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INVESTIGATION OF CONTACT FORCES OF INTERACTION OF PARTICLES OF BULK MATERIALS DURING THEIR MOVEMENT IN HELICAL DRUMS

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Abstract:

The results of an analytical study of the movement of particles of loose materials in screw drums are presented. It is shown that forces arise as a result of stochastic (probable) collisions of particles with each other and the properties of the walls of a screw drum to transfer pressure to flows of particles of bulk materials. Shown: - model of contact of particles of bulk materials in a screw drum; - a graph of the change in the magnitude of the sliding velocity in the sequence of contacting the particles of bulk materials; - the density distribution of the contacting particles of bulk materials; - the model of contacting particles of bulk materials and the scheme of their contact taking into account dynamic equilibrium; - Varieties of screw drums. The search for designs of screw drums was performed using descriptive geometry and engineering graphics using the Kompas-ZD software package. A general analysis of the kinematics of the movement of particles of bulk materials, an analytical study of the real process with the aim of choosing a conditional model of its description and obtaining an analytical relationship to determine the contact forces of interaction of N particles of bulk materials.

Keywords: *contact forces, particles of bulk materials, stochastic phenomena, directional contacts, friction forces.*

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INTRODUCTION:

Earlier, in the works [1, 2, 3, 4], the results of the research of the working parts of the equipment on the basis of screw drums are presented, allowing not only the movement of particles of bulk materials at their horizontal location, but also expanding technological capabilities and reducing the size and weight of such equipment.

At enterprises of various industries, including construction and agriculture, they use technologies and equipment in which cylindrical drums are used as working bodies, tilted in the direction of unloading, which ensures the longitudinal movement of the materials being processed. The consequence of this is the complexity of operation and a large mass of equipment. The elimination of these drawbacks can be the development and introduction of technologies and equipment, in which the original structures of screw drums with a horizontal axis of rotation will be used as working bodies, which will reduce energy costs and improve technical and economic indicators.

Screw surfaces and helical grooves located along the perimeter of the working bodies in the form of screw drums promote the movement and increase in the intensity of interaction of particles of bulk materials with each other and with the screw surface of the working body. The current imperfections are explained by insufficient research of contact forces of interaction of particles of bulk materials during their movement in screw drums, causing the emergence of complexity in the design of such equipment, therefore, conducting such a study is relevant and timely.

MATERIAL AND METHODS:

Our goal is to study the contact forces of loose particles in a rotating screw drum.

For a better presentation of the complexities of phenomena occurring during the movement of bulk materials in screw drums, some of them are made in the "Compass-3D" software package and are shown in Figure 1.

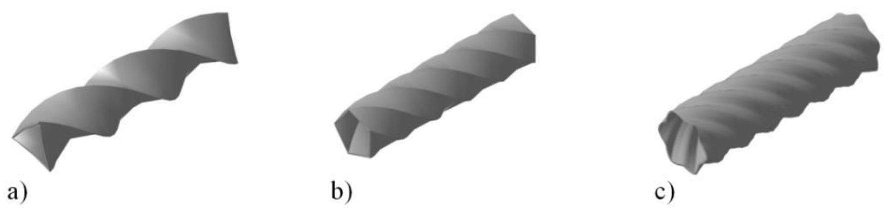

Figure 1: Varieties of screw drums made in Compass-3D software package: a) with three helixes around the perimeter of the drum and pockets of a triangular shape, b) with five helix lines around the perimeter of the drum and pockets of a triangular shape, c) with six helixes along the perimeter drum and pockets wavy shapes

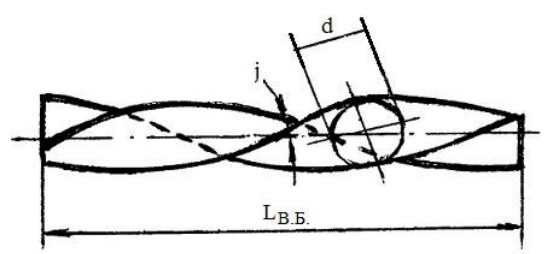

Figure 2: Front view of a screw drum with three helixes around the perimeter and pockets of a triangular shape

With some assumptions, for example:

