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SIMULATION OF RADIAL OSCILLATIONS OF A SPRING-LOADED ROLL IN A ROLL COMPACTOR

Abstract. Carried out simulation of oscillations of a spring-loaded roll in a roll compactor when interacting the powder being compacted with the rolls. Considering the separation of the feed and compaction areas in the contact area of the roll with the material being compacted, we obtain the dependence of the force acting on the roll on the gap size between the rolls. It is shown that this dependence is non-linear, and it can be described with a sufficiently high accuracy degree by an exponential function with a negative exponent in the working range. The given numerical solution of the equation of free nonlinear oscillations of the spring-loaded roll has shown that considering the deformation of the material being compacted leads to a reduction of the natural frequency of the system by 20–25 % compared to the case, where the pressure force of the powder on the roll is assumed to be independent of the gap size. The nonlinearity of the dependence of the pressure force on the gap also leads to the increase by 10 % in the calculated values of the maximum displacements. The developed approach to the calculation of oscillations of the spring-loaded roll in the roll compactor enables to take into account the peculiarities of deformation of the powder being compacted during its interaction with the rolls. In addition, it allows estimating the frequencies and oscillation amplitudes and setting the optimum range of spring rate values, at which the occurrence of resonance in the machine is not possible.

Keywords: roll compactor, powder, rolls, oscillations, elastic forces, resonance, simulation

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МОДЕЛИРОВАНИЕ РАДИАЛЬНЫХ КОЛЕБАНИЙ ПОДПРУЖИНЕННОГО ВАЛКА ВАЛЬЦ-ПРЕССА

Аннотация. Выполнено моделирование колебаний подпружиненного валка вальц-пресса при взаимодействии прессуемого порошка с валками. С учетом выделения в области контакта валка с прессуемым материалом зон подачи и прессования, получена зависимость силы, действующей на валок, от величины зазора между валками. Показано, что эта зависимость имеет нелинейный характер, причем в рабочем диапазоне с достаточно высокой степенью точности может быть описана степенной функцией с отрицательным показателем степени. Приведено численное решение уравнения свободных нелинейных колебаний подпружиненного валка, которое продемонстрировало, что учет деформирования сжимаемого материала приводит к снижению частот собственных колебаний системы на 20–25 % по сравнению со случаем, при котором сила давления порошка на валок принимается не зависящей от величины зазора. Нелинейность зависимости силы давления от зазора приводит также к увеличению на 10 % расчетных значений максимальных смещений. Разработанный подход к расчету колебаний подрессоренного валка вальц-пресса позволяет учесть особенности деформирования прессуемого порошка при его взаимодействии с валками, а также позволяет, наряду с оценкой частот и амплитуд колебаний, установить оптимальный диапазон значений коэффициента жесткости пружины, при котором появление резонанса в машине будет невозможно.

Ключевые слова: вальц-пресс, порошок, валки, колебания, силы упругости, резонанс, моделирование

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Introduction. The functioning of a roll compactor is determined both by the characteristics of the machine itself and by the parameters of the material being compacted. In an ideal case, the compacting process would be stationary and the rolls would be constantly in a true equilibrium if all powder particles being compacted have the same size, constant material density and as well as constant pressure value which ensures uniform powder feeding, etc. Variations in the above parameters, however, lead to oscillations of the rolls in a radial direction. To ensure a continuous compacting process and to reduce the forces acting on the rolls, which are caused by load variations, one of the rolls is spring-loaded. In the case of resonance, roll's oscillation can lead to inhomogeneity of the flakes, which in turn can have a negative effect on the quality of the final product.

To exclude resonance from the operating mode it is necessary to know oscillation parameters of the spring-loaded roll, which depend both on the mass of oscillating parts and spring rate, and on the amount and characteristics of the material being compacted and located between the rolls.

