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Modelling the granular flow in a rotating drum by the Eulerian finite element method

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ABSTRACT

This paper presents a numerical study on the flow behaviours of granular materials in a rotating drum based on the Eulerian-formulation finite element method (Eulerian FEM). The granular material is here assumed to be cohesionless and treated as a continuum medium described by the conventional Mohr–Coulomb elastoplastic model. It is shown that this Eulerian FEM approach can reproduce almost all the particle flow patterns that frequently happen in rotating drum, i.e. *slipping, slumping, rolling, cascading, cataracting and centrifuging*, provided that the parameters of rotational speed, coefficient of friction and internal friction angle are properly selected. On average, the predicted surface angles of a rotating bed are comparable to the experimental observations (Parker, D.J. et al., 1997. Positron emission particle tracking studies of spherical particle motion in rotating drums. Chem. Eng. Sci. 52, 2011–2022.), but the curvature of surface may be slightly over-estimated for drums comprised by big component particles. Linear distributions of particle velocity are seen along the mid-cord of the bed and agree well with the data published in the literature (Boateng, A.A., 1998. Boundary layer modelling of granular flow in the transverse plane of a partially filled rotating cylinder. Int. J. Multiphas. Flow 24, 499–521). The bulk stress inside the particle bed is also investigated, and its spatial distribution is demonstrated to depend on the rotating speed and other operational parameters.

1. Introduction

Rotating drums are important components used in various industrial processes for mixing, segregating, drying or coating of particles. Such devices are usually highly costly to construct and demand substantial energy consumption in order to maintain the normal operation, especially when they are poorly designed. Therefore, fundamental researches are needed in this area for better understanding of the drum system and improving the industrial efficiency.

Previously, it has been known that particles in a rotating drum can exhibit different flow patterns such as *slipping*, *slumping*, *rolling*, *cascading*, *cataracting* and *centrifuging* depending on the conditions of rotational speed Ω, filling level and friction coefficient between the bed and drum surfaces [1–9]. By and large, the occurrences of such flow patterns can be roughly predicted in terms of the so-called Bed Behaviour Diagram (BBD) [1,10]. But a more accurate description of such patterns will need to be based on the theoretical analysis of bed statics and elaborate experimental measurements. In this regard, Henein et al. [1] and Mellmann [10] have done some pioneering studies and developed mathematical correlations respectively to evaluate different flow regimes. More recently, Ding et al. [11] focused on the turnover time of a rolling bed and constructed a theoretical model to approximate the slumping-to-rolling transition in drums with less than 50% volumetric fill. Santomaso et al. [12] recorded the images of a rolling bed with a camera and by analysing these images, they established an empirical correlation to describe the various bed behaviours in the rotating drum and discussed the scaling up and related issues.

The flow field of particles is another interesting aspect of rotary drum which has been intensively studied in recent decades [5,6,8,13,14], particularly because of its close relevance to the rheology of granular flow [2,15,16]. Parker et al. [8] measured the particle trajectories/velocities within a *rolling/cascading* 3D drum using the Positron Emission Particle Tracking (PEPT) technique. Two distinct regions of flow field were observed within the bed: a passive region in the depth of the bed where particles are slowly driven by the drum wall; and an active region adjacent to the free surface where particles cascade down rapidly under gravity. Boateng and Barr [14] explored the particle velocity in a drum measuring 1 m in diameter and 1 m in length, using the fibre-optic probing method and found that the particle velocity follows an approximately linear distribution across the active layer. Jain et al. [5] observed a similar linear profile in the active layer of a quasi-2D rotating drum, and a nearly logarithmic velocity profile in the passive region.

The discrete element method (DEM) has prevailed in the research of granular systems because it could provide important microdynamic information, i.e. the trajectories of and transient forces acting on

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individual particles, which is normally difficult to acquire via physical experiments [17,18]. Yang et al. [19,20] have demonstrated that DEM modelling is effective in reproducing the various particle flow regimes that are observed in physical experiments. The DEM results of particle velocities can also match those from the PEPT experiment [8], provided that the DEM simulation uses the same material parameters and operational conditions as those are used in the PEPT experiment. Chen et al. [21] employed DEM to evaluate the distribution of particle velocity along the longitudinal axis of a cylindrical drum, aiming to understand the role of end wall friction on axial particle flow. More recently, DEM simulation was also conducted to ascertain the roles of inter-particle liquid bridge on solid flow dynamics [22], particle mixing [23] and particle segregation [24] in rotating drums.

Continuum modelling based on the computational fluid dynamics (CFD) and the kinetic theory of granular flow [25–28] is an alternative direction in drum study. The CFD approach is able to represent the *rolling*, *cascading*, *cataracting* and *centrifuging* flow regimes of drums, provided that a proper equation of granular viscosity is selected [25]. Furthermore, by incorporating the size effect into the granular viscosity model, He et al. [28] and Huang et al. [26] respectively attempted to reproduce the segregation phenomenon of binary mixtures in rotating tumblers using CFD method. Consistent with the common experimental observations, their results indicate a segregation pattern that small particles often concentrate in the core area of the drum while most large particles distribute in the outer ring [26]. However, it remains unclear whether the CFD method can model other aspects of the drum dynamics, e.g. the *slipping* and *slumping* flow patterns.

