Minerals Engineering 22 (2009) 1200–1208

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Investigation on measuring the fill level of an industrial ball mill based on the vibration characteristics of the mill shell

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ARTICLE INFO

Article history:
Received 3 September 2008
Accepted 24 June 2009
Available online 21 July 2009

Keywords:
Ball mill
Fill level
Vibration signal
Coal

ABSTRACT

A novel characteristic variable of fill level has been proposed, in order to reduce the influence of various factors on measuring the fill level and improve the measurement accuracy of the fill level. A relationship was developed between the fill level and the angular position of the maximum vibration point on the mill shell through theoretical calculation and on-site experiments. This relationship was studied theoretically with two assumptions. The vibration signals were then collected by an accelerometer mounted directly on the mill shell, and analyzed on the time domain to obtain the maximum vibration point on the mill shell, in order to study the correlation between the fill level and this angular position.

Both the results of theoretical calculations and experiments show that the position of the maximum vibration point on the mill shell moves to a lower angular position as the fill level increases. Comparison of the traditional and the new characteristic variable of the fill level reveals that the characteristic variable proposed in this paper is more superior and stable. It shows potential for measuring the fill level more accurately.

1. Introduction

It is well established that the ball mill pulverizing system has exceptional adaptability for processing different types of coal and facilitating maintenance, and it has been widely applied for comminuting and drying coal in coal-fired power plants. However this system is highly energy intensive and consumes about 20% of all electricity in the power plant. As the ball mill pulverizing system is non-linear, has long time delays and time-varying, the fill level of the coal powder cannot be measured accurately, which leads to the mill usually being operated under very uneconomical conditions in order to prevent coal blockage. Furthermore it is difficult for the automatic control system to accomplish steady operation of the mill. Therefore exact measurement of the fill level is a key and basic factor for realizing the automatic, reliable and efficient operation of the mill system.

Until now, many methods have been applied to measure the fill level. One of the traditional methods was measurement as a function of the differential pressure between the inlet and the outlet of the mill. As the fill level increases, more coal powder is exposed to the air flow through the mill, and the differential pressure increases. The same relationship governs the opposite condition, as the fill level decreases. However, the differential pressure signal is also affected by other factors, such as the rotational speed of the mill, the type of lifters used and their wear, particle size distribution of the mill hold-up, physical properties of the ground material and concentration of material in the air during pneumatic transportation. Zhang (2001) studied the fill level by measuring the energy consumption of the mill motor, but the wear of steel balls and the variation of ball load can seriously affect the power value of the mill. Kolacz (1997) proposed a method to measure the fill level by using a strain transducer. The transducer was installed at the middle of the mill shell. When the transducer moved to the top position of the mill shell, it measured the compression. After half a revolution, the transducer reached the bottom of the mill shell, the tension being measured. By taking the difference between the readings corresponding to compression and tension, it was possible to calculate the total strain variations that are directly proportional to the fill level. Recently the measurement and control of the fill level in the mill has also been accomplished by analyzing the acoustic signals of the mill (Xing, 2004; Sha et al., 2006a,b; Kang et al., 2006). Together with the increments of fill level, the acoustic signal shows a decreasing trend, and vice versa. However, the acoustic signal will be variable with a greater difference even under the same fill level condition because of the disturbance of other noise near the mill, the variations of steel ball load and the water content of the coal during milling.

Since the vibration strength of the mill shell and the bearing housings can to a large extent provide information on the fill level (Sha et al., 2006a,b), vibration methods have recently been carried out to develop techniques for monitoring the fill level. As the

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doi:10.1016/j.mineng.2009.06.008

accelerometer can be mounted easily on the front and rear bearing housings, traditional vibration methods can be used to measure the fill level, based on the vibration signals of the bearing housings. Among these vibration methods, some characteristic values of the fill level, such as amplitude (Behera et al., 2007; Lv et al., 2002), energy (Zhao et al., 2003), power (Zhang and Zhang, 2000) and root mean square (RMS) (Hao and Lv, 2003; Zhu et al., 2003) have been extracted from the vibration signals of the bearing housings. However, besides the impact of steel balls, there are still some other factors and vibration sources, which can cause the vibration of bearing housings. These vibration sources can also affect the characteristics of the time and frequency domain of vibration signals of the bearing housings. So the vibration signals of the bearing housings do not accurately reflect the collision condition of the steel balls and the fill level information in the mill. Due to difficulties in accelerometer installation and vibration data transmission, to date there has been little work on monitoring the fill level by processing the vibration signals of the mill shell but the work of Gugel et al. (2003) and Gugel and Moon (2007) is noteworthy. In their work, two vibration sensors, 180° apart, were used to collect the signal information from the mill shell, so that the instantaneous readings could be averaged. The averaged data were then fed into a dynamic neural network and a fill level measurement from 0% to 100% was output.

