RESPONSE OF PRIMARY GRINDING MILL PERFORMANCE TO CHANGES IN OPERATING CONDITIONS USING AN ON-LINE SURFACE VIBRATION MONITOR

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ABSTRACT

Opportunities to monitor and control primary grinding mill performance are strongly sought after in the mineral processing industry. Currently, limited on-line information about mill charge motion and content is available to mill operations for control purposes, leading to periods of lower throughput, instability, variable product size and accelerated mill liner and lifter wear. In response to this need, CSIRO has developed an on-line surface vibration monitor for primary grinding mills which produces data that has been shown to provide new information about the mill charge in terms of toe and shoulder position, as well as potentially key features such as the overall charge level, the distribution between rock and balls in the mill, and the impact of the charge on the mill liners and lifters.

This paper outlines the key features of the on-line monitor system, particularly those relating to data transmission, data analysis, and the design of the monitor and its independent power supply. It describes the coupling of single vibration sensor data from the CSIRO on-line monitor to the actual operating conditions of a SAG mill and how the vibration response and hence mill operating conditions vary as a function of time, including during mill equipment failures such as a broken discharge grate. Opportunities for improved mill control based on the data from the on-line monitor are also discussed, as well as the implications in terms of mill processing and maintenance performance.

Recently a CSIRO monitor was also installed on a ROM ball mill and analysis of the vibration sensor data from this installation is currently underway. Preliminary findings from this installation will be presented along with comparisons of generic information, such as toe position (measurement precision and operation variability) and vibration signal (intensity, sensitivity and operation variability), between this type of primary grinding mill and AG/SAG mills.

Keywords: surface vibration, AG/SAG mills, primary grinding, instrumentation, process control

INTRODUCTION

Plant operators are increasingly reliant on instrument measurements to gauge the real time operational status of critical plant equipment. Therefore, opportunities to monitor and control primary grinding mill performance are strongly sought after in the mineral processing industry. Currently, limited on-line information about mill charge motion and content is available to primary grinding mill operations for control purposes, potentially leading to periods of lower throughput, instability, variable product size and accelerated mill liner and lifter wear.

It was demonstrated in a number of short-term trials that a surface vibration monitoring system based on accelerometers fixed to the mill liner bolts was responsive to changes in mill operating conditions in a systematic way.
way. The system was shown to provide new information about the mill charge in terms of toe and shoulder position, as well as potentially key features such as the overall charge level, the distribution between rock and balls in the mill, and the impact of the charge on the mill liners and lifters (Campbell et al, 2003). This promising outcome led to a second phase of work investigating and designing a prototype system for a more permanent installation, the preliminary details of which were reported previously (Campbell et al, 2006).

Since the initial installation of a prototype continuously powered acoustic vibration monitor system on an industrial semi-autogenously grinding (SAG) mill, testing, evaluation and a program of continued improvement has been undertaken to improve the ruggedness, and hence reliability, of the system hardware. This paper outlines the key features and hardware improvements of the on-line monitor system, particularly those relating to data transmission, data analysis and the design of the monitor and its independent power supply. It describes the coupling of single vibration sensor data from the CSIRO on-line monitor to the actual operating conditions of a SAG mill and how the vibration response and hence mill operating conditions vary as a function of time, including during mill equipment failures such as a broken discharge grate. Opportunities for improved mill control based on the data from the on-line monitor are also discussed, as well as the implications in terms of mill processing and maintenance performance.

Experience gained from the operation of the prototype mill monitor installation was incorporated into a second mill monitor system recently built and installation onto a run-of-mine (ROM) ball mill. Analysis of the vibrating sensor data from this installation is currently underway and some preliminary findings from this installation are presented along with comparisons of generic information, such as toe position (measurement precision and operation variability) and surface vibration signal (intensity, sensitivity and operation variability), between this type of primary grinding mill and AG/SAG mills.

