k – Froude number, ($k = r\omega^2 g^{-1}$). It depends on the amplitude r of the crankshafts of the straw walkers and the angular velocity ω; α – angle of walker surface:

$$\omega t_3 - \omega t_1 = \mathrm{ctg}(\omega t_1 + \alpha) + \sqrt{\mathrm{ctg}^2(\omega t_1 + \alpha) + 2 - 2\frac{\sin(\omega t_3 + \alpha)}{\sin(\omega t_1 + \alpha)}}. \tag{2}$$

Given the straw takeoff angle ωt_1, the angle of crankshaft rotation ωt_3 is found, at which the straw strikes the walker. After the crankshafts rotation of 360° per 0.3 sec. (when k = 2.24 and n = 200 min^{-1}), the straw take off from the walker surface once and upon striking onto it again, receives one impact [3, 4].

However, as characteristics of elasticity and viscosity of the straw layer were not taken into consideration, there was a significant mismatch between theoretical and experimental findings [6]. It was suggested to include these characteristics by assuming that the straw oscillates along the vertical axis relative to the walker [7]. Researchers also suggested to measure the oscillation by means of amplitude A_y, lag phase $\Delta\varphi_y$ and a frequency of straw layer free oscillations p_0. Researchers measured oscillation damping by the straw layer viscosity coefficient. Following theoretical examination of the relative motion of the centre of mass of the straw layer, while taking into consideration internal resistances that are proportional to the velocity, the straw takeoff angle ωt_1 was found as follows:

$$\sin \omega t_1 = \frac{\cos\alpha}{k} - \frac{A_y}{r}\sin(\omega t_1 - \Delta\varphi_y). \tag{3}$$

Depending on the viscosity and elasticity of the straw layer, ωt_1 can vary in a wide range resulting in a varied angle ωt_3 of straw impact to the surface of straw walker sections. S. Grigorjev [8] found that at the moment of straw takeoff from the walker section surface straw velocity exceeds that of the walker section. Author proved that vertical constituent of the stroke impulse at the moment of straw impact to the walker surface is directly proportional to the mass of the straw layer, inversely proportional to the angular velocity of the crankshafts ω, and is reduced with the increasing duration of the impact phase $\omega\tau$. However, the Equation 3 can be used only when characteristics of the straw layer are known.

Experimental studies indicate that while moving over the surface of walker sections, straw layer is subjected to deformation, and the impact of the walker section on the straw layer is only partial as it is reduced by the viscosity of the layer [1, 4]. Impulses resulting from the walker sections strokes are damped, their energy is dissipated, and top straw layers are impacted only partially (hysteresis losses occur). Meanwhile, grain separation through the straw layer flowing over the walker surface depends on the number of strokes hit by walker sections to the straw layer, and duration of its free throw [5, 9, 12]. The effect of the viscosity and elasticity of the straw layer on the nature of straw movement over the walker surface and on the grain separation is not sufficiently studied.

The research goal, by means of theoretical investigation, to determine such α, ω and r values, while taking into consideration characteristics of different crops, that lead to the longest time of free movement (throw) of the straw layer with the walkers crankshafts rotation at the angle 2π, and single stroke. When these conditions are met, grain separation is believed to be the most effective.

Methodology and means of the experiment

Straw movement over the walker (Fig. 1) surface is examined by taking into consideration characteristics of viscosity and elasticity of the straw layer. For this purpose a visco-elastic model is introduced (Fig. 2). In this model, elasticity of the straw layer is represented by mechanical springs with elastic components: one parallel k_x and one perpendicular k_y to the walker's surface, viscosity – by dampers with the viscosity (damping) coefficients $h_{kv,x}$ and $h_{kv,y}$. Besides the internal resistances of the layer, the resistance of ambient air (air resistance) exists. Its effect was taken into consideration through dampers with viscosity coefficients $h_{ki,x}$ and $h_{ki,y}$. Resistance force of ambient air involves two constituents, one measuring air flow around the freely-moving straw layer, and another one – air extrusion from the porous straw layer and from the gap between the straw layer and walker surface. Respectively, if the first constituent of the air resistance force is proportional to the absolute straw layer velocity $\dot{X}_s$ and $\dot{Y}_s$, the second one then depends on the relative velocity of the straw layer relative to the walker section velocity $\dot{x}_s$ and $\dot{y}_s$. As the walker section surface is made of sieve, the air resistance between the straw layer and the walker surface (the second constituent) is insignificant, thus it is reasonable to neglect it.

In reality, all the dynamic systems are not linear [10, 11], including straw flow over the walkers surface since the damping is nonlinear. Several methods exist for the calculation of nonlinear systems: harmonic balance, harmonic linearization, the method of the small parameter, averaging, Ritz-Galerkin method, the method of successive steps, etc.

