Usage of discrete element method in the research of vibrating mills with circular vibrations of the grinding chamber

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Abstract. The paper reviewed the application of the discrete element method for researching the motion of the ball load in vibration mills with circular vibrations of the grinding chamber at different amplitude-frequency characteristics. Vibration mills are actively used in various industries, in particular for road construction in the production of bitumen or mineral components. The paper presents the model of the vibration mill used in numerical calculation, the main indicators of the load’s kinematics providing the efficiency of the vibration mill, presents and analyzes the results of numerical experiments, determines the rational mode of operation of the machine.

1. Introduction

As the data used to determine the efficiency of grinding media movement based on the results of the numerical experiment, two main technological parameters of the material grinding process in the vibrating mill [1] were determined directly related to the kinematics load’s [2,3,4]. Average speed of movement of the grinding bodies, $U_{av}$, m/s. This parameter is proportional to root values of the energy intensity – intensity motion of the particles loaded into vibrating mill [5]. The number of collisions of the grinding media determines the efficiency of movement of the load in the grinding chamber of the vibrating mill and the periodicity of exposure to the grinding material, $Z$.

The main determining technological parameter of the material grinding process in the vibration mill is the energy intensity. Energy intensity – the intensity of motion of the loading particles in the vibration mill, $N_v$. The energy intensity of the grinding process is proportional to the square of the grinding media velocity formula (1) [6]:

$$U_{av} \approx \sqrt{N_v} \quad (1)$$

Oscillatory motion of grinding media leads to their collisions. The number of collisions $Z$ per unit time, per unit volume of the mixture of grinding media and material can be expressed in terms of determining values $d_b$, $n_b$ and $U$ using the method of dimensions [6]:

$$Z \approx d_b^2 n_b U \approx \sqrt{N_v} \quad (2)$$

where $d_b$ – the size of grinding balls, m; $n_b$ – number of balls per unit loading volume.
From the analysis of formula (2) it follows that the number of collisions of grinding media, leading to the grinding of the material, rises with increasing energy intensity. We can say that almost all the technological characteristics of the vibration grinding are determined by the parameter of the energy intensity of the load. Studies show [7] that in vibration mills, the frequency of collisions of grinding media in the loading volume is several thousand times higher than the number of collisions occurring during grinding in ball drum mills.

2. Purpose of the EDEM software product

For research the parameters of the average speed of grinding media and their number of collisions, an electron-digital model of the vibration mill in the EDEM system was made and a numerical experiments were carried out. EDEM is one of the leading programs of DEM (discrete element method), used to simulate the behavior of bulk materials when they move and interact with each other and parts of the equipment [8].

The discrete element method used in EDEM can be considered as a generalization of the finite element method. While modeling the process by this method, the initial positions and velocities of various particles are set. Then, based on the initial data and given the physical laws of interaction of particles, the forces acting on each particle are calculated by solving mathematical equations. For each particle, the resulting force is calculated and the Cauchy problem is also solved at the selected time interval. The result is the initial data for the next calculation step. The calculations continue for the entire duration of the process of interest. It is worth noting that such calculations are very time-consuming and require a large amount of computing resources from the computer processor and often take a fairly long period of time.

EDEM allows quickly and easily create a model granular system of solid bodies with different parameters, EDEM combines the functionality of various mechanical, material and other physical properties in the process of modeling of the motion of solid particles. Finished models can be conveniently stored in the library and with changing the initial conditions, which simplifies and accelerates the process of re-calculations by the user. A large tool for analyzing ready-made models has extensive functionality for studying the output data and interpreting them in a visual form easy to understand (graphics, videos, tables, vector fields, screenshots, etc.).

Working with the EDEM software package can be divided into the following stages of creating a calculation model:

- set the global parameters of the calculations: the model of interaction of bodies, material properties of the bodies, friction and restriction coefficients, Shear’s modulus and of the various other;
- creation of grinding body model, material selection;
- creation of grinding chamber geometry, material selection, setting of motion parameters (in particular vibrations), amplitude, frequency, angular velocity;
- the creation of a working environment and the input parameters of the calculation: the quantity or mass of grinding bodies, the generation rate of the grinding bodies fill factor etc.;
- calculation;
- analysis of calculation output.

3. Plan of research of vibration mill

To carry out the research motion of the load in the software product EDEM, an electron-digital model of a vibration mill (figure 1) with circular oscillations was created. Table 1 below lists the parameters of the vibration mill.
Figure 1. The model of the vibration mill
1 – grinding chamber, 2 – grinding bodies, 3 – direction of circulation of grinding bodies, 4 – direction of circular vibrations of the grinding chamber.

Table 1. The parameters of vibration mill model’s.

| Parameter                              | Value     |
|----------------------------------------|-----------|
| Grinding chamber length, mm            | 250       |
| The diameter of the grinding chamber, mm| 219       |
| The thickness of the wall of the grinding chamber, mm | 10       |
| Grinding chamber volume, m³            | 0.00858   |
| Number of grinding media               | 13500     |
| The radius of the grinding body, mm    | 7         |
| Load factor                            | 0.85      |
| The coefficient of restitution of the milling bodies | 0.5   |
| Coefficient of rolling friction of the grinding body | 0.5 |
| The coefficient of sliding friction of grinding media | 0.01 |

Two series of different numerical experiments were carried out. The initial data of the first experiment included 10 experiments of circular vibrations of the grinding chamber with increasing amplitude from 2 mm to 9 mm, with the same frequency equal to 50 Hz. The initial data of the second one included 6 experiments, circular oscillations of the grinding chamber with increasing frequency from 25 to 70 Hz and the same amplitude equal to 3 mm.