The information available in the literature on powder compacting machines for the production of granulated fertilizers, including potassium chloride (KCl), is mostly of descriptive or promotional nature [1–3]. The theoretical basis to determine the specifications of the used equipment has remained practically unchanged since the 1980s at the territory of the CIS countries [4–6].

Over recent years, there appeared a number of papers dealing with the determination of forces acting on rolls during powder compacting [7–9]. Both analytical and numerical methods are used for this purpose. In the paper [10] powder deformation model has been developed. This model enables to determine the forces acting on the rolls. However, the processes associated with oscillations of spring-loaded rolls have not been considered in these papers.

In the paper [11], an attempt is made to estimate the natural frequencies of a spring-loaded roll crusher. However, in this work it is assumed that the change of forces acting on the roll occurs according to the linear law, which does not correspond to the actual distribution of such forces. The purpose of this work is to develop an algorithm for calculating the oscillations of a spring-loaded roll of a roll compactor, taking into account the peculiarities of interaction between the powder being compacted and the rolls.

Results and their discussion. Figure 1 shows a computational scheme designed to describe the oscillations of a spring-loaded roll.

During rolls rotation that drives the powder being pressed, they are subjected to distributed forces from the material being compacted. The projections of these forces are indicated in the figure by F_x and F_y. The elastic force F_{el} prevents horizontal movement. The dynamic equation of motion of the spring-loaded roll can be written as follows

$$m\ddot{x} = F_x - F_{el}. \quad (1)$$

When the rolls move by a distance x from the position at which there is no spring deformation, elastic forces arise, and they are proportional to the spring deformation

$$F_{el} = cx,$$

where c is the spring rate.

Calculation of force F_x acting on the roll 2 (see Fig. 1) will be performed according to the procedure described in the paper [10]. To describe powder compression, we introduce the angle θ changing from zero (horizontal line connecting

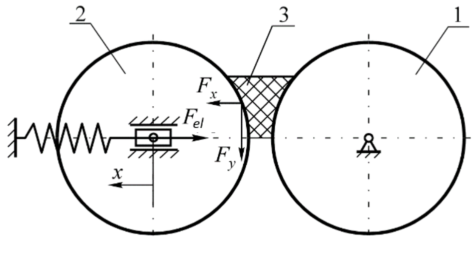

Fig. 1. Computational scheme of spring-loaded roll oscillations: *1* – a roll with a fixed axis; *2* – a roll with a movable axis; *3* – material being compacted

the rolls centres) to α as an argument (beginning the contact area between the powder and the roll). The contact area is divided into a feed area and a sealing area [12]. The feed area corresponds to the variation range of the angle θ from γ to α. The angle θ is determined by the formula

$$\alpha = \frac{1}{2}\left(\varphi + \arcsin\left(\frac{\sin\varphi}{\sin\delta}\right)\right),$$

where $\varphi = \mathrm{arctg}(f)$, f is the coefficient of friction between the powder mixture and the surface of the roll; δ is an angle of internal friction of the powder material (rad).

In the feed area, the dependence of the mean axial stress σ (also called hydrostatic pressure) on the angle θ is given by the differential equation

$$\frac{d\sigma}{d\theta} = \frac{2R\cos\theta}{h_s + 2R(1-\cos\theta)}\sigma\left[\frac{(1+\sin\delta)(\mathrm{tg}\,\theta - f)}{(1-\sin\delta)(1+f\,\mathrm{tg}\,\theta)} - \mathrm{tg}\,\theta\right], \tag{2}$$

where R is the radius of the roll; h_s is distance between roll surfaces (gap).

The boundary condition for the beginning of the powder-roll contact region is

$$\sigma(\alpha) = \frac{p_0}{1-\sin\delta}, \tag{3}$$

where p_0 is the feed pressure.

