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Discrete element simulation of particle motion in ball mills based on similarity

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ABSTRACT

Discrete element (DE) simulation of a ball mill with a large number of particles is challenging when each particle is considered. Similarity principle could be adopted to reduce the number of particles in a simulation whilst still maintaining the accurate flow behaviour of particles. This paper presents a scaling relationship between particle gravitational acceleration, mill diameter and mill rotational speed. A series of scaled simulations of particle motion with different mill diameters are carried out. Consistent motion of a single particle and multiple particles in ball mills with different diameters and rotational speeds verifies the proposed relationship, which could be an effective approach to reduce the size of simulations for ball mills.

1. Introduction

Rotating drums have been widely employed in chemical, cement, mineral and pharmaceutical industries. Ball mill is a type of rotating drum, mainly used for grinding and the particle motion in a ball mill is a major factor affecting its final product. However, understanding of particle motion in ball mills based on the present measurement techniques is still limited due to the very large scale and complexity of the particle system. Quantitative information, such as particle distributions and energy change, is still difficult to obtain through experiments. Thus, computer-based numerical methods have been proposed to further investigate the particle motion in a ball mill.

As one of the main particle-based methods, the discrete element method (DEM) was first proposed by Cundall [1] in 1979 to simulate the rock fracture problem. DEM is based on Newton's second law to track the movement of each particle in the particle assembly and simulate the collision of between particles. It has been successfully applied to soil [2,3], rock [4], powder [5–7] and other bulk materials for particle movement analysis and ceramic [8–10], concrete [11,12] and other brittle materials for crushing and crack propagation simulations. Although the DEM has provided useful results in the simulation of particle flow behaviour, it requires extremely large computer capacity as the numerical model reaches to a level of tens of millions of particles in three dimensions. As an attempt to address this large scale issue, Feng and Owen [13] proposed a scale classification method by the number of particles, such as micro-scale ($<10^6$), meso-scale (10^6–10^9) and macro-scale ($>10^9$). Micro-scale problems with less than several million particles have been modeled by DEM. However, real industrial applications may involve billions of particles as classified as macro-scale, such as a ball mill, rotary dryer, crusher, etc. DEM has been used to interpret the movement of particles and improve the operation and production of rotating drum in the last two decades. Finnie et al. [14] cited the scaling relationship for rotating drums derived from Ding et al. [15] and used DEM to simulate the process of particle movement in horizontal rotary kiln and analyzed the longitudinal and transverse particles when including filling rate and speed. Siiria et al. [16] studied the mixing process of powder and tracked the trajectories of the kinematic roots of each particle using DEM; furthermore, the authors analyzed and compared the average energy of each particle simulation system. The DEM results from the above studies helped to improve the understanding of the movement law of the particles and optimization of the equipment geometry and operation parameters.

A number of researchers have reported their simulation strategies for rotating drums in the literature, as enumerated in Table 1. For the sake of reducing the scale of the calculation, suggested ways are reducing the size of the model and the filling rate [17–23]. However, industrial rotating drums are much larger than the aforementioned studies and a detailed study on the specific effects of scaling model is still absent. Powell et al. [24] simulated a short slice of the mill thus the number of balls was reduced from 4.5 million to 110 thousand resulting in a

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Table 1
Summary of simulation work about rotating drums.

Reference paper	Drum diameter (mm)	Ball diameter (mm)	Ball number (maximum)	Filling rate (by volume)	Particle scale	DEM platform
[14]			21,333	0.2–0.4	Micro-scale	2D
[17]	1120	40–190		0.2–0.3	Micro-scale	3D
[18]	125	3–5	5208	0.1	Micro-scale	3D
[19]	254/381/900	15.2		0.4–0.24	Micro-scale	3D
[20]	70	1.3	47,000	0.3–0.92	Micro-scale	3D
[21]	573	8–20	14,431	0.35	Micro-scale	3D(EDEM)
[22]	1696	31–88	14,164	0.18	Micro-scale	3D(EDEM)
[23]	198	2.4	5400	0.107	Micro-scale	3D
[24]	8000	18.8–53	109,956	0.4	Micro-scale	3D(EDEM)
[25]	100–210	1–7	184,608	0.35	Micro-scale	3D(GPU)
[26]	1500	10	9,606,450		Meso-scale	3D(GPU)

