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A multiscale method for including fine particle effects in DEM models of grinding mills

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ABSTRACT

A multiscale model for including interstitial powder or fine particles in DEM simulations of grinding mills is proposed. This consists of a traditional DEM model at the macroscale which includes only grinding media and potential coarser fractions of feed and product. Microscale models are embedded within this macroscale model. These can be sufficiently small that the fine powder can be included in a computationally affordable manner. The direct inclusion of the fine particles in the model allows predictions to be made of the effect of the local grinding environment on these fine particles. A shear cell is a good choice for the microscale model as it can well represent the local flow conditions at different points within the mill macroscale model. Averaging the macroscale flow allows the local collisional environments to be characterised and provides estimates of the shear rate and normal stress at each of the microscale locations which then controls the configuration of each microscale shear cell. A 1-way coupled implementation of this multiscale model is demonstrated for a simple cement ball mill. The relative importance of each region of the flow is determined with the toe region being the dominant contributor to the grinding. The grinding action produced by the shearing of thin layers of powder between adjacent layers of media flowing over each other is clearly demonstrated by the behaviour predicted in the microscale models. Methods for calculating power draw that include the effect of powder and for constructing collision energy spectra for the powder are described. Finally, the importance of the cushioning effect of high powder loads on the flow behaviour of the media is demonstrated.

1. Introduction

Grinding mills are used for reducing particulates, most commonly rock and cement, from a feed size down to a much smaller product size. The grinding environment is destructive to direct measurement instruments – which restricts the availability of information about what is happening to the charge within the mill. Modelling has been used to provide predictive information about mill performance. Mill models usually fall into one of two classes; the first are process models that use some form of population balance equations for the different size fractions with selection and breakage functions specifying the probability of breakage and the results of each breakage event (Herbst and Fuerstenau, 1973; Whiten, 1974; Weller, 1981; Austin and Brame, 1983; Tuzcu and Rajamani, 2011; Tavares and de Carvalho, 2009 and many others over the last two decades); the second are particle scale computational models using the DEM (Discrete Element Method) which seek to resolve all the inter-particle and particle-mill collisions and predict the particle motions by solving Newton's equations.

DEM was first used by Mishra and Rajamani (1992, 1994) for prediction of media motion in ball mills in two dimensions. Cleary (1998, 2001a,b) then included coarse feed into more detailed two dimensional ball mill models. The first use of DEM for SAG mills was by Rajamani and Mishra (1996). Three dimensional models of a central slice of these tumbling mills were then developed by Herbst and Nordell (2001) and Cleary (2001a,c). DEM with increasing sophistication has been used to increase understanding of charge flow and structure by Morrison and Cleary (2004, 2008), Djordjevic (2003, 2005) and Cleary et al. (2008). Many authors (such as in the special issue edited by Cleary and Morrison, 2008) have since used DEM for simulating tumbling mills. DEM modelling of stirred mills, such as tower mills and pin mills was performed by Sinnott et al. (2006) and Cleary et al. (2006a) and the Isamill by Yang et al. (2006), Jayasundara et al. (2006) and Cleary et al. (2015). DEM has also been used to model high intensity stirred mills, such as the centrifugal mill by Inoue and Okaya (1996), Cleary and Hoyer (2000), Cho et al. (2006), Lee et al. (2010), Cleary et al. (2010) and Owen and Cleary (2014). A recent review

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by Weerasekara et al. (2013) describes the current status of DEM modelling of comminution machines.

The key limitation of DEM is that it is restricted in the number of particles that can be used in the mill. The earliest DEM mill models used only a few hundred particles. By 2000, models of the order of 100,000 particles were feasible. These models have continued to grow with increasing computer power. Cleary (2009a) was able to model the entire second compartment of a 3.85 m diameter 8.4 m long cement ball will with around 3.8 million particles. More recently, Cleary et al. (2015) reported a model of grinding media in a full scale M10000 Isamill with 8.5 million particles. Models up to 100 million particles are sufficient to resolve all the media in an industrial mill except for the very largest stirred mills using media less than 4 mm. For AG and SAG mills and for a ROM (run-of-mine) ball mill these model sizes are also sufficient to allow resolution of a substantial fraction of the feed rock size distribution for full mill models (including the mill ends), see Cleary and Franke (2011). Finer feed material, however, still needs to be omitted from these mill models. For fine grinding ball mills, stirred mills and high intensity mills, the maximum feed top size is of the order of 1 mm and usually much finer. Product particles which are typically one or more orders of magnitude smaller than the feed size material are even more challenging and are predominantly or entirely omitted from the model. So although large DEM media models, such as the ball mill of Cleary (2009a) can provide significant process information about the media, they cannot currently (or in the foreseeable future) account for the fine particulates.

