THE EFFECT OF THE FILLING DEGREE OF THE TUMBLING MILL CHAMBER ON THE BIFURCATION VALUE OF THE FROUDE NUMBER

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Abstract: The influence of the filling degree of the drum chamber on the bifurcation value of the Froude number in the case of self-excitation of self-oscillations of a two-fraction granular charge with a minimum swing is considered. Such a pulsating mode of the charge movement is used in the self-oscillating grinding process in a tumbling mill. The coarse fraction that simulated the milling bodies consisted of spherical particles of an incoherent granular material with a relative size in the chamber ψ_b=0.00733. The fine fraction, simulating the material to be ground, was cement with a relative particle size $\psi_m \approx 0.092 \cdot 10^{-3}$. The value of the adopted analogue of the kinematic viscosity of the two-fraction granular loading approached the value of 10^{-3} m^2/s. The main variable factor in experimental studies was the filling degree of the drum chamber with loading at rest κ_b=0.25, 0.35, and 0.45. An additional factor was the degree of filling the gaps between the spherical particles of the coarse fraction with particles of the fine fraction κ_b=0, 0.25, 0.5, and 1. The method of visual analysis through the transparent end wall of the chamber of transient processes of the loading behavior with a smooth change and fixation of the velocity was applied. The bifurcation minimum value of the rotation speed was recorded, at which the steady-state circulation mode of the load movement turns into a transient pulsation one with a minimum swing. A decrease in the bifurcation values of the Froude number Fr_b on the cylindrical surface of the chamber with an increase in κb has been established. An increase in the intensity of the decrease in Fr_b with an increase in κm was revealed. The recorded effect is due to an increase in the connected properties of a two-fraction loading during self-excitation of self-excited oscillations with an increase in κ_b and κ_m. The numerical values of the boundaries of the range of bifurcation values of the Froude number for a tumbling mill Fr_b=0.0484–1.17 have been determined. The obtained Fr_b range corresponds to the Reynolds value in the range Re=40–197. The maximum Fr_b value is obtained with coarse grinding. An increase in the likelihood of self-excitation of self-oscillations of the intra-chamber loading with a decrease in the fineness of grinding was revealed.

Keywords: tumbling mill, bifurcation value, Froude number, self-excitation of self-oscillations, filling degree, two-fraction loading.

1. Introduction

Due to a number of operational advantages, tumbling mills are widely used for fine grinding of many tough materials. On the other hand, significant frictional dissipation of energy during the movement of the intra-shallow loading entails a high energy consumption of grinding [1]. The problem of increasing the energy efficiency of the working processes of such equipment remains relevant further [2].

The relatively low energy efficiency of drum disintegrators can be significantly increased by the use of the self-oscillating grinding process [3]. Self-excitation of self-oscillations leads to loss of stability of the steady-state mode of motion of the drive unit of a tumbling mill [4]. Such instability is accompanied by fluctuations in the power of the loaded drum rotation drive [5].

The emergence of self-oscillations in the form of pulsations makes it possible to activate the circulation of the intra-chamber load. At the same time, the share of the active part of the load increases and the share of the passive part, which does not participate in grinding and additionally loads the mill rotation drive, decreases. The energy efficiency of such a process increases with a decrease in the degree of filling the chamber [6] and the content of the crushed material in the load [7]. Specific energy consumption sharply decreases with a joint decrease in the filling of the chamber and the content of the material [8].

And the technological efficiency of the implementation of the self-oscillating process significantly depends on the minimum value of the rotation speed, which corresponds to the beginning of self-excitation of self-oscillations.

The significant variability of the pulsating behavior of the charge in the rotating chamber is due to the complex multiphase polygranular structure. The establishment of rational conditions for the effective implementation of such a process is significantly difficult.

Under certain conditions, the behavior of the granular loading of the rotating chamber is characterized by a pronounced instability [9]. The manifestation of instability through the appearance of an avalanche-like collapse of the free surface of the load is of the greatest applied interest. Such collapse occurs when the chamber rotates slowly, when the load comes out of the rest state, and fast, during the formation of the wall layer.

The approximate relevance and increased complexity of the hydrodynamic problem has recently led to a sharp increase in research activity in predicting the characteristics of an avalanche-like loading collapse. The avalanche flow of granular materials in the chamber of a rotating drum was studied mainly experimentally by visualizing transient modes of motion [10–13]. A number of attempts have been made to numerically simulate such a flow [14–17]. Further development of biotechnology has increased interest in experimental and numerous studies of avalanche motion in a rotating chamber of granular biomass [18–20]. However, the results obtained relate only to flows of single-fraction granular loading, mainly at slow rotation of the chamber and low Froude numbers Fr<<1.

