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Nonlinear observability of grinding mill conditions

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Abstract: A nonlinear observer model of a grinding mill is developed. The model distinguishes between the volumetric hold-up of water, solids, rocks and balls in the mill, where solids are all ore small enough to discharge through the end-discharge grate, and rocks are all ore too large to discharge. The model includes the discharge rate, abrasion rate of rocks and the abrasion rate of balls as parameters. It is shown that with mill discharge flow-rate, discharge density and volumetric hold-up measurements the model states and parameters are locally (weakly) nonlinearly observable, but not linearly observable. Although instrumentation at the mill discharge is not yet included in industrial circuits because of space restrictions, this study motivates the benefits to be gained from including instrumentation at the mill discharge. If mills are fitted with adequate measurement instrumentation at the discharge, important mill states and parameters can be estimated.

Keywords: comminution, grinding mill, observability, parameter estimation, state estimation

1. INTRODUCTION

The mineral processing industry includes nonlinear processes with considerable modelling uncertainties, process variables that are difficult to measure and large unmeasured disturbances. For such processes the peripheral tools of the control loop, such as observers and soft sensors, are as important as the controller itself (Hodouin, 2011). Although process industries in general have benefited considerably from advanced process control (Craig et al., 2011), the mineral processing industry has yet to take advantage of model-based control.

The main impediment to implementing model-based control in the mineral processing industry, and specifically grinding mills, is the lack of sufficient measurements to estimate the necessary states and parameters (Wei and Craig, 2009). Because of continual variations in ore hardness and ore feed size distribution, parameters defining the grinding environment are time-varying. A dual particle filter was developed by Olivier et al. (2012) to estimate mill states and parameters. It was assumed measurements of the mill discharge were available, but that the rock and ball abrasion rates remained constant. A much more complex model was used by Apelt et al. (2002) to estimate mill states by means of an extended Kalman filter, but not all states were observable.

As shown by le Roux and Craig (2016), it is theoretically possible to fit an existing nonlinear grinding mill circuit model to commonly available real-time plant measurements. However, the algebraic fitting procedure is too sensitive to uncertainties in measurements as it involves the calculation of first and second order time-derivatives from noisy data. Although a relatively simple model is used, there are still too many parameters to define for this procedure to be of industrial value.

The aim of this work is to develop a simple nonlinear observer model for a semi-autogenous (SAG) mill with states and parameters that can reasonably be observed from measurements of mill inflow, discharge, and volumetric filling. Although all states and parameters are not observable for a linearised case, they are locally (weakly) nonlinearly observable.

2. GRINDING MILLS

2.1 Process Description

The open circuit SAG mill depicted in Fig. 1 receives three streams: mined ore (MFO), water (MIW) and additional steel balls (MFB) to assist with the breakage of ore. If the mill circuit is closed with a classifier such as a hydrocyclone, the underflow from the hydrocyclone also flows into the mill. The mill charge constitutes a mixture of grinding media and slurry. Grinding media refers to the steel balls and large rocks used for breaking the ore, and slurry refers to the mixture of water and all ore material that exhibit the same flow characteristics as water. The fractional volumetric filling of the mill by the total charge is represented by J_T.

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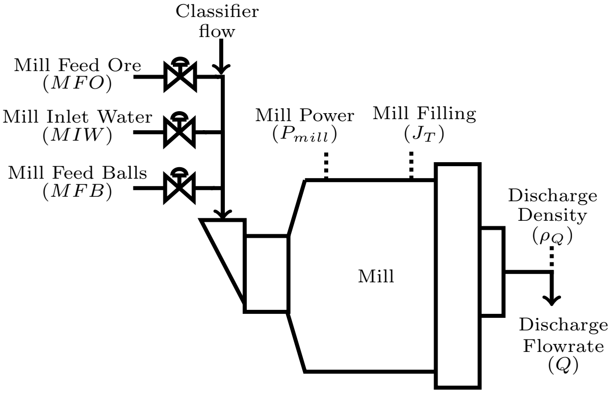

Fig. 1. A semi-autogenous grinding mill.