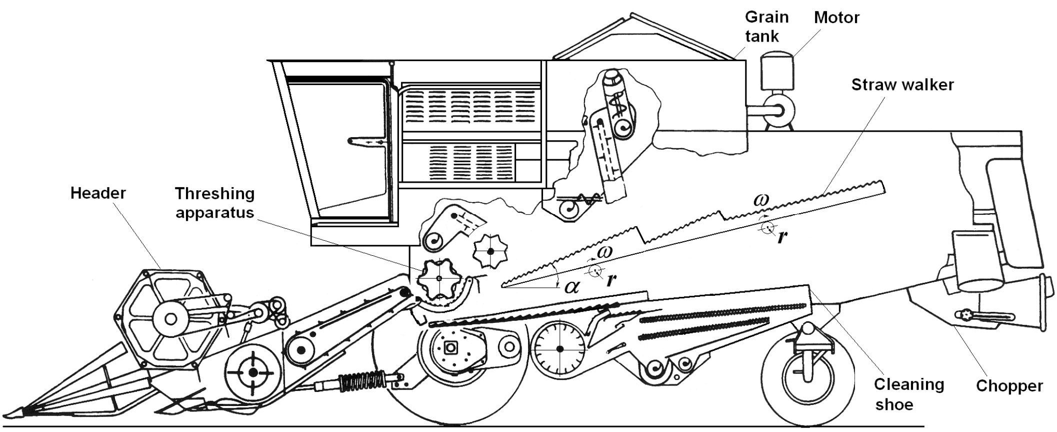


Fig. 1. Combine harvester with tangential threshing apparatus and straw walker: α – the inclination angle of walker surface; r – crankshaft radius; ω – angular velocity

Straw movement over the walkers surface can be examined in the following two stages: the first stage is associated with the elastic deformation of straw while the straw walker section moves upwards, and the straw layer laying on its surface is compressed. Whereas the second stage involves a free throw of straw after their takeoff from the walker surface, and afterwards, their stroke onto the walker surface. Consequently, for the analysis of the movement process the method of successive steps can be adopted where stages of straw movement are described by different linear differential equations with the constant coefficients, i.e., straw movement is characterized as a partially linear system. To find solutions to these equations it is sufficient to know initial conditions of each stage that are coincident with the boundary conditions of the previous stage. Boundaries between stages are found using transcendental equations.

The developed model can be adopted for modeling complex nonlinear characteristics of straw layer movement by linear elastic and viscous elements by choosing their equivalent coefficients. Elasticity and viscosity of the straw layer moving over the surface of the straw walker section were measured not by physical values but by equivalent coefficients that characterize properties of a straw layer. Their values are dependent on the amount of the straw layer supplied on the top of the walker, moisture content, thickness of the layer and composition.

The equivalent coefficients can be found through experimentation [13, 14] after recording a straw movement on a film. Given the same selected kinematics regime coefficient k, the velocity of straw flow over the walker surface v_s is found, as well as angles of rotation of the crankshaft at the straw takeoff (ωt_1) and stroke (ωt_3) to the walker surface, and the trajectory of straw movement after takeoff from the walker surface are found, etc. Analogous values, given the same coefficient k, are found through theoretical calculations (solving previously introduced equations) by varying values of equivalent elastic and viscous coefficients in a wide range. Then, results of experimentation and theoretical calculations are compared. Best matches are taken for the correct results, whereas the equivalent coefficients used in theoretical calculations are considered as defining characteristics of straw moving over the walker surface. Knowing the equivalent coefficients of elasticity and viscosity (coefficients of energy dissipation) enables analytical examination of straw movement over the walker surface under varying frequency of the crankshaft rotation, walker crankshaft radius, and the inclination angle of walker surface. By the way, if numerical values of the equivalent coefficients remain constant under the aforementioned parameters, when changing flow of the straw supplied q_s (by increasing thickness of straw layer h_s on the walker), they obtain different values. One distinction of the model of transported layer is the possibility of modeling its complex nonlinear characteristics by linear elastic and viscous elements [13].

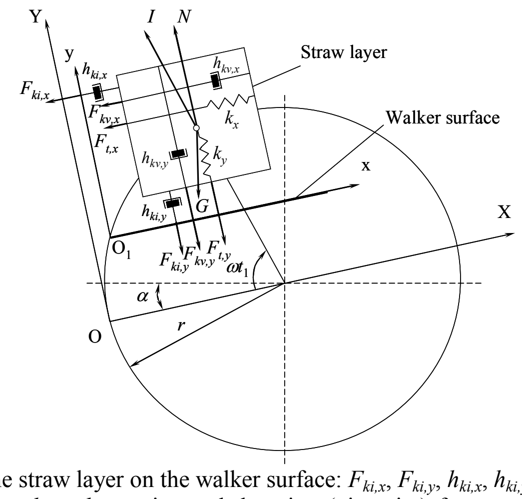


Fig. 2. Forces acting on the straw layer on the walker surface: $F_{ki,x}$, $F_{ki,y}$, $h_{ki,x}$, $h_{ki,y}$ – external damping forces and coefficients; $F_{kv,x}$, $F_{kv,y}$, $h_{kv,x}$, $h_{kv,y}$ – internal damping (viscosity) forces and coefficients; F_{tx}, F_{ty}, k_x, k_y – spring forces of the straw layer and coefficients; G – gravity force of straw layer; I – inertia force; N – normal force of the straw layer reaction to the walker surface; α – inclination angle of walker surface; r – walker crankshaft radius; ωt_1 – angle of rotation of the crankshaft at the straw takeoff from the walker

The movement of the straw layer over straw walker was filmed with the digital high-speed camera Photron 1024 PCI, at the frequency of 750 frames per second or every 0.00133 s [4]. The filmed pictures were stored in the computer connected with the camera and recorded on CD. The tests were performed in the laboratory of Aleksandras Stulginskis University.

