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Effect of particle shape in grinding mills using a GPU based DEM code

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ABSTRACT

The reduction in particle size of raw materials using grinding mills is an energy and cost intensive task. Optimization of grinding processes is not trivial as obtaining experimental information is extremely difficult due to the harsh environment. Thus, computational modeling is the most feasible option for obtaining information on the dynamics of the media. However, the computational cost of modeling each particle is high, resulting in the shape of the media being approximated by simple shapes, and in most cases, a reduction in the size of the mill. Even with these simplifications typical simulations take many weeks to months to complete making it infeasible for design prototyping and process optimization. In the last decade, the Graphical Processor Unit (GPU) has enabled large scale simulations of tens of millions of spheres in ball mills using the Blaze-DEM GPU code. Recently, this code was expanded to provide detailed contact detection for polyhedra using the volume-overlap method which is the most accurate approach amongst commercial and academic codes. In this study we first validated the code against experimental results for spherical and cube particle systems in a lab-scale ball mill. Thereafter, we performed a number of ball mill simulations with four additional polyhedral particle systems (truncated tetrahedra, Biluna, elongated hexagonal prisms and a mixed polyhedral particle systems) to study the effect of particle shape. This allows for a first investigation into the roles of particle angularity and aspect ratio on power draw, normal and shear power dissipation between particles, particles and lifters and, particles and the shell. We also show qualitative differences in charge profiles and force chain networks between the various particle systems.

1. Introduction

Milling. Size reduction of granular media is a common task in a large number of industries ranging from the formation of powders in the pharmaceutical industry to the grinding of ore in the minerals processing industry. Owing to the harsh environment when a mill is operating obtaining information on the dynamics of the material inside is very difficult. This lack of information makes the design and optimization of mills a difficult and bespoke process, relying on rule-of-thumb or adhoc design and operation patterns that have not changed in decades. While lab scale experiments can provide some information on the power draw and profile of material inside the mill, information on the forces and stresses that the media is subjected to cannot be readily obtained. Furthermore there is no guarantee that the design characteristics in a lab device scales to an industrial device. Granular material is free form in nature and cannot be described in a closed form solution for more than a few idealized scenarios. Thus direct numerical simulation on the particle scale is required, for which the Discrete Element Method (DEM) is the most popular (Cleary, 2001; Cleary et al., 2003; Morrison and Cleary, 2004; Cleary and Morrison, 2016).

Milling Process. Autogenous and Semi-autogenous (AG/SAG) mills are universally deployed in many mining operations. The standard practice is a single autogenous mill or semi-autogenous mill followed by a pair of ball mills which grinds the run-of-mine ore to a size suitable for flotation. AG/SAG mills produce a product size that is suitable for finish grinding in a ball mill, stirred media mill or a vertical mill. These mills can accomplish the size reduction task of two stages of crushing and screening. Hence, they find numerous applications in the mining industry. Both AG and SAG mills receive ore feed directly from a belt conveyor. Hence, the maximum size of ore is only limited by the conveying capacity of the belt conveyor. The ore size can be as high as 25–35 cm, and as one would expect, these naturally occurring ore are

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random in shape and size (Rajamani et al., 2011, 2014).

In AG mills due to the competence of the ore, larger particles break upon impact, and smaller particles are ground by compressive and attrition forces generated in the tumbling action. In SAG mills, in addition to self-breakage of the ore particles, the grinding balls cause additional breakage. Essentially in these mills which are as large as 9–12 m in diameter, the grinding action occurs in a system of irregular ore particles and spherical grinding balls, besides impact and attrition grinding also occurs by chipping of sharp edges. Furthermore, weakening of the larger ore particles occurs as internal damage accumulated during repeated impacts. It is well known that notable influences on mill performance include the mill properties such as lifter, liner, grate operating conditions (speed and fill level) and charge characteristics such as particle shape, angularity and aspect ratio.

Although simulations have predominantly focused on spherical particles (Morrison and Cleary, 2004; Rajamani et al., 2014; Peng et al., 2017), particle shape is increasingly being recognized as being important to consider during experimental investigations (Pourghahramani, 2012), as well as simulation based investigations. It is also important to take note of some recent studies that aim to quantify particle breakage or particle shape change during mill operations (Cleary and Morrison, 2016). In addition, ball charge may also deform over time as depicted in Fig. 1(d). During milling particles with high angularity (see Fig. 1(a) and (c)) are worn over time (see Fig. 1(b)), due to impacts with other particles and ball charge to be less angular due to high speed impact, abrasion, chipping and nipping of small particles between large particles (Cleary and Morrison, 2016). As a consequence, particles are often represented as superquadrics (Cleary and Morrison, 2016) that ultimately lack well defined angular edges for particles. However the initial ore feed into a mill has well-defined angular edges as well as newly broken particles inside the milling operation.