Particles of bulk materials m_1, m_2 we will consider the balls moving inside a screw drum along radii $r \approx r_{av}$, at the same time we will consider their contacts in cross sections of a screw drum. Contacts m_1 and m_2 occur in negligible time τ - $t_{i\ av}$. The number of collisions in our case can be determined by dependence: $n = \frac{T}{2\cdot(\tau + t_{i.av.})}$ and we will consider contacts as a semi-elastic shock. Since the particles of bulk materials are slightly deformed, when determining contact forces as friction forces, we can use the theory of semi-elastic impact, i.e., we use the conditions of the Punch contact flow distribution [5] of the expected $m^1 \leq K$. Assume that the contact points are located in the direction $\overline{r}$, and direction $\overline{\varphi}$, the particulate materials are captured by the screw drum stacks.

The probability of occurrence of a single contact in accordance with the distribution of the Poisson law can be written $m' \leq K$. What is the probability of its occurrence?

This can be determined [5] using the dependency $P_1 = 1 - e^{-l(\varphi)}$,with the opposite event $q = 1 - P_1 \cdot q = 1 - P_1$,
where: $l(\varphi)$-expected number of contacts,
Then, with a large number of experiences, non-occurrences $P_{\kappa_1 m'}$ can be determined using dependencies [5]:

$$P_{\kappa_1 m'} = \frac{(\kappa \cdot q)^{m'}}{m'} \cdot e^{-\kappa \cdot q}\,, \qquad (1)$$

$$\overline{P}_{\kappa_1 m'} = 1 - P_{\kappa_1 m'}\,, \qquad (2)$$

where $q = e^{-l(\varphi)}$.
Here (2) shows the number of contacts. m' without taking into account the directivity K and their spread of the walls of the screw drum in the direction $\bar{r}$. These random phenomena should be considered independent and the right side of the expression (2) is multiplied by two coefficients. Considering the collision of particles of bulk materials, taking into account the theory of semi-elastic impact, the speed of relative slip U_τ balls m_1 and m_2.

So, for example, depending on the speed of relative slip U_τ Between the contact surfaces of the balls m_1 and m_2, their sign and size, one or another model of sliding friction is formed. If a $U_\tau \geq 0$, then accordingly [4]:

$$R = \mp \mu \cdot N, \qquad (3)$$

where μ- sliding friction coefficient.
N and R – normal and tangential frictional forces.
If a $U_\tau = 0$, then in general $R_{0,\tau} = \mp \mu \cdot N_{0,\tau}$,
when $N_{0,\tau} = \int_0^\tau N \cdot dt$, $R_{0,\tau} = \int_0^\tau R \cdot dt$

where $N = m_1 \frac{dU_\tau}{dt}$ and $R = m_1 \cdot \frac{dU_t}{dt}$ – expressions dependent on changing normal U_r and tangential U_t, slip speed components.
Solving the system of equations of motion of colliding forces, we obtain [6]:

$$U_\tau = A_0 - A_1 \cdot N_{0,\tau} - A_2 \cdot N_{0,\tau}, \qquad (4)$$

where A_0 – const;
A_1, A_2 – functions from parameters m_1, m_2, r_1, r_2, U_1, $U_{2,\,1}$, ω_2 ;
ω_1, ω_2 – their angular rotational speeds relative to the centers in the cross-sectional plane of the screw drum.
With $U_\tau = 0$ [7]
find that $\frac{R_{o_1 \tau}}{N_{o_1 \tau}} > \mu$. In this case, we use the formula:

$$R_{0,\tau} = \pm \mu \cdot N_{0,\tau} \qquad (5)$$

If $\frac{R_{o_1 \tau}}{N_{o_1 \tau}} \leq \mu$ (μ– sliding friction coefficient $0{,}07 \leq \mu \leq 0{,}15$), will get:

$$R_{0,\tau} = \frac{A0 - A1 \cdot No,\tau}{A2}. \qquad (6)$$

Because $U_\tau = 0$ takes on the value at the end of the contact τ (figure 3) the relative sliding speed is determined by the dependence:
$U_\tau = (U_1 + \omega_1 \cdot r_1) - (U_2 - \omega_2 \cdot r_2)$;
Wherein:
– m_1 rotates against the stroke and m_2 rotates against the stroke:
$U_\tau = (U_1 - \omega_1 \cdot r_1) - (U_2 - \omega_2 \cdot r_2)$;
– m_1 rotates in the course, and m_2 rotates in the course:
$U_\tau = (U_1 + \omega_1 \cdot r_1) - (U_2 + \omega_2 \cdot r_2)$;
– m_1 rotates against the course, and m_2 rotates along:
$U_\tau = (U_1 - \omega_1 \cdot r_1) - (U_2 + \omega_2 \cdot r_2)$.