Results and discussions

The shifting Cartesian coordinate system xOy was used for the model development, with its coordinate axes moving along the circle together with the walker's crankshaft at the walker crankshaft radius r (Fig. 2). They have in parallel the non-shifting coordinate system XOY. Movement of the straw with respect to the shifting axis is relative, whereas with respect to the non-shifting axis – absolute.

In the initial position, state of the straw layer freely lying on the walker section is represented by non-deformed spring and non-compressed damper. With the walker section moving upwards, the straw layer is compressed, and the vertical constituent of its relative displacement, y_s, in respect to the walker section surface is directed downwards (negative). Thickness of the straw layer is reduced to minimum (spring and damper are compressed). Rate of deformation depends on the rigidity of the straw layer (spring), and velocity of deformation spread – on the internal viscosity of the straw layer (viscosity of filler within damper).

When the reaction force of the straw layer to the walker surface N becomes zero, its state is represented by the compressed spring (with an energy stored in it), and at this moment straw takes off the walker surface. After the takeoff, during the following free throw, due to the energy stored within, a straw layer expands (spring returns from the deformed state into the initial one). This happens only until the straw reaches the highest point of free throw trajectory. During free fall under gravity straw layer expands even further (the spring is stretched).

When the walker section moves upwards, the falling straw layer (stretched spring) strikes the walker surface and straw receives impact resulting in straw layer deformation (compression of a spring). Straw deformation takes place until the moment when their reaction force N becomes equal to zero again, and the straw layer takes off the walker surface, and the process is repeated. This is how straw is transported towards the end of walker section, and at the same time grains are separated from straw and penetrated through walker sieve. Processes of straw transportation and grain separation that are interdependent occur simultaneously.

Straw walker crankshafts are rotated in a clockwise direction. The angle of rotation of the crankshaft, ωt, is measured from the axis OX. Assuming that ω is the angular velocity of the crankshaft rotation, after the particular time period t, the angle of rotation will be ωt_1, and point O of the walker section will be in the position O_1. Then, coordinates of the walker section point O_1 will be as follows:

$$Y_{kl} = r\sin\omega t\,;\;\; X_{kl} = r\cos\omega t\,. \tag{4}$$

Equation 4 defines a position of the walker point O_1 at any moment of time. Then, velocity and acceleration constituents of the point O_1 with respect to the non-shifting coordinate axes XOY are as follows:

$$\dot{Y}_{kl} = r\omega\cos\omega t\,;\;\; \dot{X}_{kl} = -r\omega\sin\omega t\,; \tag{5}$$

$$\ddot{Y}_{kl} = -r\omega^2\sin\omega t\,;\;\; \ddot{X}_{kl} = -r\omega^2\cos\omega t\,. \tag{6}$$

Forces acting on the straw layer:

a) inertia: $I_y = m_s\ddot{Y}_{kl} = -m_s r\omega^2\sin\omega t$; $I_x = m_s\ddot{X}_{kl} = -m_s r\omega^2\cos\omega t$; (7)

b) gravity: $G = -m_s g$; (8)

where g – acceleration of gravity, in m/s^2;
m_s – mass of the straw layer, in kg;

c) dry friction (Coulomb's law): $F_{tr} = f_s N$; (9)

where f_s – the coefficient of static friction between the straw layer and the walker surface;

d) internal viscous friction (damping): $F_{kv,y} = -h_{kv,y}\dot{y}_s$; $F_{kv,x} = -h_{kv,x}\dot{x}_s$; (10)

where: $h_{kv,x}$ and $h_{kv,y}$ – coefficients of internal damping or viscous friction of the straw layer, N·s·m^{-1},
$\dot{x}_s, \dot{y}_s$ – constituents of the straw layer relative velocity with respect to axes xOy coincident with the walker surface, m·s^{-1};

e) external viscous friction (damping): $F_{ki,y} = -h_{ki,y}\dot{y}_s$; $F_{ki,x} = -h_{ki,x}\dot{x}_s$; (11)

where $h_{ki,x}$ and $h_{ki,y}$ – coefficients of ambient air resistance or air viscous friction, N·s·m^{-1};
f) elasticity: $F_{t,y} = -k_y y_s$; $F_{t,x} = -k_x x_s$; (12)
where k_x, k_y – the coefficients of rigidity of the straw layer, N·m^{-1};
x_s, y_s – constituents of relative displacement of the straw layer with respect to axes xOy coincident with the walker surface, m;
g) normal reaction: $N = \left| h_{kv,y}\dot{y}_s + k_y y_s \right|$. (13)

The internal force of viscous friction, F_{kv}, is present within the straw layer only while it is moving jointly with the walker, and after its takeoff from the walker surface, external force of viscous friction, F_{ki}, starts acting.

The viscous friction forces (F_{kv} and F_{ki}) and elasticity force F_t are opposite to the direction of the movement of the straw layer. F_{kv} is proportional to the relative, with respect to the walker section, velocity of deformation spread, $\dot{x}_s, \dot{y}_s$, within the straw layer, whereas F_{ki} – to the absolute $\dot{X}_s$ and $\dot{Y}_s$. The elasticity force of the straw layer, F_t, is proportional to relative, with respect to the walker section, displacement of deformation (x_s and y_s) within the straw layer. After the takeoff of the straw layer from the walker surface, effect of the force F_t is excluded from the consideration.