Motivation. While there have been numerous studies on lifter design, power draw, wear and grinding, etc., these studies have been limited in the number of particles, simulating just spheres or simple superquadrics owing to the large computational cost associated with the DEM. This study intends to quantify the importance of particle shape with defined angular edges experimentally, and demonstrate that polyhedral shape representations are sufficient to capture well defined angular edges. This is achieved by validating our implementation against experiment for cubic and spherical particles at the university of Utah.

1.1. Overview of DEM computing

Established discrete element software frameworks rely mostly on multi-core central processing unit (CPUs) computing platforms (Shigeto and Sakai, 2011) on which the number of polyhedral particles that can be simulated in a realistic time frame on typical workstations is limited. The largest DEM computational simulations to date of polyhedra have been done by the group at the University of Illinois using the code BLOCKS3D (Zhao et al., 2006). Seung et al. reported in his PhD thesis (Jaelee, 2014) that a one second simulation of a million polyhedral particles would require 18 months wall time. In this thesis an impulse based method similar to what is used in gaming was proposed that requires 8.5 days wall time. However such an approach disregards most of the physics that is required for a scientific study and is not considered robust enough for use in engineering applications. Mack et al. simulated 322 polyhedra (Mack et al., 2011) while Hohner et al. used a few thousand polyhedra particles.

In the last decade the Graphics Processor Unit (GPU) has become increasingly important as an alternative computational platform for discrete element simulations (Govender et al., 2014a; Radeke et al., 2010). The GPU has allowed for simulations of tens of millions of particles to be performed within a realistic computing time frame and financial budget (Govender et al., 2014b; Zhang et al., 2013; Rajamani et al., 2011; Xu et al., 2011; Hromnik, 2013). Although the GPU has numerous advantages it also presents various challenges to implementations of the DEM. The complexity of resolving contact for non-trivial particle shapes like polyhedra poses particular challenges on the GPU due to the divergent nature of polyhedral contacts as well as contact models requiring history. This is a result of the limited computational complexity and memory restrictions on the GPU. Although the GPU is an ideal match for DEM simulations, the current learning curve associated with GPU development is high as the technology is fairly new and rapidly changing when compared to traditional CPU development. Even with this increased computational capacity, the majority of the effort has been directed to spherical particles on the GPU (Shigeto and Sakai, 2011; Xu et al., 2011; Hromnik, 2013; Longmore et al., 2013).

1.2. Overview of BlazeDEM

The BlazeDEM-GPU framework allows for efficient representation and computation of poly-disperse systems for both spherical and polyhedral (convex and non-convex) shaped particles as depicted in Fig. 2.

A key feature of the framework is the geometry can be represented using typical CAD geometry (STL format) or computationally and memory efficient representations called "world" and "volume" objects where possible. "World objects" are planar representations (where any number of vertices can make up a surface) that have two faces joining such that it does not form a convex edge or primitives such as cylinders, cones, etc. as opposed to a triangle only STL mesh depicted in Fig. 3(a) or a collection of particles as in Fig. 3(b) (Longmore et al., 2013; Abou-Chakra et al., 2004; Hromnik, 2013). Finally "volume objects" allow for convex representations with edges and can be considered as polyhedra, which by default do not move under the influence of other particles, however they can deform which allows for surface wear to be captured geometrically. Fig. 3(c) depicts the representation in Blaze-DEM of a mill where the surface is an analytical world object (cylinder) and the lifters are "volume objects". A number of industrial devices can be represented using a combination of world and volume objects allowing for memory and computational efficiency. Note: regular STL files can be combined with volume and world objects as depicted in 3(d) where the

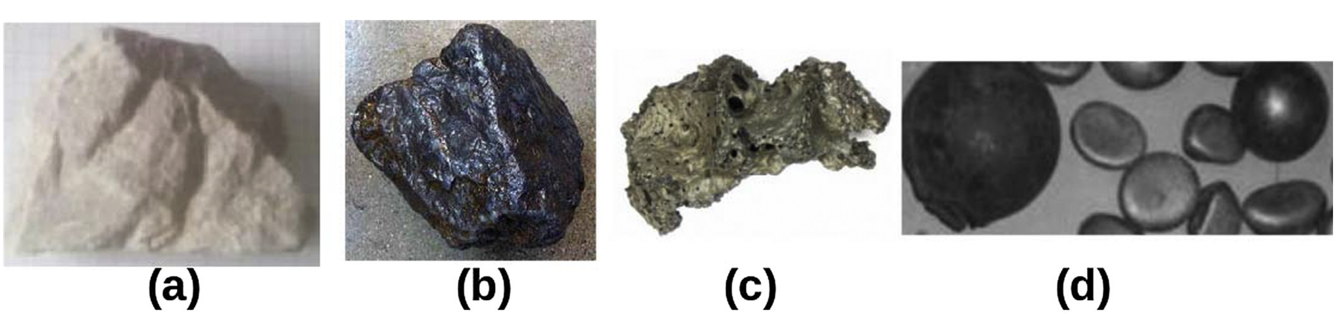

Fig. 1. (a)-(c) Shape of typical material in mills, (d) new and worn balls from a ball mill.