Solving the equation (2) taking into account (3), we obtain

$$\sigma(\theta) = \frac{p_0}{1-\sin\delta}\exp\left(-\int_\theta^\alpha Q_{\text{supply}}(\varsigma)d\varsigma\right).$$

The function introduced here is defined by the formula

$$Q_{\text{supply}}(\varsigma) = \frac{2R\cos\varsigma}{h_s + 2R(1-\cos\varsigma)}\left[\frac{(1+\sin\delta)(\mathrm{tg}\,\varsigma - f)}{(1-\sin\delta)(1+f\,\mathrm{tg}\,\varsigma)} - \mathrm{tg}\,\varsigma\right].$$

Having the dependence σ(θ), the standard pressure p on the roll and shear stress τ_f can be calculated

$$p = \frac{\sigma}{1+f\mathrm{tg}\theta}, \quad \tau_f = fp.$$

The angle γ corresponding to the transition to the sealing area is obtained by solving a non-linear equation

$$K\frac{\sin\gamma}{\cos^2\gamma}\left(1 - 2\cos\gamma + \frac{h_s}{2R}\right) = \frac{(1+\sin\delta)(\mathrm{tg}\,\gamma - f)}{(1-\sin\delta)(1+f\,\mathrm{tg}\,\gamma)} - \mathrm{tg}\,\gamma 12,$$

where K is compaction index [12].

In the sealing area, for the average axial stress instead of the formula (2), one should use the equation

$$\frac{d\sigma}{d\theta} = \sigma K\,\mathrm{tg}\,\theta\left(1 - \frac{2R\cos\theta}{h_s + 2R(1-\cos\theta)}\right). \tag{4}$$

The continuity equation is used as the boundary condition

$$\sigma(\gamma)\big|_{\text{supply}} = \sigma(\gamma)\big|_{\text{pressing}}. \tag{5}$$

Solving the equation (4) with regard for (5) gives

$$\sigma(\theta) = \frac{p_0}{1-\sin\delta}\exp\left(-\int_\gamma^\alpha Q_{\text{supply}}(\varsigma)d\varsigma\right)\exp\left(-\int_\theta^\gamma Q_{\text{pressing}}(\varsigma)d\varsigma\right),$$

where

$$Q_{\text{pressing}}(\varsigma) = K\,\mathrm{tg}\,\varsigma\left(1 - \frac{2R\cos\varsigma}{h_s + 2R(1-\cos\varsigma)}\right).$$

The standard pressure on the roll and the shear stress can be expressed as the function σ(θ) and for the sealing area the corresponding formulas are as follows

$$p = \sigma(1+\sin\delta) - \tau_f \operatorname{tg}\theta;$$

$$\tau_f = \frac{\sigma \operatorname{tg}\theta}{(1+\operatorname{tg}^2\theta)(1+\sin\delta)}\left[\frac{2\sin\delta}{1-\sin\delta} + K\left(1-\frac{h_s + 2R(1-\cos\theta)}{2R\cos\theta}\right)\right].$$

The projection of the equivalent force F_x acting on the roll of length H, in turn, is determined by integrating the combination of normal and shear forces distributed over the contact surface of the powder with the roll

$$F_x = RH\int_0^\alpha (p\cos\theta + \tau_f \sin\theta)d\theta.$$

Figure 2 shows the force dependence on gap size between the rolls, obtained for the case $R = 0.5$ m, $H = 0.1$ m, $f = 0.3$, $K = 3$. This dependence is approximated with a high degree of accuracy by the following expression

$$F_x = 253h_x^{-1,814}. \quad (6)$$

Since the dependence $F_x(h_s)$ is non-linear, the eq. (1) is the non-linear differential equation of the second order. Its solution enables to find the parameters of free and forced oscillations of the rolls arising during operation.