If the mills are wet, as a result of feeding water into the mill, which is the case for many mills then the situation is somewhat improved as the particles below 1 mm combine with the water to form a slurry which can be treated as a separate phase. This can be accounted for computationally by using a coupled fluid mechanics solver to predict the transport and behaviour of the slurry phase. A method that is well suited for this purpose in mills is the SPH (Smoothed Particle Hydrodynamics) method. Coupling of SPH to DEM for mills is described in Cleary et al. (2006b) and Cleary (2015). However, this type of model only provides information on the average interaction of the phases and the transport behaviour of the slurry. It does not provide information on the effect of collisions between larger particles on the fine particles in the interstitial slurry.

For dry mills, such as used in cement and where water availability is poor, it is still not possible to include any of the feed or product particles (usually termed powder) in the DEM model. This means that there is currently no viable particle scale modelling approach that is able to predict even where the powder is spatially located within the mill let alone what the effect of the media shear and collisions has on the powder. Transport of fine particles can be investigated using DEM at laboratory scale. Cleary and Morrison (2011) used such a model to determine where powder resides within a tumbling mill for different powder fill levels and to understand how the interstitial powder changed the grinding environment and affected powder consumption. In particular, this showed that the powder cannot be assumed to be spatially uniform in the region where the media is located. Particle size and shape change and breakage can also be explicitly predicted by DEM (see Cleary and Morrison, in press; Delaney et al., 2013 respectively) but again only at laboratory scale.

So although DEM models are able to provide valuable information on overall flow and the dynamics of the charge and of the flow of coarser particles such as media and coarse feed and some coarser product, it is not able to provide information about either the transport or breakage of the fine particles. Since these are both critical for mill performance, this represents a significant capability gap in the DEM modelling of mills. In order to predict breakage of fine particles (either directly as shown in Delaney et al. (2013) or indirectly using energy spectra calculated using DEM, such and in Morrison and Cleary (2004)) it is essential to include the fine particles in the model.

A multiscale DEM mill model is therefore proposed with two computational levels corresponding to the two physical scales that are critical in a mill. The top level is termed the macroscale and includes only the balls, coarse feed and mill geometry – so this is just the conventionally used DEM approximation in all DEM mill models to date. At specific locations within this macroscale model microscale models are embedded. These are small scale DEM models that are physically sufficiently small that the computational cost of simulating them even with fine particles included is feasible. These microscale models are therefore able to include the powder and so are able to predict ball effect on the powder and also the powder effect on the balls. The paper describes the computational structure of the multiscale scale model, the use of Couette cells for the microscale models and demonstrates its usage on a very simplified 4 m diameter cement mill.

2. DEM method

The DEM code used in this study has been used extensively for modelling of grinding mills, see Cleary (1998, 2001a,b,c, 2004, 2009a,b) and Morrison and Cleary (2004, 2008) for details and examples of such comminution simulation. In this method, the motion and collisions of all particles are predicted. The particles are allowed to overlap and the amount of overlap Δx, and normal v_n and tangential v_t relative velocities determine the collisional forces via a contact force law. A linear spring-dashpot model is used for the contact force where the normal force is:

$$F_n = -k_n \Delta x + C_n v_n. \tag{1}$$

This consists of a linear spring to provide the repulsive force and a dashpot to dissipate a proportion of the relative kinetic energy. The maximum overlap between particles is determined by the stiffness k_n of the spring in the normal direction. The normal damping coefficient C_n is chosen to give the required coefficient of restitution ε (defined as the ratio of the post-collisional to pre-collisional normal component of the relative velocity).

The force in the tangential direction is given by:

$$F_t = \min\left\{\mu F_n, \sum k_t v_t \Delta t + C_t v_t\right\}, \tag{2}$$

where the vector force F_t and velocity v_t are defined in the plane tangent to the surface at the contact point. The summation term represents an incremental spring that stores energy from the relative tangential motion and models the elastic tangential deformation of the contacting surfaces, whilst the dashpot dissipates energy from the tangential motion and models the tangential plastic deformation of the contact. The total tangential force F_t is limited by the Coulomb frictional limit μF_n, at which point the surface contact shears and the particles begin to slide over each other. For more details on the contact model and the relative performance differences of different contact models for inelastic collisions, see Thornton et al. (2013).

3. Multiscale strategy for DEM modelling of mills

A novel hierarchical multiscale model framework for allowing the inclusion of fine particles within the particle scale model is proposed in this paper. It allows prediction of the collisional behaviour of the fine particles and their effect on the grinding media. The first level of the model is referred to as a macroscale model. This is a conventional DEM model of a mill made using the same assumptions in terms of truncating the particle size distributions as is usually used by most researchers. Embedded within this