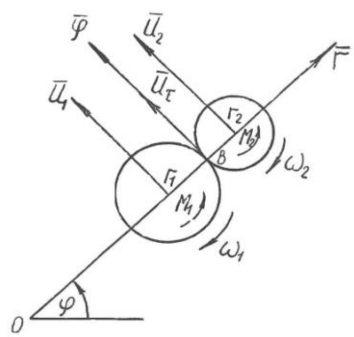

Figure 3: Model of the contact of particles of bulk materials in a screw drum

To calculate the sliding friction forces at different U_τ, it is necessary to use formulas (3), (5) or (6).
In our case $U_{\tau\,min} \leq U_\tau \leq U_{\tau\,max}$ and r_1 , $r_2 << r = r_{av}$ from the condition m_1, m_2 around the circumference $r = r_{av}$, $U_1 \approx U_2 \approx r \cdot \dot{\varphi}$. Formulas for U_τ greatly simplified since ω_1, $\omega_2 \neq$ const in general. If in particular ω_1, $\omega_2 =$ const, then in this case U_τ = const. Figure 4 presents a graph of the change in the values of slip speeds.

Figure 4: Graph of changes in the magnitude of the slip velocity during contacting the particles of bulk materials

On contact on the direction line $\bar{r}$ (figure 3) rotation speed $\dot{\varphi}_1 = \dot{\varphi}_2 = \dot{\varphi}_B = \dot{\varphi} + \dot{\varphi}_\tau = \dot{\varphi} + \frac{1}{2} U_\tau$ stacks up as a result of rolling in, with slippage if $U_\tau \neq 0$ in this case cos $æ_i = 1$, then the number of summations:

$\frac{1}{r} \sum_{i=1}^{n} U_{\tau_i} \cdot \text{Cos } æ_i$, (7)

where æ – angle between vectors $\overline{U}_{\tau_i}$ and direction $\overline{\varphi}$.

Expression (7) can be represented as

$\varphi_\tau = \int_0^\pi U\tau(t) \cdot \text{Cos } æ_{(t)} \cdot dt$

Integrating the second equation of the known differential system [8]

$$\begin{cases} m \cdot (\ddot{\rho} - \rho \cdot \dot{\varphi}^2) = F_\rho; \\ m \cdot (\rho \cdot \ddot{\varphi} + 2\dot{\rho} \cdot \dot{\varphi}) = F_\varphi \end{cases} \quad (9)$$

taking into account $\tilde{\varphi} = \varphi + \varphi_\tau$,

get the time derivatives:

$\dot{\varphi} = \frac{d\varphi}{dt}$, $\ddot{\varphi} = \frac{d\dot{\varphi}}{dt} = \frac{d^2\varphi}{d \cdot t^2}$, $\dot{\rho} = \frac{d\rho}{dt}$, $\ddot{\rho} = \frac{d^2\rho}{dt}$

Since the determination of the magnitude U_τ (t) depends on ω_1, ω_2 = const, construct and simplified types of models to establish boundaries for the values ω_1, ω_2. In this case, we use the energy balance equation:

$$\frac{J_{p.k}}{2} \cdot \omega^2 = m \cdot \frac{V_0^2}{2} + N_1 \cdot \frac{\cdot \omega_1^2}{2} + N_2 \cdot \frac{J \cdot \omega_1^2}{2} + Q_N,$$
(10)

where $J_{p.k} \approx m_{p.k.} \cdot \frac{R_H^2 + r_{av}^2}{2} \approx m_{p.k}$

r^2 – moment of inertia of the screw drum, m = $N_1 \cdot m_1 + N_2 \cdot m_2$ generally;

ω – screw drum rotation speed;

$V_0 = \omega \cdot r$ – the speed of "capture" of the entire mass m of a rotating screw drum at the moment t = t_0 (φ_0= - $\frac{\pi}{2}$) ; J_1 = 0,4 $m_i \cdot r_i^2$;

(τ =1,2) – moments of inertia of balls m_1, m_2;

Q_N – unaccounted types of energy (such as partial transition to heat when considering semi-elastic contacts m_1, m_2, "Entrapments of m - masses" by the walls of a screw drum and some other nature).