Assume that the roll is made of steel and that its mass is $m = 900$ kg. If the nominal roll gap makes $h_s = 6$ mm, then it follows from fig. 2 that the corresponding value of the pressing force is $F_x = 2732$ kN. If we set that the undeformed state of the support spring corresponds to roll gap $h_{s0} = 4$ mm, we obtain the following spring rate of the support spring

$$c = \frac{F_x}{h_s - h_{s0}} = \frac{2732\cdot 10^3}{0{,}006 - 0{,}004} = 1366\cdot 10^6 \text{ Н/м}.$$

Consequently, taking the position corresponding to the undeformed state of the support spring and substituting the expressions of the applied forces in the eq. (1), we obtain

$$900\ddot{x} = \frac{253}{(x+0{,}004)^{1{,}814}} - 1366\cdot 10^6 x. \quad (7)$$

Figure 3 shows graphs of free roll oscillations obtained by the Runge–Kutta's Fourth Order Method for the case when at the initial moment of time the roll gap h_s was 5 mm and the initial speed of coordinate variation x was absent. The solid line corresponds to the differential eq. (7), and the dashed line to the

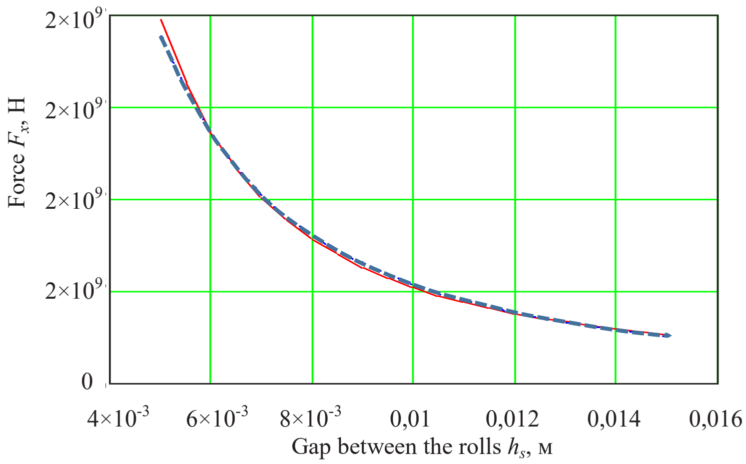

Fig. 2. Dependence of the force F_x on the gap h_s between the rolls at the feed pressure $p_0 = 106$ Pa: the solid line is the exact dependence; the dashed line is an approximation by the eq. (6)

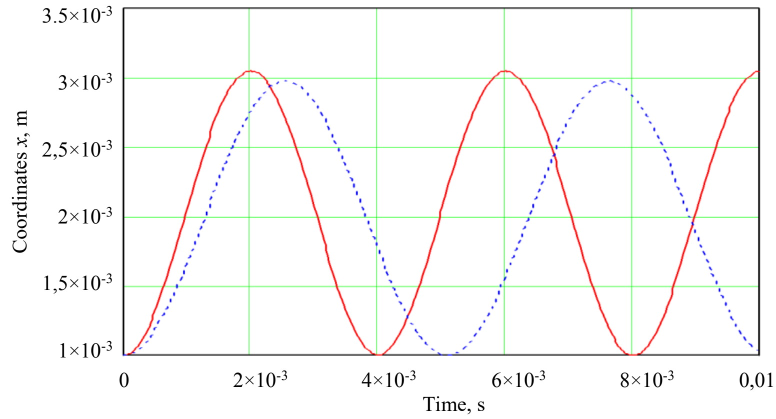

Fig. 3. Graphs of free roll oscillations considering the deformation features of the material being pressed (solid line) and without such consideration (dashed line)

version in which the force from the side of the material being compacted was assumed constant (this version corresponds to the well-studied linear oscillations of a material system with single degree of freedom).

From the graphs provided, one can see that taking into account the deformation of the material being compacted results in a 20–25 % decrease in the natural frequencies of the system. Due to the nonlinear dependence of the force F_x on the displacement, the maximum displacement from the equilibrium position is approximately 10 % higher compared to the case of linear oscillations.