In this study, a continuum approach referred to as the Eulerian-formulation finite element method (Eulerian FEM) is employed to investigate the flow behaviours of granular materials in a partially filled cylindrical drum. The FEM approach, built upon the conventional elastoplastic theories, can describe the dual solid and fluid-like behaviours of granular material. Our recent studies have demonstrated that this FEM approach can satisfactorily reproduce the critical stress dip phenomenon in sandpiles [29] and the discharge dynamics in hoppers [30]. Here it will be further applied to three-dimensional drum systems, with particular interest in the diverse flow patterns, the kinematics such as angle of surface and velocity profile, and the stress distribution within a rotating bed. Wherever possible, the simulated results are compared with published experimental data to assess the applicability of FEM to this flow system.

2. FEM simulation aspects

2.1. Model and boundary conditions (BCs)

Two types of drums were commonly studied in the literature, namely three dimensional (3D) thick drums [3,8,14] and quasi-2D thin drums [4–6,31]. The difference between them lies in the fact that 3D drums have distanced end walls such that particle flow in the middle drum is barely influenced by the walls and thus distributes more uniformly along the drum axis [21]. In contrast, the mobilisations of particles within quasi-2D drums depend heavily on the friction of end walls [3,21,32] and are much more difficult to deal with in numerical modelling. Besides, since there are usually just a few particles along the axis of a quais-2D drum, we consider that it is not so appropriate to treat the particle assembly under this situation as a continuum and simulate it with FEM. Therefore, only the case of 3D drum will be focused on in the current FEM simulation.

Fig. 1 sketches the geometry of the drum under study and the FEM model used in our simulations. Note that since $l \gg D$ in 3D drums, the transversal sections in the middle part can be regarded as planes of symmetry for the drum. In order to save computational cost, the original 3D geometry can be simplified to a slice model by exploiting this symmetric characteristic, as shown in Fig. 1. Such a treatment is analogous with the commonly adopted periodic BC in DEM simulations [33–36], except that the periodic BC allows materials to move through the boundaries while the symmetrical BC here does not. The use of symmetrical BC also means that the axial motion of particles is neglected in the present FEM simulation.

The numerical simulations are performed with the Eulerian method that has been provided in the commercial software package Abaqus (Version 6.10-1). The dimension of the computational domain is taken to be slightly greater than the drum diameter D and discretised with Eulerian elements. As the current Eulerian method only supports 3D elements, and therefore the z-axis dimension of computational domain Z_{thick} must be non-zero in order to keep the 3D geometry even though it is of no significance to the calculated results. The drum wall is modelled using rigid shell elements by assuming that its thickness and the deflection under material load are negligible. Its movement is constrained throughout the simulation at all degrees of freedom except for the rotational freedom about the z axis (longitudinal axis of cylinder). As an initial condition, parts of the Eulerian elements should

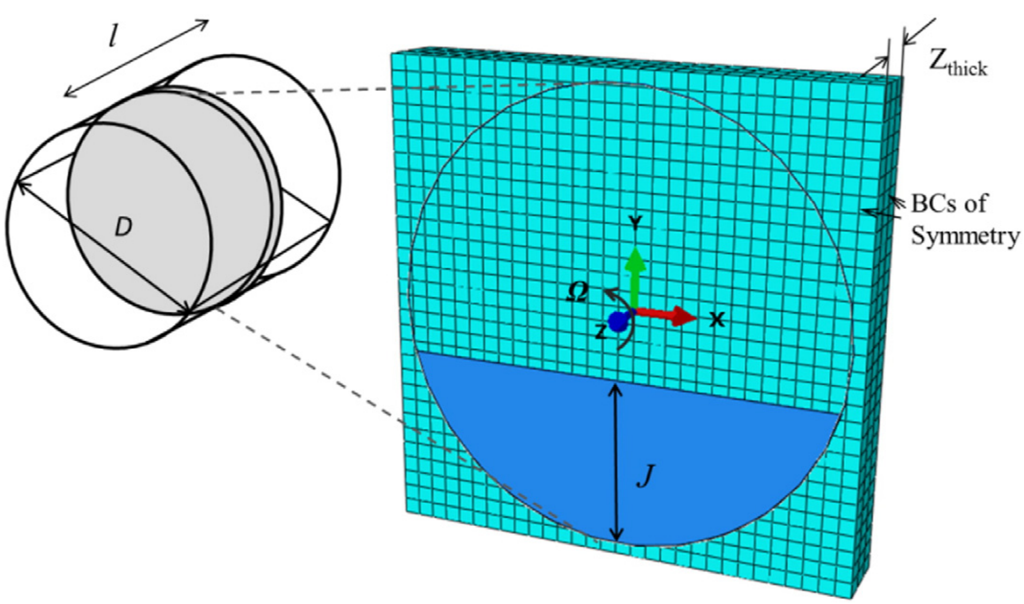

Fig. 1. FEM discretization of the drum system with BCs of symmetry on the front and rear surfaces. A coarsened mesh is shown here for illustration — the actual mesh density is described in Table 3.