When the straw moves jointly with the walker section, their slide forward or backwards on its surface is possible. As the walker sections have raised side edges, it is assumed they prevent straw from sliding on the walker surface. In the absence of sliding, the straw layer is only insignificantly shifted along x axis in result of elastic deformations of the straw layer. This shift is also left out of the consideration, i.e., as long as the walker section moves upwards with the straw laying on it, i.e., until N becomes equal to zero, it is assumed that the horizontal constituent of the relative displacement of the straw layer, x_s, with respect to the walker section, is equal to zero.

Joint movement of the straw layer with the walker section is comprised of two stages: impact stage and post-impact stage. In the impact stage, the straw layer undergoes deformation, thus $y_s > m_s g k_y^{-1}$. The impact stage reaches its end when $y_s \le m_s g k_y^{-1}$, and afterwards the post-impact stage follows. During the post-impact stage the straw layer moves jointly with the walker section until it is thrown off. The boundary between these stages can be found by solving a transcendental equation which is obtained by assuming that the vertical constituent of the relative displacement of the straw layer with respect to the walker section, y_s, is equal to the static deformation of the straw layer: $y_s = m_s g k_y^{-1}$.

The differential equations are used to define visco-elastic movement of the straw layer. At the beginning of the process, the walker section moves upwards and the straw laying on its surface undergo compression, i.e., the elastic deformation of straw takes place.

The equations of the relative motion of the straw layer with respect to the walker section are obtained by projecting the acting forces along the shifting axes x and y.

Projection of forces along y axis:

$$-m_s\ddot{y}_s - m\ddot{Y}_{kl} - h_{kv,y}\dot{y}_s - k_y y_s - m_s g\cos\alpha = 0\,, \qquad (14)$$

where α – the inclination angle of the walker section to the horizontal axis.

Rearrangement of the Equation (14) results in the following:

$$\ddot{y}_s + 2n_{kv,y}\dot{y}_s + p_y^2 y_s = -g\cos\alpha + r\omega^2\sin\omega t\,, \qquad (15)$$

where: $n_{kv,y}$ – equivalent coefficient of damping that is used to measure internal resistance of the straw layer to deformation along the y axis, s^{-1}: $2n_{kv,y} = \dfrac{h_{kv,y}}{m}$;

p_y – equivalent frequency of the straw layer free oscillations, s^{-1}: $p_y^2 = \frac{k_y}{m}$.

From the Equation (15) the following homogenous differential equation is derived:

$$\ddot{y}_s + 2n_{kv,y}\dot{y}_s + p_y^2 y_s = 0. \quad (16)$$

The characteristic equation of the differential Equation (16) is written as follows:

$$\lambda^2 + 2n_{kv,y}\lambda + p_y^2 = 0. \quad (17)$$

Roots of the equations are calculated:

$$\lambda_1 = -n_{kv,y} - \sqrt{n_{kv,y}^2 - p_y^2} \text{ and } \lambda_2 = -n_{kv,y} + \sqrt{n_{kv,y}^2 - p_y^2}. \quad (18)$$

Depending on values of $n_{kv,y}^2$ and p_y^2, the following 3 cases are possible: when $n_{kv,y}^2 < p_y^2$, free suppressive oscillations occur in the system, and solutions to the Equation (17) are complex consolidated square roots; when $n_{kv,y}^2 > p_y^2$ – system does not oscillate but its movement is aperiodic, and roots of the equation are real and negative; when $n_{kv,y}^2 = p_y^2$ – suppression is marginal (critical), and the equation has two iterative square roots [10].

Homogenous solution to the Equation (16):

$$\tilde{y} = C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t}, \text{ when } \lambda_1 \neq \lambda_2. \quad (19)$$

This is not a periodical solution, and the process is not oscillatory. Suppression is so high that a system, when thrown out of balance and further not disturbed does not oscillate but gradually returns to the state of static balance. This movement is aperiodic. It is defined by the following equation:

$$\tilde{y} = C_1 e^{\left(-n_{kv,y} - \sqrt{n_{kv,y}^2 - p_y^2}\right)t} + C_2 e^{\left(-n_{kv,y} + \sqrt{n_{kv,y}^2 - p_y^2}\right)t}. \quad (20)$$

Formulation (18), showing square roots of the Equation (17), is rearranged as follows:

$$\lambda_1 = p_y\left(-\frac{n_{kv,y}}{p_y} - \sqrt{\frac{n_{kv,y}^2}{p_y} - \frac{p_y^2}{p_y^2}}\right), \quad (21)$$

where $\frac{n_{kv,y}}{p_y} = \varepsilon_{kv,y}$ – the coefficient of damping.

Thus:

$$\lambda_1 = p_y\left(-\varepsilon_{kv,y} - \sqrt{\varepsilon_{kv,y}^2 - 1}\right). \quad (22)$$

The following denotations are introduced:

$$\kappa_{1,y} = -\varepsilon_{kv,y} + \sqrt{\varepsilon_{kv,y}^2 - 1}; \; \kappa_{2,y} = -\varepsilon_{kv,y} - \sqrt{\varepsilon_{kv,y}^2 - 1}. \quad (23)$$

Afterwards:

$$\lambda_1 = p_y \kappa_{1y} \text{ and } \lambda_2 = p_y \kappa_{2y}. \quad (24)$$

Denoting leads to the following: $z_y = \frac{\omega}{p_y}$ – dynamic amplification factor. It follows that $p_y = \frac{\omega}{z_y}$.