The aim of these numerical experiments was to determine the effect of the amplitude and frequency of oscillations on the motion of grinding media in the grinding chamber of the vibration mill. Among the many parameters describe the output in the model EDEM Analyst to assess the milling process in vibration mill was selected:

1) the average speed of the grinding media, which is defined as the rate of change in the position of the particle along the axes X, Y and Z, and the addition of the values of the three vectors:

\[ U_{av} = \left[ U_{av} \right] = \sqrt{U_x^2 + U_y^2 + U_z^2} \]  (3)
2) the number of collisions of balls, which is defined as the contact between the grinding media at the time of recording the control point of the simulation.

3) distribution of grinding media in zones depending on their speed.

4. Research result

As can be seen from the graph of the velocity dependence on the amplitude of the oscillations shown in Figure 2, the speed increases exponentially with the amplitude of the oscillations. The minimum average speed equal to 0.3076 m/s grinding bodies have an amplitude equal to 2 mm. The maximum average speed of grinding bodies equal to 1.499 m/s is observed at an amplitude of 9 mm. This is a consequence of the more active mechanical action of the grinding chamber on the grinding bodies, due to its greater amplitude of oscillations.

Based on the analysis of the graph of the number of collisions of grinding media of the mill from the amplitude shown in Figure 2, a gradual decrease in this value to the extreme point is noticeable. At an amplitude equal to 8 mm, the number of collisions of grinding media is 13288. Then there is an increase in this indicator to 16535 at an amplitude equal to 9 mm, which is slightly less than the maximum indicator in 17402 collisions recorded at an amplitude of 2 mm. The decrease in the number of collisions of grinding media in the range of vibration amplitude 2-8 mm, due to the fact that at these values, part of the load goes into a suspended state, and the free volume between the balls in the load increases, respectively, the number of contacts between the grinding media decreases.

![Figure 2. Dependences of the average speed (1) and the number of collisions of grinding media (2) on the vibration amplitude of the grinding chamber of the vibration mill.](image)

From the analysis of the graphs of the dependence of the average speeds of the grinding bodies and their number of collisions on the amplitude, it can be concluded that the most preferred mode of operation of the vibration mill with a body length equal to 250 mm, a diameter of 219 mm, a load factor equal to 0.85, loaded with grinding bodies of the same diameter of 14 mm. will be observed at an amplitude equal to 3 mm. With such parameters of circular oscillations, the number of collisions of grinding media at a time is still large enough, but at the same time, the growth of the amplitude to the extreme values shown in these experiments can lead to an increase in the power consumption of the vibration mill, since achieving such amplitude values will require the use of more powerful vibration exciters. The research notes that the optimal value for the vibration amplitude of the grinding chamber of the vibration mill is a range from 2 to 5 mm [6]. In addition, it is worth noting that with the growth
of the amplitude, the vibration loads on the foundation will increase many times, and the wear of the grinding chamber and grinding bodies will accelerate.

After determining the optimal value of the amplitude equal to 3 mm, the effect of changes in the oscillation frequency on the loading motion in the vibration mill was researched by conducting a second series of calculations with increasing frequency. From the graph of the dependence of the average speed on the amplitude of the circular oscillations shown in Figure 3, it follows that the speed increases linearly with an increase in the oscillation frequency. The minimum average speed equal to 0.339 m/s grinding media have an amplitude equal to 25 Hz. The maximum average speed of grinding media equal to 0.543 m/s is observed in the experiment with a set frequency of 70 Hz.

Based on the analysis of the graph of the dependence of the number of collisions of grinding media of the mill on the oscillation frequency shown in Figure 3, a decrease in this value to the minimum point at a frequency of 30 Hz is seen. At this frequency, the number of collisions of grinding media is equal to 15401, which is less than the index of the number of collisions of grinding media equal to 15876 at the lowest considered frequency of 25 Hz. This is followed by the growth of this parameter to 16947 at the maximum value of the investigated frequency equal to 70 Hz.

Further, a stagnant loading zone was researched in the model with a vibration amplitude of 3 mm and a frequency of 50 Hz, (which includes grinding bodies with an average speed of up to 0.4 m/c, shown in blue in figure 4), located in the Central part of the chamber and moves along a circular trajectory during grinding. From the end of the grinding chamber (Figure 4, (a) the stagnant zone is minimal in volume, this is due to the collision of grinding media with the end of the chamber and then Bouncing them off it. On a quarter (Figure 4, (b) and half (Figure 4, (c) the length of the grinding chamber, the stagnant zone is approximately one-third of the total volume of grinding bodies. Of the longitudinal section of the grinding chamber (Figure 4, (d) it follows that the stagnant zone extends to its entire length.
Figure 4. The distribution of particle velocities from the end of the vibration mill (a), a quarter of the length of the grinding chamber (b), half the length of the grinding chamber (b), in the longitudinal section (g).

5. Conclusions
In total, the most rational parameters of the operating mode for a laboratory sample with a body length equal to 250 mm, a diameter of 219 mm, a load factor equal to 0.85, loaded with grinding media of the same diameter of 14 mm will be a vibration amplitude equal to 3 mm and a vibration frequency equal to 50 Hz.

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