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Modeling ball impact on the wet mill liners and its application in predicting mill magnetic liner performance

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ABSTRACT

Numerous studies have been conducted in the past and models have been developed to simulate ball motions in horizontal mills. Equations and computer programs have been published to calculate falling velocity of the grinding media upon impacting the mill shell (liner). However, these equations and programs are only suitable for dry mill applications.

To accurately simulate the impact of falling balls on the liners in wet mills, the authors have developed models to determine the ball impact location and velocity as the ball contacts the mill liner. Drag and buoyancy forces are considered when the ball submerges in the pulp inside the mill. Models can be used to enhance mill liner design and optimize the operation of horizontal wet mills such as horizontal ball mills.

The models are applied to calculate the falling ball impact on the metal magnetic mill liners. Various scenarios are simulated and results are used to predict the performance of magnetic mill liners in various ball mill applications.

1. Introduction

In a horizontal ball mill, particle size reduction is achieved by rubbing or impacting heavy masses in the rotating cylinder. Those masses, consisting of ore particles and grinding balls, either cascade down the surface or fall (cataract) through the free space onto the material or, under certain circumstances, onto the mill liners.

Various tests and studies have been conducted in the past and models developed to simulate ball motions in the mills and calculate the ball impact load on the shells (Orford et al., 2005; Cleary et al., 2003; McBride and Powell, 2006; Huang et al., 2010; Moys et al., 2002). Modeling softwares are available on the market using discrete element methods (DEM) that can create straightforward schematic views of ball trajectories. The results of many tests and DEM simulations confirmed that under suitable conditions, both cascading and cataracting movements exist in the same ball mill.

Fig. 1 is a DEM trajectory image with velocity vectors in a SAG mill of 11.58 m in diameter and rotating at 75% of critical mill speed.

Almost all the tests and studies were either conducted in dry mills or based on the assumption that pulp in the mills has little influence on ball trajectories and the degree of impact the balls have on mill shells.

The motion of balls in pulp is obviously different from that in air since the falling balls face significant drag force and buoyancy in the pulp. In this paper, the mathematical deduction of the falling ball motions in the pulp including these forces is presented. Models are developed to determine ball velocity and in turn, the ball impact load exerted onto the mill liners. They are used for the simulation of ball impact on the mill liners to predict the performance of metal magnetic mill liners in various scenarios.

2. Ball detachment angle and impact velocity in dry mills

In a horizontal grinding mill, balls that contact the mill liners have the highest linear speed, and are therefore brought to the highest position, which results in the farthest ball travel distance with the highest velocity, producing the most impact on the liners. The behavior/reaction of these balls are the objects of this study (see Fig. 2).

The rotation of the mill drum creates a centrifugal force. If the peripheral speed is too high, the mill begins to act like a centrifuge and the grinding mass, including balls and ore, do not fall back but stay on the perimeter of the mill. The point where the mill becomes a centrifuge is called the "critical speed". Ball mills and SAG mills in the mining industry normally operate at 70–80% of the critical speed. Such percentage of the critical speed is called specific speed.

For the meanings of all the symbols in this paper, refer to Section 7, Symbols.

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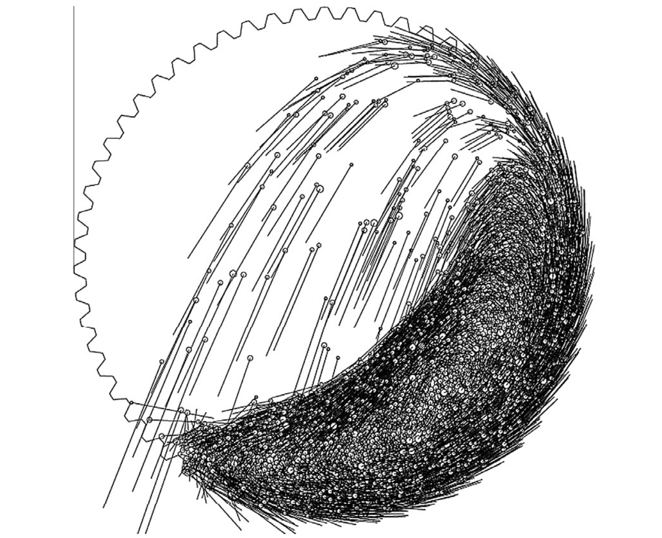

Fig. 1. A DEM simulation of ball fall trajectory in a SAG mill. Compliment of Process Engineering Resources, Inc.