If the excitation frequency (crankshaft rotation velocity) ω matches the frequency of straw layer free oscillations p_y, resonance is expected.

It follows that:

$$\lambda_1 = \frac{\kappa_{1,y}}{z_y}\omega \text{, analogously } \lambda_2 = \frac{\kappa_{2,y}}{z_y}\omega . \tag{25}$$

The obtained values are inserted into the Equation (20):

$$\tilde{y} = C_1 e^{\frac{\kappa_{1,y}}{z_y}\omega t} + C_2 e^{\frac{\kappa_{2,y}}{z_y}\omega t} . \tag{26}$$

The solution to the non-homogenous part of the Equation (15) is found using a method of indefinite coefficients: when $\lambda_{1,2} \neq \pm\omega i$, it is defined by the following formula:

$$\bar{y} = K_1 \cos\omega t + K_2 \sin\omega t + K_3 . \tag{27}$$

Denoting leads to the following:

$$K_1 = -\frac{2n_{kv,y}r}{\omega\left(\frac{1}{z_y^4} - \frac{2}{z_y^2} + 1 + \frac{4n_{kv,y}^2}{\omega^2}\right)},\ K_2 = -\frac{r\left(\frac{1}{z_y^2} - 1\right)}{\frac{1}{z_y^4} - \frac{2}{z_y^2} + 1 + \frac{4n_{kv,y}^2}{\omega^2}},\ K_3 = -\frac{g\cos\alpha}{p_y^2}.$$

Since $p_y = \frac{\omega}{z_y}$, then $K_3 = -\frac{r\cos\alpha\ z_y^2}{k}$, where $k = \frac{r\omega^2}{g}$ – coefficient of the kinematic operation regime of walkers (ratio of inertia and gravity forces), also known as the Froude number.

The general solution to the Equation (15) is found from Equations (26) and (27):

$$y_s = C_1 e^{\frac{\kappa_{1,y}}{z_y}\omega t} + C_2 e^{\frac{\kappa_{2,y}}{z_y}\omega t} + K_1 \cos\omega t + K_2 \sin\omega t + K_3 . \tag{28}$$

For the calculation of values of the constants C_1 and C_2 the initial conditions are defined. In a steady regime, before the movement, on the surface of walker section (before takeoff), the straw layer moves freely (flies), thus elastic deformation starts with the beginning of the impact, i.e., under initial conditions $t = t_3$; $y_s(t_3) = y_{s3}$; $\dot{y}_s(t_3) = \dot{y}_{s3}$; t_3 – time at which the straw layer strikes the walker surface; y_{s3} – a relative displacement of the straw layer (coordinate) with respect to the walker section at the moment of the strike to the walker surface; $\dot{y}_{s3}$ – a relative velocity of the straw layer with respect to the walker section at the moment of the strike to the walker surface.

The velocity of the straw layer is obtained by finding the derivative of the Equation (28) as follows:

$$\dot{y}_s = C_1 \frac{\kappa_{1,y}\omega}{z_y} e^{\frac{\kappa_{1,y}}{z_y}\omega\ (t_1 - t_3)} + C_2 \frac{\kappa_{2,y}\omega}{z_y} e^{\frac{\kappa_{2,y}}{z_y}\omega\ (t_1 - t_3)} - K_1 \sin\omega t + K_2 \cos\omega t\ . \tag{29}$$

Inserting initial conditions to the Equations (28) and (29), values of the constants C_1 and C_2 are calculated as follows:

$$C_1 = \frac{z_y\dot{y}_{s3} - \kappa_{2,y}y_{s3} + \sin\omega t_3\left(\kappa_{2,y}K_2 + z_yK_1\right) + \cos\omega t_3\left(\kappa_{2,y}K_1 - z_yK_2\right) + \kappa_{2,y}K_3}{e^{\frac{\kappa_{1,y}}{z_y}\omega t_3}\left(\kappa_{1,y} - \kappa_{2,y}\right)}, \tag{30}$$

$$C_2 = \frac{z_y\dot{y}_{s3} - \kappa_{1,y}y_{s3} + \sin\omega t_3\left(\kappa_{1,y}K_2 + z_yK_1\right) + \cos\omega t_3\left(\kappa_{1,y}K_1 - z_yK_2\right) + \kappa_{1,y}K_3}{e^{\frac{\kappa_{2,y}}{z_y}\omega t_3}\left(\kappa_{2,y} - \kappa_{1,y}\right)} . \tag{31}$$

Inserting values y_s from (28) and velocity from (29) $\dot{y}_s$ of a relative displacement of straw elastic deformation with respect to the walker section into the Equation (13), the reaction force is found as follows:

$$N = m\left(R_1 e^{\frac{\kappa_{1,y}}{z_y}\omega(t_1-t_3)} + R_2 e^{\frac{\kappa_{2,y}}{z_y}\omega(t_1-t_3)} + R_3\cos\omega t + R_4\sin\omega t + R_5 \right), \tag{32}$$

where: $2n_{kv,y}C_1\dfrac{\kappa_{1,y}}{z_y} + p_y^2 C_1 = R_1$; $\quad 2n_{kv,y}C_2\dfrac{\kappa_{2,y}}{z_y} + p_y^2 C_2 = R_2$;

$p_y^2 K_1 + 2n_{kv,y}K_2 = R_3$; $\quad p_y^2 K_2 - 2n_{kv,y}K_1 = R_4$; $\quad p_y^2 K_3 = R_5$.

