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Numerical investigation of granular flow similarity in rotating drums

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ABSTRACT

The theory of flow similarity has not been well established for granular flows, in contrast to the case for conventional fluids, owing to a lack of reliable and general constitutive laws for their continuum description. A rigorous investigation of the similarity of velocity fields in different granular systems would be valuable to theoretical studies. However, experimental measurements face technological and physical problems. Numerical simulations that employ the discrete element method (DEM) may be an alternative to experiments by providing similar results, where quantitative analysis could be implemented with virtually no limitation. In this study, the similarity of velocity fields is investigated for the rolling regime of rotating drums by conducting simulations based on the DEM and using graphics processing units. For a constant Froude number, it is found that the particle-to-drum size ratio plays a dominant role in the determination of the velocity field, while the velocity field is much more sensitive to some material properties than to others. The implications of these findings are discussed in terms of establishing theoretical similarity laws for granular flows.

Introduction

Rotating drums are employed in a rich variety of industrial practices to enhance the mixing, aggregation, and heat transfer of granular materials (Zhu, Zhou, Yang, & Yu, 2008; Liu, Ge, Xiao, & Li, 2008; Xu, Xu, Zhou, Du, & Hu, 2010). Six flow regimes are commonly recognized under different rotational speeds, while the rolling regime (characterized by an upper flowing layer and lower plug flow) is frequently encountered in industrial applications (Chou & Lee, 2009). Essentially, the rolling regime falls into the category of so-called "dense granular flows", where there are enduring force chains between adjacent particles (MiDi, 2004; Campbell, 2006; Sun, Jin, Liu, & Zhang, 2010). The dense granular flows generally exhibit rather complicated rheological behavior, and the scaling laws of rotating drums are thus still not well established owing to the lack of general and reliable constitutive laws (Forterre & Pouliquen, 2008; Ji & Shen, 2008; Zhang, Behringer, & Goldhirsch, 2010). These disadvantages usually result in large discrepancy between theoretical predictions and actual behavior in the scale-up of industrial equipment. Consequently, an in-depth investigation of the scaling behavior of rotating drums is important for understanding the physical mechanisms of granular flows and the optimization of operating conditions.

To investigate the general scaling behavior of all flow regimes in horizontal rotating drums, a series of dimensionless numbers have been identified (Ding, Forster, Seville, & Parker, 2001; Mellmann, 2001), including the filling level, Froude number (*Fr*), ratio of particle diameter to drum diameter (referred to as the "size ratio" hereafter), and material properties. By combining fundamental dimensionless numbers, several new dimensionless groups have also been proposed for specific conditions (Alexander, Shinbrot, & Muzzio, 2002; Chou & Lee, 2009). In regard to the rolling regime, an experimental study employing flow visualization demonstrated the critical roles of the Froude number and size ratio in determining the profile and thickness of the upper flowing layer, while the dynamic angle of repose was found to depend on the material properties (Orpe & Khakhar, 2001). Liu, Specht, Gonzalez, and Walzel (2006) further revealed that the material properties affect the maximum thickness and mean particle velocity of the upper flowing layer. Additionally, it was reported that the surface velocity has different relations with the Froude number depending on the rotational speed (Alexander et al., 2002), and the relationship between the mean velocity and thickness of the flowing layer has different forms depending on the size ratio (Félix, Falk, & D'Ortona, 2007). In summary, the scaling behavior in the rolling regime of rotating drums is rather complicated, and the flow details (such as

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the velocity profile) have not yet been systematically investigated in experiments owing to the limitations of current technologies.

As a numerical approach, the discrete element method (DEM) (Cundall & Strack, 1979; Zhu, Zhou, Yang, & Yu, 2007) has notable advantages in the description of velocities of granular materials, where the trajectories of all particles are explicitly tracked. Moreover, the material properties can be adjusted much more easily than in experiments. The DEM is thus a powerful tool for the investigation of scaling behavior in granular flows. Apart from the classical linear contact model in which interparticle forces are simplified, there already exist various nonlinear models, which are theoretically more accurate but also computationally more intensive. Fortunately, general-purpose graphics processing units (GPUs) can effectively alleviate this burden to some extent, and have been increasingly applied to various numerical problems (Xu et al., 2011a; Ren et al., 2013). In this work, with a nonlinear contact model implemented on a GPU platform, the velocity fields in three-dimensional (3D) horizontal rotating drums were explored extensively for various size ratios and material properties. At a fixed filling level and Froude number in the rolling regime, a rigorous investigation of the similarity of different velocity fields was carried out.

The paper is organized as follows. The Simulation method section details the nonlinear DEM model, the computational conditions and parameters, and the statistical method employed to analyze the velocity field. The Results and discussion section presents results from the investigation of the similarity of velocity fields in rotating drums, and discusses the implications of these findings. Finally, conclusions are drawn and future work on the scaling laws of granular materials is summarized in the Conclusions section.

Simulation method

DEM model

The DEM method requires suitable descriptions of the contact mechanism of granular materials. The interparticle interactions are complex to some extent and dissipative in nature owing to inelastic collisions and frictional forces. Additionally, besides the effect of sliding friction, it has been revealed that rolling friction plays an important role, particularly under certain circumstances (Zhu et al., 2007). Among a variety of DEM models for dry particles without adhesion, the formulations proposed by Zhou, Wright, Yang, Xu, and Yu (1999) are adopted in this work; these have been widely employed in various applications (Dong, Wang, & Yu, 2013; Ren et al., 2013). The model is briefly explained below.

