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A novel method for modelling of interactions between pulp, charge and mill structure in tumbling mills

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ABSTRACT

Modelling the pulp fluid and its interaction with both the charge and the mill structure is an interesting challenge. The interaction is normally modelled with a combination of CFD and DEM, where the DEM particles (grinding balls) create the structure through which the fluid penetrates, and in its turn creates forces on the grinding balls. However, in a tumbling mill, many free surfaces are found and that limits the use of CFD. An alternative computational approach is here necessary.

The smoothed particle hydrodynamic (SPH) method has earlier been used to model a ball charge and its interaction with the mill structure. In the present contribution, a SPH description of the pulp fluid is introduced. The lifters and the lining are still modelled with the finite element method (FEM), and the grinding balls with DEM. This combined computational model makes it possible to predict pressure within the pulp fluid. It is also possible to predict how the dampening effect of the pulp liquid is affected by its viscosity and density. The charge induced torque in a laboratory-scale ball mill is used for validation, and the mechanical shock waves travelling in the mill system are described.

1. Introduction

Understanding of the charge motion within the mill is of importance in mill optimisation. Both the breakage of ore particles and the wear of liners/ball media are closely linked to the charge motion. To study these phenomena in a physically correct manner, suitable numerical models for different parts of the mill system have to be utilised. Validation of the models is, of course, of major importance. Several parameters do significantly influence the effectiveness of the grinding operation; however, some of these parameters are either difficult or laborious to measure. Intermittent in situ or ex situ, measurements of these are most often prone to errors and there is often a long time-delay before the acquired data can be fed to the control system. Measuring the driving torque and relate it to the process by numerical models can be one possible way to validate, control and optimise the grinding system.

For a long time, discrete element methods (DEM) have been used as simulation tools to gain insight into particulate flow processes. Cundall (1971) introduced DEM for analyses of rock mechanic problems. When applied to comminution it gives an opportunity to study many more aspects of grinding in detail than has been possible to date, e.g. charge viscosity and charge size distribution, collision forces, energy loss spectra and power consumption. An initial attempt to use DEM to describe the interaction of large grinding balls and the lining was presented by Rajamani (2000). Other authors, for example Mishra (2003a,b) studied the inter-particle force law and contact parameters in DEM simulations to improve predictions of tumbling mill performance. However, some improvements of today's DEM models can be identified; for example, the structure of the mill (geometry and material composition) may be modelled with the finite element method (FEM). One step towards a more physically realistic mill model was taken by Jonsén et al. (2011). They used a combined DEM–FEM model to study the interaction between the charge and the mill structure.

To solve astrophysical problems in open space, Lucy (1977) and at the same time Gingold and Monaghan (1977), invented the smoothed particle hydrodynamics (SPH) method independently. It is a mesh free, point-based method for modelling fluid flows, which has been extended to solve problems with material strength. Today, the SPH method is used in many areas such as fluid mechanics (for example; free surface flow, incompressible flow and compressible flow), solid mechanics (for example; high velocity impact and penetration problems) and high explosive detonation over and under water. In the SPH method, a problem domain is represented by a set of particles or points, cf. Liu and Liu (2003). Besides representing the problem domain, the points also act as the computational frame for the field approximation. Each point is given a mass and carries information about spatial

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coordinate, velocity, density and internal energy. Other quantities as stresses and strains are derived from constitutive relations. The mesh free Lagrangian formulation and the adaptive nature of the SPH method result in a method that handles extremely large deformations. In the work by Jonsén et al. (2012), a step towards a more physically correct description of the ball charge was taken by using SPH to model the grinding balls. For structural analysis in the present work, FEM has been used. FEM is a numerical solution method based on continuum mechanics modelling, a constitutive relation for the actual material is described and the governing equations are solved (Zienkiewicz and Taylor, 2000).

When working with numerical modelling of physical systems many factors affects the accuracy of a mechanical response computation, for example: the smoothness and stability of the response, the inadequacies and uncertainties of the constitutive equation, the boundary and initial conditions and the uncertainties in the load. Such analyses of the computability of nonlinear problems in solid mechanics were investigated by Belytschko and Mish (2001). Validation of the models is therefore important for building confidence in numerical results.