When the reaction force N becomes zero, the straw takes off the walker's surface and afterwards moves freely until striking the walker surface again. Adopting the method of successive steps for the solution of nonlinear systems, the transcendental equation is made for the purpose of finding joints of stages of the straw movement, by setting the Equation (32) equal to zero:

$$N = m\left(R_1 e^{\frac{\kappa_{1,y}}{z_y}\omega(t_1-t_3)} + R_2 e^{\frac{\kappa_{2,y}}{z_y}\omega(t_1-t_3)} + R_3\cos\omega t + R_4\sin\omega t + R_5 \right) = 0. \tag{33}$$

Rearrangement of the Equation (33) enables to determine the angle of rotation of the crankshaft, ωt_1, at the moment of straw takeoff from the walker surface:

$$R_1 e^{\frac{\kappa_{1,y}}{z_y}\omega(t_1-t_3)} + R_2 e^{\frac{\kappa_{2,y}}{z_y}\omega(t_1-t_3)} + \sqrt{R_3^2 + R_4^2}\sin\left(\omega t_1 + arctg\frac{R_3}{R_4}\right) = -R_5. \tag{34}$$

Taking into account the characteristics of the straw layer, the Equation (34) can be used to calculate the moment of the straw takeoff from the walker surface ωt_1, in a steady operation regime, by changing the frequency of rotation of crankshafts ω, walker crankshaft radius r, and the inclination angle of walker surface α. For the purpose of finding the angle ωt_1, a software package was used for computations.

The angle of the straw takeoff, ωt_1, depends not only on the kinematic parameters of walkers, but also on the angle of rotation of the crankshaft, ωt_3, provided the straw layer has previously struck the walker surface.

The period when the straw moves apart from the walker (after their takeoff). Equations of the straw layer relative movement with respect to the walker section following the straw takeoff are found by projecting the acting forces along the shifting axes x and y.

After the straw layer takeoff from the walker surface, its further movement is resisted by the force of external viscous friction F_{ki}, i.e., the ambient air resistance. During the free movement, effect of the straw layer internal forces is left out of the consideration. Projection of forces along y axis:

$$-m_s\ddot{y}_s - m\ddot{Y}_{kl} - h_{ki,y}\dot{y}_s - m_s g\cos\alpha = 0. \tag{34}$$

Rearrangement of the Equation (34) leads to the following:

$$\ddot{y}_s + 2n_{ki,y}\dot{y}_s = -g\cos\alpha + r\omega^2\sin\omega t, \tag{35}$$

where: $n_{ki,y}$ – equivalent coefficient of damping that is used to measure external resistances of the straw layer free movement along the y axis, s^{-1}: $2n_{ki,y} = \dfrac{h_{ki,y}}{m}$.

The homogenous equation is derived from the Equation (35):

$$\ddot{y}_s + 2n_{ki,y}\dot{y}_s = 0 . \tag{36}$$

The following is the solution to the Equation (36):

$$\tilde{y}_1 = C_3 + C_4 e^{\kappa_{3,y}\omega\, t} , \tag{37}$$

where: $\kappa_{3,y} = \dfrac{2n_{ki,y}}{\omega}$.

The solution to the non-homogenous part of the Equation (35) is found using a method of indefinite coefficients: when $\rho_1 = 0$; $\rho_2 = -2n_{ki,y}$, it is defined using the following formula:

$$\bar{y}_1 = K_4 \cos\omega t \; + K_5 \sin\omega t \; + K_6 , \tag{38}$$

where: $K_4 = \dfrac{\kappa_{3,y} r}{1+\kappa_{3,y}^2}$, $K_5 = \dfrac{-r}{1+\kappa_{3,y}^2}$, $K_6 = -\dfrac{g\cos\alpha}{2n_{ki,y}}$.

Then, the equation for computing the displacement of straw free movement is derived from the Equations (37) and (38):

$$y_s = C_3 + C_4 e^{\kappa_{3,y}\omega\, t} + K_4 \cos\omega t \; + K_5 \sin\omega t \; + K_6 . \tag{39}$$

For the calculation of values of the constants C_3 and C_4 the initial conditions are defined. In a steady regime, before the free movement (flying) of the straw, the straw move freely (flies) on the walker surface until takeoff, thus free movement of the straw starts at its takeoff, i.e., under initial conditions $t = t_1$; $y_s(t_1) = y_{s1}$; $\dot{y}_s(t_1) = \dot{y}_{s1}$; t_1 – time of the straw layer takeoff from the walker surface; y_{s1} – relative displacement of the straw layer (coordinate) with respect to the walker surface at the moment of their takeoff from the surface; $\dot{y}_{s1}$ – relative velocity of the straw layer with respect to the walker section at the moment of the straw takeoff from the walker surface.