MILL MONITOR SYSTEM AND RECENT ENHANCEMENTS

The key features of the original prototype of a ruggedized continuous mill monitoring system were described in Campbell et al (2006). A number of changes have subsequently been made to the various components of the mill monitor during evaluation of the prototype system. A schematic of the latest on-line system design is shown in Figure 1 and a brief outline of the main system components, with an emphasis on the enhancements made, follows.

Figure 1. Schematic of an on-line mill monitor system utilizing acoustic emission sensors
Inertial power supply

Continuous power to the on-mill components of the monitor is ideally provided by an inertial power supply. A photograph of the latest design, which was constructed for installation on a ROM ball mill, is shown in Figure 2.

![Inertial power supply](image)

**Figure 2.** Photograph of a recently constructed and installed inertial power supply

This arrangement is applicable when the power supply can be mounted on the feed (or discharge end) of a mill, where the centre of rotation of the pendulum weight is within 2.7 m of the centre of rotation of the grinding mill, and when a power cable can be run between the power supply and a transmitter box mounted either in an adjacent girth gear or on the shell of the mill. Alternatively, power could be provided by a suitably designed battery box.

**Gearbox/stepper motor assembly**

For the prototype unit installed on a SAG mill, duplicates of the gearbox and stepper motor assembly were manufactured and swapped out at various intervals for inspection. Typically, only the main bearing holding the pendulum weight was replaced at around one year intervals as a preventative maintenance measure. The duplicate assemblies operated over a period of six years during testing of the prototype. The success of this combination in the prototype unit meant that similar components were used in the construction of a monitor for a ROM ball mill.

**Electronic regulator**

During evaluation, a number of modifications were made to the electronic regulator that provides a constant voltage output for the electronic equipment on the mill. These included changes to some of the components used, their mounting to the circuit board and the introduction of additional vibration dampening for the electronic circuit board, all of which extended the service life of the electronic regulator to over one year. In addition, for the ROM ball mill installation, the electronic regulator was mounted in a separate box on the outside of the drum housing the gearbox/stepper motor assembly to further improved reliability, inspection, and service access.

**Accelerometer Modules**

The initial sensor modules used Bruel and Kjaer type 8309 accelerometers in combination with charge converters in order to provide a voltage output representing the surface vibrations detected through the liner bolts on which the sensors were mounted. These charge converters proved susceptible to failure due to vibration on the mill,
typically failing within three to 11 months after installation despite various attempts to extend their operating life. In late 2007, testing began of an alternative accelerometer (ENDEVCO 7259B-10) with an integrated charge converter. The use of this accelerometer enabled a redesign of the housing, and led to a module of reduced size and enhanced ruggedness. These new accelerometers, in conjunction with the redesigned housing, proved to be successful in significantly extending the life of these modules, most of which have now been in operation for nearly three years. Figure 3 shows a photograph of the current module design mounted on a lifter bolt of a ROM ball mill.

Figure 3. Photograph of a current accelerometer module mounted on a ROM ball mill

Transmitter/Receiver Unit

The original telemetry system was a commercial (Datatel) transmitter/receiver system (Campbell et al, 2006) operating at around 200 MHz. However previously unidentified intermittent radio frequency (RF) signals, produced by electrical equipment operating near the prototype installation, could not be effectively separated from the RF signals carrying the acoustic emission data from the sensors. This interference significantly reduced the integrity of some facets of the vibration signal. Consequently, CSIRO built a new telemetry system based around the earlier trial unit (Spencer et al, 1999, 2000; Campbell et al, 2001, 2003) utilizing Sennheiser transmitters and receivers. While use of the Sennheiser units reduced the frequency bandwidth of the monitor system, from 50 kHz with the Datatel unit, to less than 20 kHz, it had been established that a significant amount of the relevant information was likely to be in the region below 20 kHz (Campbell et al, 2006).