If we assume that the distribution of energy for the rotation of m_1 and m_2 is directly proportional to the ratio of their masses (perhaps some other probabilistic law of distribution occurs, see, for example, the kinetic theory of gases), i.e.

$\frac{J_1}{2} \cdot \omega_1^2 = \frac{m_1}{m_2} \cdot \frac{J_2}{2} \cdot \omega_2^2$,

then it follows

$r_1 \cdot \omega_1 = r_2 \cdot \omega_2$ (11)

If we neglect the term in expression (9) Q_N, then, taking into account formula (10), we obtain the upper bound for the estimate:

$r_1 \cdot \omega_1 = r_2 \cdot \omega_2 \leq \frac{\omega \cdot r}{2} \cdot \sqrt{5 \left(\frac{m_{p.k.}}{m} - 1\right)}$, (12)

where $m_{p.k.} \geq m$.

With this value N_1 m_1, $N_2 \cdot m_2$, m, $m_{p.k.}$ can be shown as a ratio of screw drum loading volumes.

Will consider:

A_{11} – contact event where m_1 and m_2 rotate counterclockwise;

A_{12} – contact event, where m_1 - rotate counterclockwise, m_2 - rotate clockwise.

Since in the course of experiments, such contacting contributed to an increase in the longitudinal velocity of the bulk materials;

A_{21} – contact event, where m_1 and m_2 rotate, opposite to the rotation of the event A_{12};

A_{22} – contact event, where m_1 and m_2 rotate, opposite to the rotation of the event A_{11}.

The analysis shows that in our case the event A_{12} - contact event will occur, where m_1 rotates in the opposite direction, m_2 rotates clockwise.

Then, under the conditions of the binomial distribution, the probability [5]:

$R_{к,n} = 1 - \sum_{i=0}^{k-1} P_{i,n}$,

$P_{i,n} = C_n^i \cdot P^i \cdot (1-P)^{n-i}$ (13)

where C_n^i – The number of combinations of elements n through i.

Since in practice the laws of binomial and Poisson pass into a normal law and if we introduce some characteristic in the form of a median deviation E=0.25 r_1, then the expected number of contacts over the entire area of the ball zone of the sphere r_1 is 0.82. The probability density distribution of this law is presented in Figure 5.

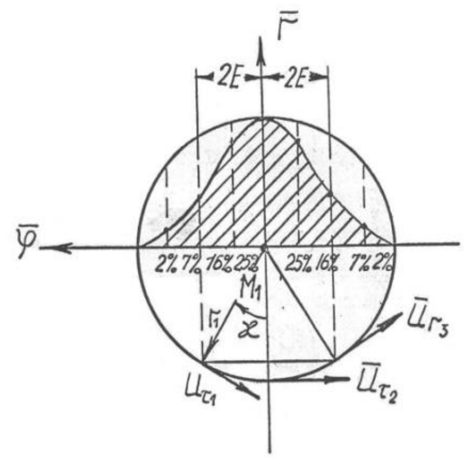

Figure 5: Distribution density of the contacting particles of bulk materials

What is remarkable points of contact, lying on the surface of the ball belt? They are characterized by angles. $æ_i \leq æ_i$ =30% so what 087 cos $æ_i \leq 1$.