Then, the equation is formulated for establishing the velocity of the straw free movement:

$$\dot{y}_s = C_4 \kappa_{3,y} e^{\kappa_{3,y}\omega(t_3 - t_1)} - K_4 \sin\omega t_1 + K_5 \cos\omega t_1 . \tag{40}$$

The initial conditions are inserted into the Equations (39) and (40), and values of the constants C_3 and C_4 are calculated as follows:

$$C_3 = \frac{\dot{y}_{s1} - \kappa_{3,y} y_{s1} + \cos\omega t_1 \left(\kappa_{3,y} K_4 - K_5\right) + \sin\omega t_1 \left(\kappa_{3,y} K_5 + K_4\right) + \kappa_{3,y} K_6}{\kappa_{3,y}} , \tag{41}$$

$$C_4 = \frac{\dot{y}_{s1} + K_4 \sin\omega t_1 - K_5 \cos\omega t_1}{\kappa_{3,y} e^{\kappa_{3,y}\omega t_1}} . \tag{42}$$

The straw will fall onto the walker surface when the vertical constituent of the relative displacement becomes zero. For this purpose the transcendental equation is derived by setting the Equation (39) to zero:

$$C_3 + C_4 e^{\kappa_{3,y}\omega(t_3 - t_1)} + K_4 \cos\omega t_3 + K_5 \sin\omega t_3 + K_6 = 0 . \tag{43}$$

Rearrangement of the Equation (43) leads to the following:

$$C_3 + C_4 e^{\kappa_{3,y}\omega(t_3 - t_1)} + \sqrt{K_4^2 + K_5^2}\, \sin\left(\omega t_3 + \operatorname{arctg}\frac{K_4}{K_5}\right) = K_6 . \tag{44}$$

The angle of rotation of the crankshaft ωt_3 at the straw strike to the walker surface is found from the Equation (44).

Using Equations (34) and (44), moments can be determined, within the single period $T = 2\pi\omega^{-1}$ of walkers operation, when the straw layer moves jointly with the walker ($\omega\tau$), and the angle of rotation of the crankshaft ωt_2, when the straw move freely (flies):

$$\omega t_2 = \omega t_3 - \omega t_1 ; \tag{45}$$

$$\omega \tau = \omega t_1 + 2\pi - \omega t_3 . \tag{46}$$

The review of the published theoretical research findings regarding straw flow over the walker surface and grain separation, and comprehensive analysis thereof lead to the conclusion that major effect on the grain separation comes from the free movement of the straw layer, however the impact impulse by the walker section is also important [1, 2, 5]. This leads to the conclusion that over the period while the crankshaft of the walker rotates one turn (over the single period $T = 2\pi\omega^{-1}$), the straw layer has to remain in the expanded state for as long as possible, i.e., move freely, and the duration of the impact by the walker section $\omega\tau$, must be made as short as possible. The duration of both moments (ωt_2 and $\omega\tau$) depends on the angular frequency of the rotation of crankshaft ω, walker crankshaft radius r, and the inclination angle of walker surface α.

Theoretical research is aimed at finding optimum values of the aforementioned variables, under which ωt_2 would reach its maximum provided that $\omega\tau + \omega t_2 \le 2\pi$, when $\omega\tau>0$. This restriction was assumed in order to avoid the so-called double jumps that happen when crankshafts are rotated at higher angular frequency when in the first place upper and afterwards lower straw layers undergo only one impact in 2 periods. Double jumps are not effective for grain separation as the straw layer is too sparsely struck by the walker section [4]. Accordingly, the entire straw layer must be at least once struck by the walker surface during each period.

Separation efficiency of straw walkers decreases rapidly with increasing straw throughput because the thicker straw layer cannot be loosened enough and grain gets caught in the straw [15]. Theoretical research shows the viscosity of the thicker straw layer to be higher, whereas the frequency of free oscillations slightly lower. Increasing thickness of the straw layer from 0.3 to 0.5 m, the coefficient measuring its internal resistances $n_{kv,y}$ increases from 281 s^{-1} to 326 s^{-1}. Based on the derived Equations (34) and (44), graphical characteristics were obtained enabling to establish the effect of the angle of rotation of the crankshaft on the straw layer takeoff from the walker surface (Fig. 3a) and on the strike to it (Fig. 3b). Increasing thickness of the straw layer makes its takeoff from the walker surface (Fig. 3a) more delayed and strike to it (Fig. 3b) – more advanced. The duration of straw layer free movement ωt_2 is longer when the straw layer is thinner (Fig. 4) with the straw remaining longer in the expanded state thus preventing grains from escaping through thick straw layer.