Coupled with the change in telemetry system was the introduction of a radiating cable running around the shell of the mill with two receiving aerials adjacent to this cable but mounted off the mill, as illustrated in the schematic of Figure 1. This replaced the Datatel arrangement of a single transmitting aerial on the mill and four receiving aerials evenly spaced around the mill. The new receivers were equipped with a diversity system to enable selection of whichever aerial had the strongest signal at any given time. These changes have resulted in reliable, clean vibration signals and the original radiating cable remained operational for nearly six years before being replaced.

Data Acquisition

Hardware

Recording of raw sensor outputs from the receivers and processing of that data is achieved via a high speed (100 000 samples per second) data acquisition card manufactured by National Instruments and an industrial computer supplied by Advantech. A trigger bolt mounted on the mill and magnetic proximity switch are used to initiate data acquisition and provide both angular position and mill speed information.
Software

The main program is written in Visual C/C++ and runs in a Command window. This program uses several functional libraries including commercial device drivers and compiled MATLAB signal processing routines to provide functions for the executable code during data collection, data analysis and data output. Minor changes have been made to the processing software to improve the robustness of the software including locating and trapping unexpected variable conditions to prevent inadvertent program termination. However, the analysis and control routines remain unchanged since completion of the AMIRA P667A Project (Campbell et al, 2006).

System interfaces

User interfaces

Interaction with the main program and output data is done via a user interface and a trend-plotting program respectively. The user interface was updated to a Windows-based program to make the interface more user-friendly. This application allows the user to view, and if required, update the various parameters required by the software to process the data; for example, the angular location of the sensors on the mill with respect to the proximity switch. The trend-plotting program has been enhanced to allow the user to select the sensor whose data is to be displayed on the computer screen. The actual time between data set outputs will vary depending on a number of factors such as the number of mill revolutions collected for averaging and analysis, the number of sensors (maximum of four), the data sampling rate, and the processing and output options selected by the user.

Plant interface options

The site-specific output data is saved to a result file and resides in a shared directory on the system’s industrial computer. Access to the data file can be achieved via a number of different options with the choice likely to be dependent on local requirements at the installation site. The prototype system has a plant interface module that provides 4-20 mA outputs for up to four monitor measurements, which currently are toe position, shoulder position, total signal power (all from a single selected sensor) and mill speed as determined via the proximity system.

Remote access

The original mill monitor system incorporated a 56 kbit/s dialup modem operating over the analogue phone system to enabled remote access to the mill monitor PC, albeit with very slow transfer speeds and periodic connection issues. Recently this function on the prototype system has been upgraded and now utilizes a 3G wireless modem and a commercial web-based remote access package called LogMeIn®. The results so far indicate a far superior means of remote access and data retrieval from site. Because the application is web-based, access can be gained from any location with access to the internet.

RESULTS

Two continuous mill monitoring systems have been successfully installed on industrial scale primary grinding mills. One was the prototype system installed on a SAG mill, which was progressively upgraded based on operating experience, and the other was a system recently installed on a ROM ball mill. These systems were both setup so that data from the accelerometers mounted on these mills would be collected and processed as an individual data set over a period of 12 mill revolutions, representing about 1 min of operation. The raw signal data is then processed by the data analysis software to determine key outputs of interest including the toe and shoulder positions of the charge, average total vibration signal power, and distribution of the vibration power between selected frequency bands. The methods of determining these measurements have been outlined previously (Spencer et al, 1999, 2000).

Some examples of the results obtained from these monitors are presented and discussed in terms of the actual operating conditions of the mills and how the vibration response and hence mill operating conditions vary as a function of time. Some comparisons are also made between the signal characteristics from the two different mills.
SAG mill installation

The CSIRO mill monitor installation in Australia is on a 4900 kW SAG mill, 8.5 m in diameter and 4.3 m long. This mill is variable speed and typically operates between 11 and 11.5 rpm.

An example of the profile of the smoothed signal power detected by an accelerometer, as a function of the rotational position, for 12 individual consecutive mill rotations is shown in Figure 4.