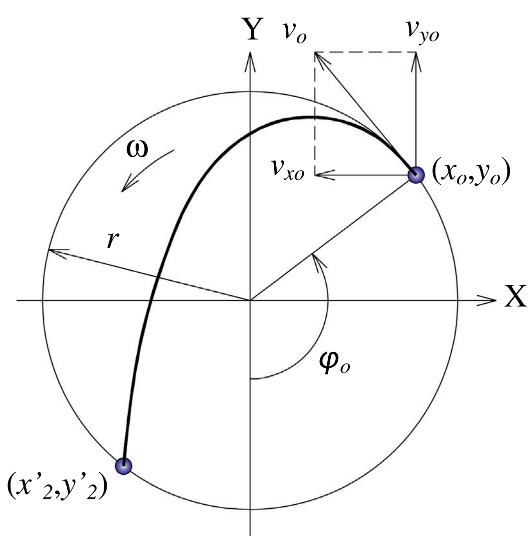

Fig. 2. Ball projectile in a dry mill.

When a mill operates at a speed lower than the critical speed, the ball and other mass moves with the mill at a linear velocity v_0 that is the same as the tangential speed at the point:

$$v_0 = \omega \cdot r \tag{1}$$

The ball will leave the mill wall at some point before reaching the highest point. The detachment polar angle φ_0 can be obtained with the equation below:

$$\varphi_0 = \arccos\left(-\frac{\omega^2 r}{g}\right) \tag{2}$$

with $\frac{\pi}{2} \leqslant \phi_0 \leqslant \pi$ for $0 \leqslant \omega \leqslant \sqrt{\frac{g}{r}}$.

The coordinate of the detachment point can be obtained by the following:

$$x_0 = r \cdot \sin\varphi_0 \text{ and } y_0 = -r \cdot \cos\varphi_0 \tag{3}$$

And the linear velocity can be further broken down into the horizontal and the vertical components:

$$v_{x0} = -v_0 \cdot \cos\varphi_0 \text{ and } v_{y0} = v_0 \cdot \sin\varphi_0 \tag{4}$$

The ball starts a projectile motion and its path can be described as $x = -r \cdot \cos\varphi_0 + v_0 t \cdot \sin\varphi_0 - \frac{1}{2} g t^2$.

$$y = r \cdot \sin\varphi_0 + v_0 t \cdot \cos\varphi_0 \tag{5}$$

By applying the following condition:

$$x^2(t) + y^2(t) = r^2 \tag{6}$$

the impact point on the shell can be deduced.

Schilz (Schilz, 1998) presented the relations between the impact polar angle and the detachment polar angle:

$$\cos(\varphi'_2) = \cos(3\varphi_0) \text{ and } \sin(\varphi'_2) = -\sin(3\varphi_0) \tag{7}$$

The coordinate of the impact point can be calculated with the following equations:

$$x'_2 = r \cdot \cos\varphi'_2 \text{ and } y'_2 = r \cdot \sin\varphi'_2 \tag{8}$$

The impact velocity can be obtained from:

$$v'_2 = \sqrt{v'^2_{x2} + v'^2_{y2}} \tag{9}$$

where

$$v'_{x2} = v_{x0} \text{ and } v'_{y2} = \sqrt{2g(y_0 - y'_2)} \tag{10}$$

3. Ball falling in pulp, impact velocity in wet mills

The discussions in Section 2 for dry mills can also be applied to the wet mills up to the point just before the balls reach the pulp surface at point (x_1, y_1). See Fig. 3 for the ball movement curve in the pulp of a wet mill.

The coordinate of point (x_1, y_1) at which the ball hits the pulp surface can be derived from resolving the equation $y = y_1$ and Eq. (5).

The horizontal velocity, vertical velocity and their combined velocity at (x_1, y_1) can be obtained:

$$v_{x1} = v_{x0}, \quad v_{y1} = \sqrt{2g(y_0 - y_1)} \text{ and } v_1 = \sqrt{(v_{x1}^2 + v_{y1}^2)} \tag{11}$$

The horizontal and vertical motions shall be treated separately since the forces applied to the ball are from two different directions.

In the horizontal direction, the ball is subject to a single force – drag (Website of Wikipedia, 2010):

$$F_x = m a_x = m\frac{dv_x}{dt} = -\frac{1}{2}\rho v_x^2 A C_D \tag{12}$$

Since $m = \frac{1}{6}\pi d^3 \rho_s$ and $A = \frac{1}{4}\pi d^2$, from Eq. (12), the following can be deducted:

$$-\frac{dv_x}{v_x^2} = \alpha \cdot dt \tag{13}$$

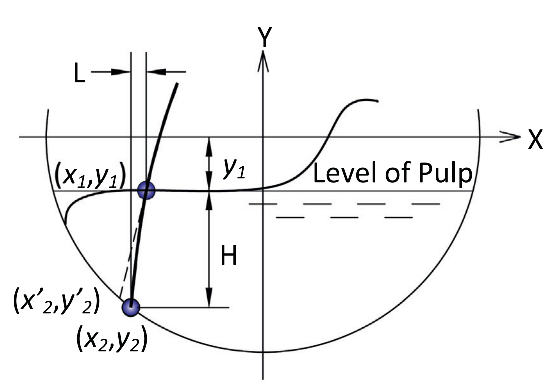

Fig. 3. The ball movement in the pulp in a wet mill.