According to Newton's second law of motion, particle motion is governed by

$$m_i \frac{d\mathbf{v}_i}{dt} = \sum_j \left(\mathbf{F}_{ij}^n + \mathbf{F}_{ij}^s\right) + m_i \mathbf{g}, \tag{1}$$

and

$$I_i \frac{d\omega_i}{dt} = \sum_j \left(\mathbf{R}_i \times \mathbf{F}_{ij}^s - \mu_r R_i \left|\mathbf{F}_{ij}^n\right| \hat{\boldsymbol{\omega}}_i\right), \tag{2}$$

where m_i, $\mathbf{v}_i$, ω_i, and I_i are the mass, translational velocity, angular velocity, and moment of inertia of particle i, respectively. The normal and tangential contact forces between neighboring particles i and j are denoted $\mathbf{F}_{ij}^n$ and $\mathbf{F}_{ij}^s$, respectively, while $\mathbf{R}_i$ is a vector pointing from the center of particle i to the contact point. The rolling friction coefficient is represented by μ_r, and $\hat{\omega}_i$ denotes the unit vector of angular velocity.

Table 1
Parameters used in the present simulations.

Parameter	Base value	Explored range
Particle density, ρ (kg/m^3)	2500	
Particle diameter, d (mm)	3.0	1.0–7.0
Young's modulus, Y (N/m^2)	1.0×10^7	1.0×10^6–1.0×10^8
Poisson's ratio (ν)	0.5	0.1–0.9
Sliding friction coefficient (μ)	0.5	0.1–1.0
Rolling friction coefficient (μ_r)	0.002	0.001–0.01
Normal damping coefficient, η_n (s^{-1})	1.0×10^{-6}	1.0×10^{-7}–1.0×10^{-5}
Drum diameter, D (mm)	150	100–210
Drum length, L (mm)	24	16–33.6
Rotational speed, ω (rpm)	32.66	27.6–40
Filling level (%)	35	
Number of particles	6832	543–184,608
Time step, Δt (s)	4.0×10^{-7}	2.5×10^{-7}–4.0×10^{-7}

On the basis of Hertz theory for normal interaction (Johnson, 1985) and Mindlin and Deresiewicz (1953) theory for tangential interaction, the proposed interparticle forces have the form (Zhou et al., 1999)

$$\mathbf{F}_{ij}^n = \left[\frac{2}{3}E\sqrt{\bar{R}}\delta_n^{1.5} - \eta_n E\sqrt{\bar{R}}\sqrt{\delta_n}\left(\mathbf{v}_{ij}\cdot\hat{\mathbf{n}}_{ij}\right)\right]\hat{\mathbf{n}}_{ij}, \tag{3}$$

and

$$\mathbf{F}_{ij}^s = -\mathrm{sgn}\left(\delta_s\right)\mu\left|\mathbf{F}_{ij}^n\right|\left[1-\left(1-\frac{\min\left(\delta_s,\delta_{s,\max}\right)}{\delta_{s,\max}}\right)^{1.5}\right] \tag{4}$$

where $E = Y/(1-\sigma^2)$ with Y and σ being the Young's modulus and Poisson's ratio, respectively; $\bar{R} = R_iR_j/(R_i+R_i)$ with R_i and R_j being the radii of particles i and j, respectively; $\hat{\mathbf{n}}_{ij}$ is a unit vector pointing from the center of particle j toward the center of particle i; η_n is the normal damping coefficient accounting for the energy dissipation due to inelastic collisions; and μ is the sliding friction coefficient. The parameters δ_n and δ_s are the normal and total tangential displacement, while $\delta_{s,\max}$ is the maximum tangential displacement given by

$$\delta_{s,\max} = \mu\frac{2-\sigma}{2(1-\sigma)}\delta_n \tag{5}$$

This 3D DEM model is implemented in a GPU-based algorithm coded with CUDA (NVIDIA, 2010; Xu, Qi, Ge, & Li, 2011b), and parallelized using the message passing interface (Gropp, Lusk, Doss, & Skjellum, 1996). Owing to the significant speedup of GPU-powered parallel computation provided by the Mole-8.5 supercomputer (Wang & Ge, 2013) at Institute of Process Engineering (IPE), many cases can be simulated for a long period in a systematic parametric study of flow similarity.

Simulation conditions

As schematically illustrated in Fig. 1(b), the horizontal drum in the present work is partially filled (filling level of 35%) with solid particles. The drum rotates around its axis in the clockwise direction with prescribed angular velocity ω, while the radius and length of drum are denoted R and L, respectively. The geometrical parameters of the drum and particles, and the material properties of the particles are listed in Table 1. The maximum (184,608) and minimum (543) particle numbers correspond to the cases with a drum diameter of 150 mm and particle diameters of 1.0 and 7.0 mm, respectively. Time steps within the range of 2.5×10^{-7}–4.0×10^{-7} s are chosen for different cases according to certain criteria (Li, Xu, & Thornton, 2005; Dong et al., 2013), while the time integration is performed using the popular leap-frog algorithm.