In this paper, the relationship between the fill level and the position of the maximum vibration point of the mill shell has been established, and a new characteristic variable of fill level is proposed. This research consists of three main components: theoretical calculations, experimental and vibration signal processing. Firstly, the angular positions of the maximum vibration point on the mill shell for various ball loads and fill level conditions were calculated theoretically under ideal conditions. Secondly, a series of experiments were carried out at an industrial ball mill in a coal-fired power plant, and the vibration signals were collected directly from the mill shell. Finally, the new feature value of the fill level was extracted by analyzing and processing the vibration signals of the mill shell, at the same time the traditional and the new characteristic variable of the fill level being compared and discussed.

2. Theoretical calculation

Compared with steel balls in other layers, the steel balls in the outermost layer have the highest impulse and kinetic energy in the course of falling, and the maximum vibration on the mill shell is generated by the falling impact of steel balls in this layer. The positions of steel balls in the outermost layer can be seen in Fig. 1. When the ball in the outermost layer impacts directly on the mill wall, the collision point is the maximum vibration point of the mill shell. When the ball in the outermost layer impacts on the coal powder, the impact energy is delivered to the mill shell, which also leads to a maximum vibration point on the mill shell. In this research, the correlation between the fill level and the position of the maximum vibration point of the mill shell was studied. If this relationship can show a certain regularity, the fill level can be studied by using this point.

In the on-site tests, a 3.5-m-diameter by 6.0-m-long industrial tubular ball mill was operated at 17.57 rpm (77% of critical speed). For the theoretical calculations, the size and the speed of the mill are the same as the test mill.

The position of the maximum vibration point of the mill shell is calculated theoretically under two assumptions described as follows:

(1) During the working status of the mill, except for a steel ball in the outermost layer, as shown in Fig. 2, the coal particles and other steel balls are accumulated at the bottom of the roller at static state. In Fig. 2, the length of line CH denotes the accumulated height of the coal particles and steel balls in the mill, and the line AE represents the accumulated surface.
(2) In Fig. 2, there is no displacement in the x direction for the movement trajectory of the ball in the outermost layer, and the x coordinate of this ball is always equal to zero.

When the ball reaches the detachment point G, as shown in Fig. 2, this ball will begin a parabolic movement. The intersection point (collision point) between this parabolic trajectory and the accumulation surface is point D $(0, a, b)$. The distance between the maximum vibration point on the mill shell and point D is the shortest among the distances between the mill shell and point D. Point B $(0, y, z)$ (see Fig. 2) denotes the maximum vibration point. Here the minimum distance is obtained with a constraint condition, which is expressed by:

$$\begin{cases} u = m^2 = (a-y)^2 + (b-z)^2 \\ y^2 + z^2 = R^2 \end{cases} \tag{1}$$

where m is the distance between points B and D. In Eq. (1), the minimum value of u is needed, and the following formula can be obtained by the constraint condition.

$$z = -\sqrt{R^2 - y^2} \tag{2}$$

Then the parameter u can be calculated as follows:

$$u = (a-y)^2 + \left(b + \sqrt{R^2 - y^2}\right)^2 \tag{3}$$

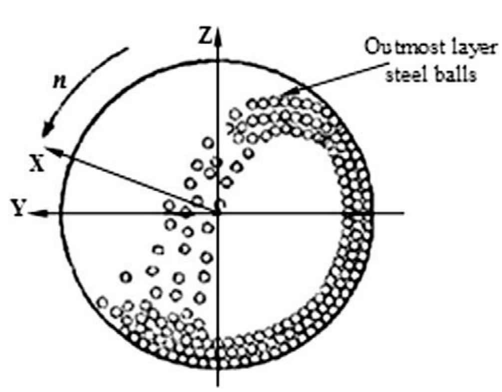

Fig. 1. Schematic diagram of motion of steel balls in different layers in the mill.

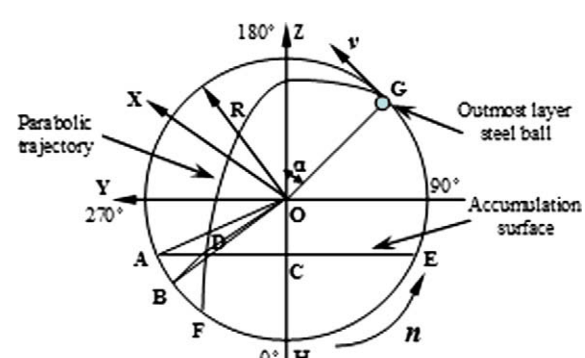

Fig. 2. Schematic diagram of motion trajectory of the steel ball in the outmost layer in the mill (mill diameter = 3.5 m, length = 6.0 m, mill speed = 17.57 rpm, ball load volume = 15%, fill level = 15%).