At the same time, the value of the Froude number is critical. The character of the steady flow at low Fr differs sharply from the character of the flow at large Fr. In particular, when flowing around an obstacle, the value Fr=1 bifurcational with respect to the form of realization of the translational flow with the possibility of self-excitation of an isolated wave [21].

In [22], the value of the chamber rotation rate was established for self-excitation of self-oscillations with the maximum range of a single-fraction granular load. However, the change in the degree of filling the chamber with the load was not taken into account. Similar studies for a two-fraction loading with a change in the degree of filling in the range of 0.175–0.25 were carried out in [23]. This filling of the chamber with loading is mainly used only for ultrafine grinding. In [24], only the change in the dilatancy and the amplitude of self-oscillations of a single-fraction loading was studied for the degree of filling the chamber in the range of 0.15–0.5.

The influence of the degree of filling the chamber in the traditional range 0.25–0.45 on the bifurcation value of Fr in the case of self-excitation of self-oscillations of a two-fraction loading remains unexplored.

2. Methods

Experimental physical visualization of transient processes of behavior of two-fraction granular loading of the chamber when changing and fixing the speed of rotation of the drum was adopted as a research method. A two-dimensional flow was visually observed through the transparent end wall of the chamber in a plane perpendicular to the chamber axis. The limiting edge effect of the granular medium on the end walls of the chamber was insignificant.

The drum rotation speed gradually increased from rest to the start of self-excitation of self-oscillations of the load. In this case, the range of self-oscillations has a minimum value. The bifurcation speed of drum rotation was fixed, corresponding to the transition of flow regimes. The minimum value of the stationary rotation speed ω_b was considered bifurcational, at which the steady-state circulation mode of the load movement turns into a transient pulsation one when the rotation is accelerated.

The bifurcation value of the Froude number on the cylindrical surface of the chamber Fr_b

$$Fr_b = \frac{\omega_b^2 R}{g},$$

where R – radius of the cameras, g – gravitational acceleration.

The value of the Reynolds number on the cylindrical surface of the chamber was also estimated, which corresponded to the results obtained for setting the bifurcation speed of rotation ω_b, Re

$$Re = \frac{\omega_b R^2}{\nu},$$

where ν – analog of the kinematic viscosity of the granular load.

Two-fraction granular intra-chamber loading was used. The coarse fraction simulated the grinding bodies of a tumbling mill. The fines simulated the material to be ground in the mill.

The degree of filling the drum chamber with coarse particles by loading at rest κ_b was chosen as the main variable factor in experimental studies. The discrete values of the chamber filling were κ_b=0.25 (fine grinding), 0.35 (medium grinding), and 0.45 (coarse grinding).

As an additional research factor, the degree of filling the gaps between spherical particles of a coarse fraction with particles of a fine fraction at rest κ_m was used. The fines content in the feed was κ_m=0, 0.25, 0.5, and 1.

The relative sizes of the particles of the two fractions in the chamber were used as criterion parameters. Such ratios for large $\psi_b = d_b/(2R)$ and small $\psi_m = d_m/(2R)$ fractions depend on the absolute particle sizes of these fractions d_b and d_m.

The coarse fraction of the load consisted of spherical parts of an incoherent granular material with a relative size ψ_b=0.00733. The fine fraction was cement with a relative size $\psi_m \approx 0.092 \cdot 10^{-3}$.

The value of the adopted analogue of the kinematic viscosity of the two-fraction granular loading approached the value of $\nu \approx 10^{-3}$ m^2/s.

3. Results

As an example, **Fig. 1** shows sequential pictures of motion during self-excitation of self-oscillations of an intra-chamber load, corresponding to bifurcations of the rotation speed ω_b. For this case Fr_b=0.123, Re=63.8.

To analyze the results obtained, graphical dependences of the bifurcation value of the Froude number Fr_b on the change in the degree of filling the chamber with loading κ_b were obtained (**Fig. 2**).