reduction of simulation time by at least 50-fold. From the above reference survey, it is found that most of the DEM simulations are very different to the real mill systems and thus it is difficult to use DEM to deal with all the particles in a real mill, even with graphics processing unit (GPU) computing [25–27], parallel computing [28,29], continuum approximation [30,31], etc. Modern GPUs are very efficient at manipulating computer graphics and image processing, and their highly parallel structure makes them more efficient than general-purpose CPUs for algorithms where the processing of large blocks of data is done in parallel. Ge et al. [25,26] adopted GPU to accelerate the numerical simulation in which quasi-real-time simulation is reached. Parallel computing can speed up DEM simulations and may be the most powerful solution. Using parallel computing or GPU computing to accelerate the calculation is a very attractive method, but it needs a good computer configuration as support. Continuum mechanics may be applied to both discrete and heterogeneous media through the use of homogenization theory, which provides a mathematically elegant and rigorous framework for replacing a discrete collection of interacting entities by an equivalent homogenous continuum. The use of the continuum mechanics method may be difficult to capture a variety of physical particle information from the micro-scale, and it is difficult to analyse the relationship between the particle forces.

The present work aims to attempt the huge particle computing system problem and simulation difficulty. Firstly, the motion and force states of particles in the ball mills will be analyzed according to the force balance principle. A series of conversion formulas for the mill's structural and kinematic parameters based on centrifugal force are derived. Then, six sets of three-dimensional DEM models of ball mills are established, where the movement of single particle and multi particles is numerically simulated, respectively. The conversion formulas are validated by simulation results of single particle in terms of the motion trajectories and energy change. In addition, particle motion and mass flow of multiple particles is investigated in detail to further verify the above formulas.

2. Scaling theory

2.1. Force balance of particles in the ball mills

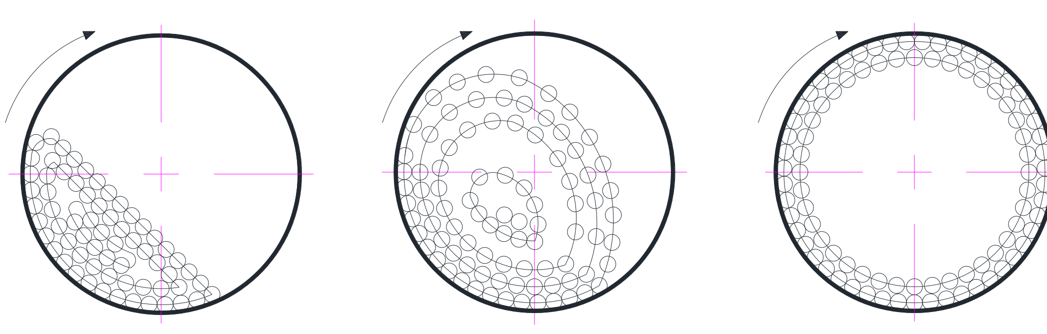
The movement of the particulate materials in the ball mills is closely related to the rotational speed of the mill. With the increase of rotational speed of the mill, the movement of the particulate materials mainly undergoes slipping, cataracting and centrifuging [32], as shown in Fig. 1. In a ball mill, the grinding media (steel balls) are attached to the mill liner due to inertial and centrifugal forces when the mill starts to rotate. Then, the grinding media move to a certain height and are thrown under gravity. After throwing the grinding media crush the particulate materials within the ball mills to achieve comminution.

Fig. 2 shows a kinematic trajectory model of the particle throwing process in the mill, where the throwing movement has a significant influence on the efficiency of the ball mill. By retrieving a certain particle in the outermost layer of the ball mills, the motion trajectories of the particle at different time during the process of dropping can be analyzed. As shown in Fig. 2, R is the radius of ball mills; point A is the particle detachment point; α is the detaching angle (angle between OA and the vertical direction); ω is the rotational speed of mill, and t_0–t_5 is the different time points in the motion trajectory. When the outer particle is located at point A, the vertical component of the centrifugal force of the particle is equal to the gravity but in the opposite direction. Assuming the particle is a mass point and ignoring the role of friction, we have:

$$F = mg\cos\alpha \tag{1}$$

where F is the centrifugal force (scalars), m is the mass of the particles, g is the gravitational acceleration, and α is the detaching angle. Then, based on centrifugal force calculation formula, F can be written as:

$$F = mv^2/R = mR\omega^2 \tag{2}$$



(a) Slipping (b) Cataracting (c) Centrifuging

Fig. 1. Schematic diagram of the material movement in the ball mill.