![Figure 4. Signal power as a function of mill rotation angle from a SAG mill](image)

At this installation, the mill is rotating in a clockwise direction when looking at the discharge end of the mill. The convention used by the software to specify the angular position of the accelerometers at any given time is to designate the 0° (or 360°) position as the equivalent to the 3 o’clock position on a clock with the angles increasing as you move in an anti-clockwise direction around the mill. The data is plotted starting from near the position of the proximity switch (in this case located at 209°). Following the profile from right to left tracks the change in signal power as the accelerometer rotates with the mill in an anti-clockwise direction. Hence for the data set shown the vibration signal has a minimum power level near 100°, defined as the shoulder position, and a maximum power level near 300°, defined as the toe position.

Examples of mill monitor response to operating condition changes

Figure 5 illustrates the trend in the toe position calculated from the vibration signal coming from an accelerometer sensor mounted on a bolt of a discharge end lifter.

The large short-term excursions in toe angle are predominantly due to mechanical issues causing a short-term build-up in load within the mill followed by operator actions to restore more normal operation; they are not in this instance due to poor control. During this period the toe angle shows an underlying trend to a lower position over time possibly because of the gradually wear of the mill lifters. The period plotted, approximately three months, represents the time interval between replacements of the shell lifters for this mill.

Figure 6 shows the calculated toe values and measured signal power for a period leading up to abnormal operation resulting from a broken discharge grate in the mill.

The CSIRO mill monitor recorded the significant changes in toe position and vibration signal power as a result of the mill load increasing. Typical mill operation produces toe values of around 295-305° for this mill. During the period in which the mill load increased, the toe values recorded at the discharge end peaked at 330° before the mill was shutdown to replace a broken discharge grate. Meanwhile the surface vibration signal power substantially declined as the mill filled. Having a system that is able to directly measure changes in operating conditions as evidenced by changing toe position and signal vibration levels available to the operator, and/or
producing an alarm when departures from normal operation occur, should provide valuable information, particularly as operators have become more reliant on feedback from instrumentation.

![SAG Mill - charge toe position from a single sensor](image)

**Figure 5.** Calculated toe values over a three-month period from a sensor mounted on a SAG mill

![Example of system outputs during an abnormal mill operation event (broken grate)](image)

**Figure 6.** Example of system outputs during an abnormal mill operation event (broken grate)

The surface vibration monitoring system can detect changes in SAG mill steel ball load. A simple indicator of this appears to be the 2.5-6 kHz band power fraction, however it should be noted that no attempt has been made in this study to 'tune' the frequency band for optimal predictive performance. A higher accuracy quantitative prediction of steel ball load for a pilot-scale SAG mill has previously been achieved via more complex multivariate statistical analysis methods applied to surface vibration power spectral data (Spencer *et al.*, 2006).

Figure 7 shows data for a period before and after an adjustment to the targeted ball charge in the SAG mill. The calculated values from a steel mass balance model developed by the site for this mill show a steel loading variation over the period of up to approximately 3%. There is a reasonable correlation between the 2.5-6 kHz band power fractions of the surface vibration from a sensor mounted on a discharge lifter bolt. Corresponding to the increase in the fraction of vibration power in the 2.5-6 kHz band is a decrease in the 1-2.5 kHz band power...
fraction and it is hypothesized that the surface vibrations associated with steel ball impacts on the mill lifters dominate the 2.5-6 kHz frequency range while impacts of large rocks contribute to surface vibrations in the 1-2.5 kHz frequency band.

![Graph](image)

**Figure 7.** Response of the mill monitor to a change in steel load in an industrial SAG mill

The available data on mill operating conditions, such as mill power draw, rotation speed, feed rate, pulp density and feed particle size, over the period shown in Figure 7 were examined and while there were significant changes over time scales of a few days there was nothing that could be correlated with the step change in the discharge sensor 2.5-6 kHz band power fraction.