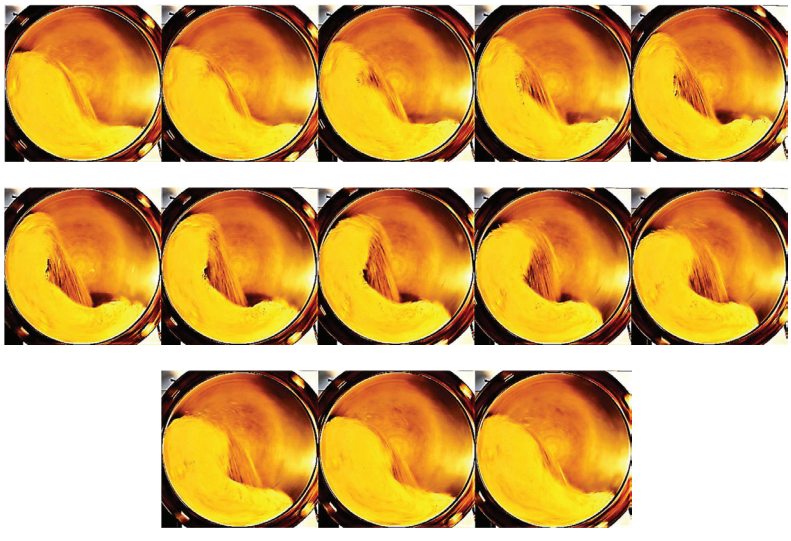

Fig. 1. Consecutive pictures of the load movement for one period of self-oscillations with a minimum swing at κ_b=0.35, κ_m=1

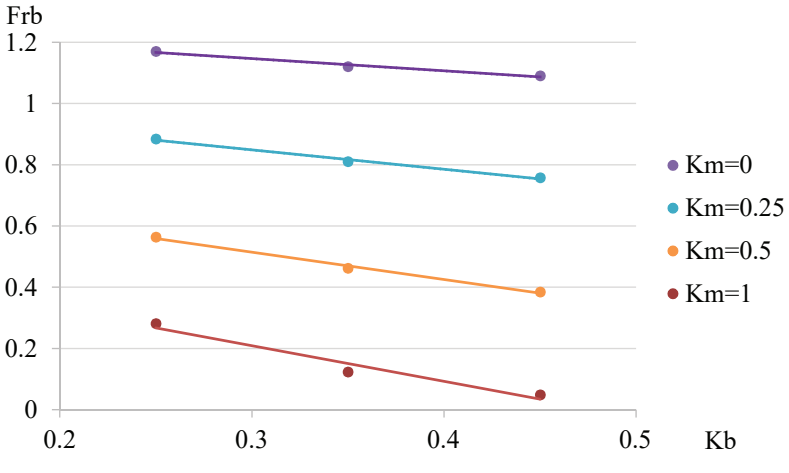

Fig. 2. Dependences of Fr_b change on κ_b

The obtained range of the bifurcation value of the Froude number Fr_b corresponds to the value of the Reynolds number in the range Re=40–197.

4. Discussion of the results

The results obtained significantly refine the known data on the bifurcation value of the Froude number for tumbling mills.

At the beginning of self-excitation of self-excited oscillations when the bifurcation value Fr_b is reached, pulsations with a minimum swing arise in the upper part of the free surface of the loading (**Fig. 1**).

The Fr_b value decreases with an increase in the degree of filling the chamber κ_b (**Fig. 2**). The intensity of the decrease increases with an increase in the content of such material κ_m.

The value of the established range of bifurcation values of the Froude number varies within Fr_b=0.0484–1.17 (**Fig. 2**).

The advantage of the results obtained is that the effect of the degree of filling the chamber with the load on the conditions of self-excitation of self-excited oscillations is taken into account. The disadvantages include the neglect of the flow of the radial size of the chamber and the Reynolds number Re, as well as the content of the crushed material.

The bifurcation value of the Froude number acquires the maximum value with coarse grinding. Therefore, the possibility of self-excitation of self-oscillations with a minimum range seems to be the most probable at the previous stage of grinding.

At the same time, for further clarification, the influence of the structure of the multifractional intra-shallow loading on the frequency characteristics of the conditions for self-excitation of self-oscillations is required.

5. Conclusions

The regularities of the change in the rheological properties of the self-oscillating two-fraction loading of the rotating drum chamber with the relative particle size of the coarse ψ_b=0.00733 and the fine fraction $\psi_m \approx 0.092 \cdot 10^{-3}$ have been revealed.

An increase in the connected properties of the load is established during self-excitation of self-oscillations with an increase in the degree of filling the chamber.

The effect of a decrease in the bifurcation values of the Froude number with an increase in the degree of filling the chamber with loading in the range κ_b=0.25–0.45 was recorded.

An increase in the coherent properties of the load with an increase in the content of the crushed material was revealed.

The effect of an increase in the decrease in the Froude bifurcation numbers with an increase in the content of the crushed material in the charge in the range κ_m=0–1 has been established.

The numerical values of the boundaries of the range of bifurcation values of the Froude number for a tumbling mill Fr_b=0.0484–1.17 with the value of the Reynolds number in the range Re=40–197 have been determined.

An increase in the likelihood of self-excitation of self-oscillations of the intra-chamber loading with a decrease in the fineness of grinding has been revealed.

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