When P_m, taking into account (1), (2) so what P ≈ 0,82, can be represented as:

$$P_m{}' = 0{,}82 \cdot \left(1 - \sum_{i=0}^{\kappa-1} P_{i,n}\right)\cdot\left(1 - \frac{(k\cdot q)^{m'}}{m'!}\cdot e^{-\kappa\cdot q}\right), \quad (14)$$

where

$P_{i,n} = C_n^i \cdot P^i(1\text{-}P)^{n-i}$, $q = e^{-L(\varphi)}$, $-\frac{\pi}{2} \leq \varphi \leq \frac{\pi}{2}$

P – probability characteristic;

L(φ) – mathematical expectation of the number of coatings on the surface of the ball belt S_{m_1} square by squares S_{m_2} cross sections of balls m_2, i.e.

$$L(\varphi) = \frac{S_{m_1}}{S_{m_2}} \cdot K(\varphi),$$

where $K(\varphi) = \frac{1-\mathrm{Sin}\varphi}{2}$ - degree of coverage: when $\varphi = \varphi_0 = -\frac{\pi}{2}$ (at the point of "mass capture") $L(\varphi_0) = L_{max} = \frac{S_{m_1}}{S_{m_2}}$ as a function φ; at $\varphi = +\frac{\pi}{2}$ - the number of collisions is the smallest (the scattering of balls is already m_1 significant) and $L(\varphi = +\frac{\pi}{2}) = L_{max} \approx 0$ – no collisions.

Therefore:

$$L(\varphi) \approx \frac{S_{m_1}}{S_{m_2}} \cdot (1 - \mathrm{Sin}\,\varphi),$$

where

$S_{m_1} = 2 \cdot \pi \cdot r^2{}_1$, $S_{m_2} = \pi \cdot r_2{}^2$.

We write, instead of dependence (5) with regard to formula (3):

$$F_{fr.1,2} = -\mu \cdot P_m \cdot N, \quad (15)$$

Thus (Figure 6b), even under the condition of contacting the balls, circular motion is preserved $r = r_{av}$ – radius, work is done $F_{r\,1.2} \cdot \Delta r \sim \dot{\varphi}^2\, r \cdot \Delta r$, resulting in loss of kinetic energy [9].

$$\Delta W = \frac{1}{2} \cdot \frac{m_1 \cdot m_2}{m_1 + m_2} \cdot (1 - k^2)\cdot(V_1 - V_2)^2, \quad (16)$$

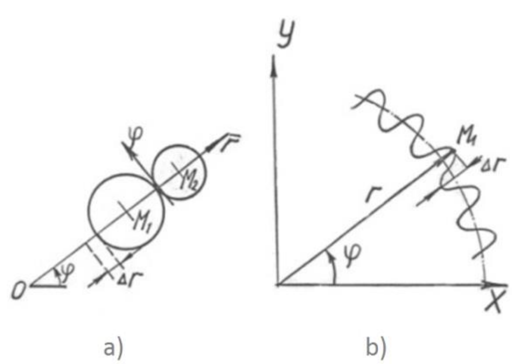

Figure 6: Schematic simulation of contacting particles of bulk materials: a) model of contacting particles of bulk materials, b) scheme of contacting particles of bulk materials, taking into account dynamic equilibrium

After introducing some empirical coefficient $K_v = \frac{1}{2} \cdot (1\text{-}K^2)$; $\Delta w = N \cdot \Delta r$ and counting $\cdot(V_1 - V_2)^2 = \dot{\varphi}^2 \cdot r \cdot \Delta r$ contact forces of interaction of N particles of bulk materials m_1 and m_2 can be determined by the formula:

$$N = -\frac{m_1 \cdot m_2}{m_1 + m_2} \cdot K_v \cdot r \cdot \dot{\varphi}^2. \qquad (16)$$

RESULTS AND DISCUSSION:

In the results of the research, an analytical dependence was obtained to determine the contact forces of interaction of N particles of bulk materials in screw drums. It should be assumed that the steady-state process of movement of particles of bulk materials in screw drums can be considered in some sense “weighted”, accompanied by contact phenomena, where the pressure of the lower particle of a rotating screw drum will be higher compared to the “upper layers” and the whole mass of loose particles materials will be somehow evenly distributed throughout its volume.

CONCLUSION:

The article not only obtained an analytical relationship to determine the contact forces of the interaction of N particles of bulk materials in screw drums, but also outlined ways to optimize the parameters of the dimensions of the equipment's working parts in the form of a screw drum. It is shown that to create a methodology for calculating and designing screw drums, it is necessary to study and obtain dependencies to determine: the power consumed for friction during elastic relative slip in the zone of contact of particles of bulk materials; the work of the elastic friction friction; the speed of longitudinal movement of particles of bulk materials, therefore, the size of the screw drum, and thus solve the problem of optimizing its design as a whole.

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