It is important to have in mind the complex nature of the milling process. To decrease the gap between model and reality more physically precise models are necessary. A pure DEM model provides useful information on charge motion, collision forces, energy loss spectra, power consumption etc., cf. Tano (2005). Data that is important for improving the milling efficiency and gaining more understanding of the process itself. A step towards a more physically correct numerical description of mill systems was the combined DEM–FEM model presented by Jonsén et al. (2011). With the DEM–FEM model forces and mechanical waves as well as structural responses and their influence on the charge motion can be studied. The model gives the opportunity to optimize the material selection of the mill structure. In the work by Jonsén et al. (2012) a combined SPH–FEM model was used in simulations of tumbling mill processes. With a SPH–FEM model, structural response and its influence on the charge motion could be studied in greater detail. The model gave not only the opportunity to optimize the material selection of the mill structure but also to study the internal workings of the charge. FE-codes are well developed and already used for optimisation of mechanical response of structural parts. Critical response values e.g., stress and strain can be identified during the milling process.

The comminution process is complex and to include all phenomena that occur in a single numerical model is today not possible. Therefore, modelling the internal working of the charge and the physical interaction between the charge and the mill structure is the major goal and limitation of this work. The combined SPH–DEM–FEM model presented here can predict the classical DEM results, but can also predict responses from the mill structure like, e.g., stress and strain, as well as the pulp liquid flow and pressure. All parts of the mill system will affect the response and a SPH–DEM–FEM model gives the opportunity to study the influence of the mill structure and for e.g. pressure and shear stresses in the charge. The validation of this task is done by comparing numerical results with experimental measurements from grinding in an instrumented small-scale batch ball mill equipped with an accurate torque meter. A description of this mill and its use for validating torque measurements was presented by Jonsén et al. (2013).

2. Experimental setup

Experimental measurements were done by Stener (2011) on a laboratory scale ball mill. The mill was built by SALA (SALA international K706250/1981) and has recently been modernized with new measurement equipment and control logic. The mill has a stainless steel drum with four equally spaced lifters and a size of $\varnothing 300 \times 450$ mm, see Fig. 1. The rotational speed can be set between 10-100 rpm and is maintained by a closed loop regulator. The mill critical rotational speed (N_c) is 77 rpm.

The torque applied to the mill charge is measured as the reaction force applied on a load cell a distance (s) from the centre of rotation, see Fig. 2. Measured force (F) and torque arm length (s) gives applied torque (τ), which together with angular velocity (ω) gives power (P):

$$\tau = F \cdot s, \tag{1}$$

$$P = \tau \cdot \omega, \tag{2}$$

The only frictional loss which could cause bias in the measurements comes from the two ball bearings supporting the mill drum. This is negligible since this friction is small and also compensated for during system calibration.

2.1. Measurement system

The force is measured by a load cell (S-E-G instrument HN8-20-0), which according to the specification should have a measurement error smaller than ±0.075 Nm. The force signal is amplified by a signal amplifier (Dataforth DSCA38-12C) with a specified accuracy and linearity corresponding to an error less than ±0.02 Nm. Data acquisition is made with a 12-bit analogue input module (National instruments NI 9201). The 12-bit resolution gives a resolution in torque of 0.13 Nm.

The rotational speed of the mill is measured with an inductive proximity sensor working on what can be described as a tooth wheel with one missing tooth (6-1 teeth). Since this method counts the number of revolutions during a long period of time the accuracy in the average rotational speed measurement is high.

During all the experiments data was sampled at 100 Hz and average torque was calculated as a function of time and also as a function of mill angular position. When the torque is averaged on angular position the mill revolution is divided into 180 bins, each representing 2°, see Fig. 4b. Each sample is then added to an average in the bin corresponding to the measured angular position.

2.2. Calibration

The system is calibrated in two steps. First a static torque calibration and then a dynamic zero calibration. In the first step a separate torque arm are loaded with a set of calibration masses to

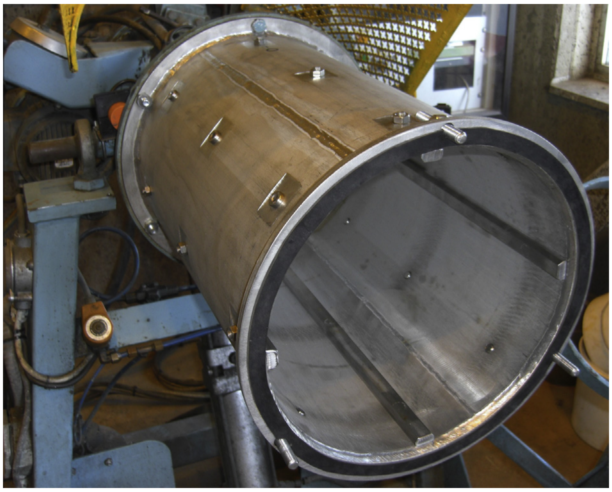

Fig. 1. SALA laboratory ball mill.