**ROM ball mill installation**

Recently a CSIRO mill monitor was installed on a 10400 kW ROM ball mill in South Africa. This mill has an inside diameter of 7.2 m, is 8.0 m long and rotates at a fixed speed of 12 rpm.

An example of the profile of the smoothed signal power detected by an accelerometer on the ROM ball mill, as a function of the rotational position for 12 individual consecutive mill rotations, is shown in Figure 8.

![Graph](image)

**Figure 8.** Signal power as a function of mill rotation angle from a ROM ball mill
At this installation the mill is rotating in an anti-clockwise direction. The convention used by the software to specify the angular position of the accelerometers at any given time is as described above. The data is plotted starting from near the position of the proximity switch (in this case located at 337°) and, since this mill rotates in an anti-clockwise direction when viewed at the discharge end of the mill, following the profile from left to right tracks the change in signal power as the mill rotates through a full revolution.

The signal profile for this ROM ball mill differs from that of the SAG mill in that it shows a secondary minimum and maximum. For the example data set shown, the vibration signal has a minimum power level near 70° (the shoulder position) and a maximum power level near 220° (the toe position). As mentioned there is a secondary maximum near 20°, within the region occupied by the charge. At present the physical meaning of the secondary maximum in surface vibration power inside the charge is not known. It could be due to a mismatch between mill rotation speed and steel load (analogous to rilling in AG/SAG mills – see Campbell et al. 2003). Further investigation would be required to ascertain if this was indeed due to some adverse mill operating state or some other facet of the charge motion.

Examples of mill monitor response to operating condition changes

Figure 9 illustrates the trend in the toe position calculated from the vibration signal coming from an accelerometer sensor mounted on a lifter bolt in the discharge half of the mill.

![Figure 9](image)

Figure 9. Calculated toe values over a 3.5 month period from a sensor mounted on a ROM ball mill

As was the case for the SAG mill, there are several occasions where large variations in the toe position occur. Unlike the SAG mill there is no underlining trend over time. For this ROM ball mill the change out frequency of the shell lifters is much less frequent than for the SAG mill and hence the proportion of wear in the same time period would be expected to be significantly less.

The average toe position for the period of 3.5 months shown in Figure 9 was 222°, although over the period the measured value varied by over 10° above and below this position.

Figure 10 shows the calculated toe values and selected process variable data for a one day period of abnormal operation as a result of difficulties with the feed to the mill.

Over the period of the day, there are significant changes in the mill power draw mostly related to the issue with the mill feed. For the period shown, generally the toe position measured by the mill monitor tracks the changes in mill power. A decrease in mill power draw often corresponds to a decrease in the angular value of the toe position. This situation actually signifies an increase in mill load. For example, when the mill power draw increases sharply shortly after 4 am there is a corresponding increase in the angular value of the toe position of 10° indicating a decrease in the overall mill charge. However there are periods when the toe position changes...
even though there is little change in mill power, such as between 3 pm and 5 pm and again at the end of the day. This example indicates that the monitor is capable of detecting dynamic changes in the mill charge that are perhaps not as evident from other on-line mill operating parameters and also illustrates the sensitivity of the monitor sensor to changes in the operating condition for this mill.

![Figure 10. Example of changes in toe value during abnormal feed conditions for a ROM ball mill](image)

**CONCLUSIONS**

A continuous mill monitoring system has been developed for use on primary grinding mills that is capable of providing on-line measurements of the mill charge such as toe and shoulder position.

Outputs from the system can potentially be used to provide operators with early warnings of abnormal events as well as key features such as changes in the overall charge level, the distribution between rock and balls in the mill, and the impact of the charge on the mill liners and lifters.

Trials of two installed monitors have proven that the mill monitor design is rugged enough to be able to operate on an industrial primary grinding mill for a year, or more, between routine servicing.

While initially developed for use on AG/SAG mills, the monitor can also be installed on other primary grinding mill types such as ROM balls mills.

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