The considered case of roll oscillations corresponds to nonlinear oscillations of the considered system. In the case of small deviations Δx from the equilibrium position, dependence (6) can be linearized [13]. In this case, the expression for the pressure force on the roll of the material being compacted in the neighborhood of the point with the coordinate x is written in the following form

$$F_x = F_{x0} - k\Delta x, \tag{8}$$

where F_{x0} is the value of the pressing force corresponding to the coordinate x; k is the stiffness coefficient determining the deformation of the material being compacted in the area under consideration.

The value of the rate k can be obtained by differentiation of the dependence, shown in Fig. 2, with respect to parameter h_x:

$$k = -\frac{\partial F_x}{\partial h_x}.$$

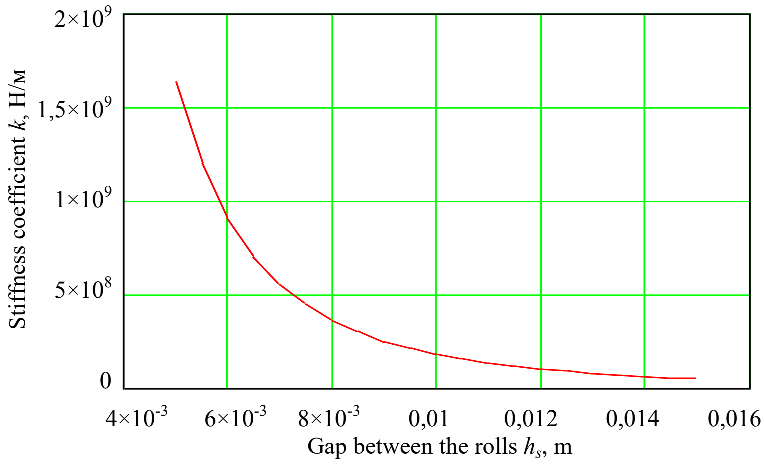

Fig. 4. Dependence of the stiffness coefficient of the material being compacted on the gap between the rolls at the feed pressure p_0 = 106 Pa

Figure 4 shows graph of the stiffness coefficient of the material being compacted depending on the gap between the rolls.

Substitution of the expression (8) into the eq. (1) leads to obtaining the small oscillations' equation of a spring-loaded roll $m\ddot{x} = F_{x0} - kx - cx$, the known solution of which [13] enables to estimate the frequencies of small natural oscillations corresponding to specific gap between the rolls using the formula

$$\omega = \sqrt{\frac{c+k}{m}}.$$

Thus, the developed approach to the calculation of oscillations of the spring-loaded roll in the roll compactor enables to take into account the peculiarities of deformation of the powder being compacted during its interaction with the rolls. In addition, the considered approach allows estimating the frequencies and oscillation amplitudes and setting the optimum range of spring rate values, at which the occurrence of resonance in the machine is not possible.

Conclusion. Carried out simulation of oscillations of a spring-loaded roll in a roll compactor when interacting the powder being compacted with the rolls. Considering the separation of the feed and compaction areas in the contact area of the roll with the material being compacted, we obtain the dependence of the force acting on the roll on the gap size between the rolls. It is shown that this dependence is nonlinear, and it can be described with a sufficiently high accuracy degree by an exponential function with a negative exponent in the working range. The given numerical solution of the equation of free nonlinear oscillations of the spring-loaded roll has shown that considering the deformation of the material being compacted leads to a reduction of the natural frequency of the system by 20–25 % compared to the case, where the pressure force of the powder on the roll is assumed to be independent of the gap size. The nonlinearity of the dependence of the pressure force on the gap also leads to an increase by 10 % in the calculated values of the maximum displacements. The developed approach to the calculation of oscillations of the spring-loaded roll in the roll compactor enables to take into account the peculiarities of deformation of the powder being compacted during its interaction with the rolls. In addition, it allows estimating the frequencies and oscillation amplitudes and setting the optimum range of spring rate values, at which the occurrence of resonance in the machine is not possible.

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