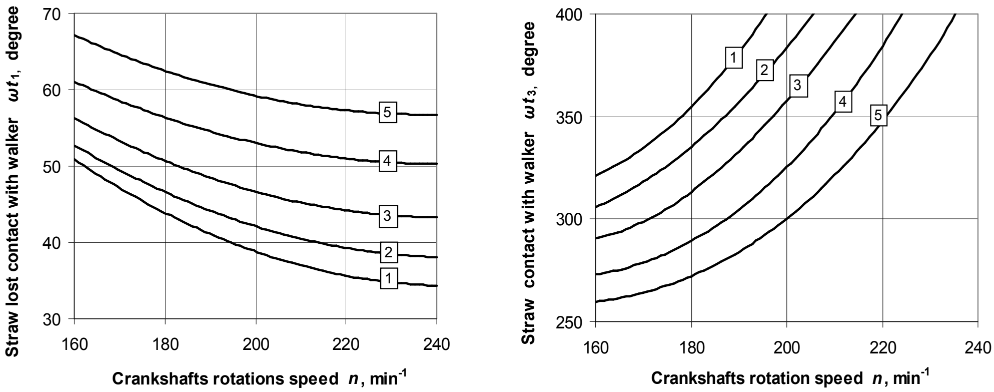
The effect of the ambient air resistance, which is measured by the coefficient of damping $n_{ki,y}$, on the straw layer movement is by 7-9 times less than that acting inside the layer.

With the increasing thickness of the straw layer, the optimum crankshafts rotation frequency increases, i.e., with the increasing ω the straw layer moves freely longer, during a single period, and receives one impact from the walker. Consequently, the separation process is the most intensive. Research indicates that the optimum rotation frequency of straw walkers with the crankshafts of standard radius (r = 0.05 m), provided that h_s = 0.3 m, is 210 min^{-1}, and at h_s = 0.5 m – 230 min^{-1}, then the maximum numerical value of ωt_2 is 330 degrees.

With the increasing inclination angle of the walker surface α the moments of the straw takeoff and contact become more advanced in time, their difference remains almost constant ranging α from 0 to 30 degrees. This leads to conclusion that inclination angle of walker surface, with the exception of the first one, has no significant effect on the grain separation. Only steps present in the joints of walker sections are effective.

Conclusions

Based on the proposed mathematical model, the movement of the elastic and viscous straw layer, measured by the equivalent coefficients, over the walker surface was examined and equations formulated for calculating the angles of rotation of crankshafts, moments of the straw layer takeoff ωt_1 and contact ωt_3 with the walker surface and of the free flying ωt_2. The provided equations were used to calculate the optimum values of ωt_1 and ωt_3 (when ωt_2 = max) leading to the final results that walker crankshafts must be rotated at frequency of 215 min^{-1} (r = 0.05 m, h_s = 0.4 m) for the straw layer to receive one impact with the walker surface, whereas this frequency must be 230 min^{-1} when h_s = 0.5 m.



a) b)

Fig. 3. The effect of the crankshafts rotation frequency (n) on the angle of the straw layer takeoff (ωt_1) (a) and contact (ωt_3) with the walkers surface (b); (r = 0.05 m, α = 10°, $n_{ki,y}$ = 34 s^{-1}, w_s = 12 %): 1 – h_s = 0.1 m, $n_{kv,y}$ = 262 s^{-1}, p_y = 220 s^{-1}; 2 – h_s = 0.2 m, $n_{kv,y}$ = 270 s^{-1}, p_y = 220 s^{-1}; 3 – h_s = 0.3 m, $n_{kv,y}$ = 281 s^{-1}, p_y = 220 s^{-1}; 4 – h_s = 0.4 m, $n_{kv,y}$ = 296 s^{-1}, p_y = 210 s^{-1}; 5 – h_s = 0.5 m, $n_{kv,y}$ = 326 s^{-1}, p_y = 205 s^{-1}

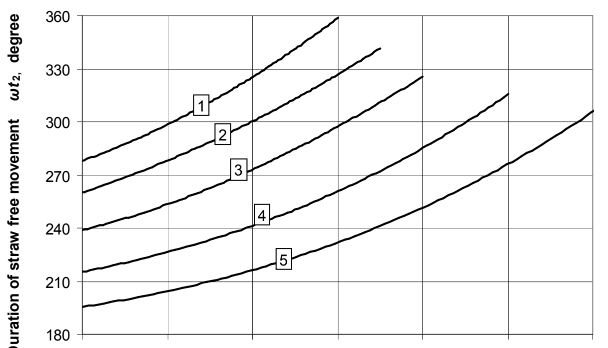


Fig. 4. The effect of the crankshafts rotation frequency (n) on the duration of straw free movement (ωt_2); (r = 0,05 m, α = 10°, w_s = 12 %): 1 – h_s = 0.1 m, $n_{kv,y}$ = 262 s^{-1}, p_y = 220 s^{-1}; 2 – h_s = 0.2 m, $n_{kv,y}$ = 270 s^{-1}, p_y = 220 s^{-1}; 3 – h_s = 0.3 m, $n_{kv,y}$ = 281 s^{-1}, p_y = 220 s^{-1}; 4 – h_s = 0.4 m, $n_{kv,y}$ = 296 s^{-1}, p_y = 210 s^{-1}; 5 – h_s = 0.5 m, $n_{kv,y}$ = 326 s^{-1}, p_y = 205 s^{-1}

The calculated equivalent coefficients of the viscosity of the straw layer transported over the walker surface demonstrate that impulses are more suppressed in the thicker straw layer. Examination of the straw layer (from 0.3 to 0.5 m) movement over the walker surface revealed that numerical values of the viscosity equivalent coefficients are increased by 25 %, and specific oscillations are slightly reduced, resulting in reduction of ωt_2 values by 55 degrees.

The effect of the ambient air resistance, which is measured by the coefficient of damping $n_{ki,y}$, on the straw layer movement is by 7 to 9 times lower than that acting inside the layer.

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