The mill is rotated along its longitudinal axis by a motor. As shown in Fig. 2, the charge in the mill is lifted by the inner liners on the walls of the mill to a certain height from where it cascades down, only to be lifted again by the rotating action of the mill. If the rotational speed is sufficiently fast, the material in the charge will become airborne after reaching the top of its travel on the mill shell. The uppermost point where material leaves the mill shell is defined as the shoulder of the charge. The airborne particles follow a parabolic path, reaching a maximum called the head and making contact again with the mill charge at the bottom of the mill. The cascading motion of the charge causes the ore to break through impact, abrasion and attrition. The mill grind is the fraction of material in the discharge of the mill below the specification size and indicates the efficiency of the mill to break the ore. The power draw (P_{mill}) of the motor turning the mill is an indication of the kinetic and potential energy imparted to the charge.

The ground ore in the mill mixes with the water to create a slurry. The slurry in a mill begins to form at the shoulder of the charge. The toe of the slurry starts to grow downwards towards the toe of the charge with increasing flow-rate. While the toe of the slurry is less than or equal to the toe of the charge, discharge occurs via the grinding media. When the toe of the slurry exceeds the toe of the charge, a slurry pool forms at the bottom of the mill. Slurry discharge is then a combination of flow via the grinding media and the slurry pool (Latchireddi and Morrell, 2003). Slurry pool conditions should be avoided as they decrease the mill power draw and the breakage rate by cushioning material falling from the charge shoulder to the charge toe. The slurry is discharged through an end-discharge grate where the aperture size of the end-discharge grate limits the particle size of the discharged slurry. The flow-rate of slurry at the mill discharge is given by Q. It is assumed that the in-mill slurry density is equal to the discharge slurry density (ρ_Q).

2.2 Industrial Circuit Measurements

The survey of Wei and Craig (2009) indicates that P_{mill} and J_T are commonly measured variables on industrial plants, whereas Q and ρ_Q are not explicitly included as real-time measured variables for any of the plants surveyed.

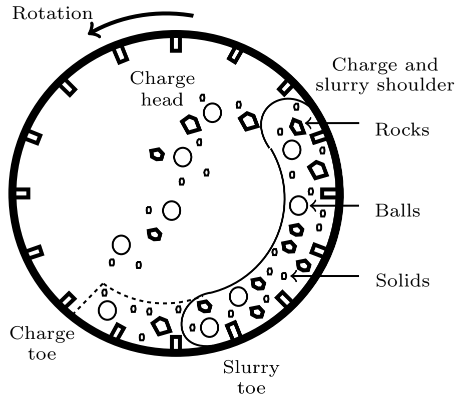

Fig. 2. Cross-section of a semi-autogenous grinding mill.

Table 1. Description of circuit variables.

Variable	Unit	Description
MIW	[m^3/h]	Flow-rate of water to the mill
MFO	[t/h]	Feed-rate of ore to the mill
MFB	[t/h]	Feed-rate of steel balls to the mill
J_T	[-]	Fraction of mill volume filled with charge
Q	[m^3/h]	Mill discharge flow-rate
ρ_Q	[t/m^3]	Mill discharge density
P_{mill}	[kW]	Mill power draw

The mass of the mill and the charge inside the mill is generally measured using either load cells or bearing pressure. Because this is not a direct measurement of J_T, the relation between J_T and a mass measurement needs to be determined whenever a mill survey is performed. For different mill charges, accurate mill filling measurements after mill stops can be used to calibrate the relationship between the mass measurement and J_T. The calibration exercise should be repeated at reasonable intervals as the loss of liner mass through wear and tear will cause a drift in the accuracy of the relationship. Once the drift in the data is quantified, an empirical liner wear model can be constructed to predict the service life of liners and adjust the relationship between the mass measurement and J_T over time. With careful planning, the mass to J_T relationship can easily be checked within half an hour from mill stop to start (Powell et al., 2009).

This study assumes measurements of Q and ρ_Q are available. Because of space restrictions at the discharge trommel of the mill, inclusion of flow and density instrumentation at the mill discharge is not yet a viable reality (Napier-Munn et al., 2005). Through careful planning and design of greenfield comminution circuits it should be possible to install existing flow and density instrumentation at a mill discharge trommel. In the case where the mill discharges into a sump, ρ_Q and Q can be back-calculated from a flow-balance if all other inflows and outflows are measured, but this is highly sensitive to the accuracy of measurements at the sump. This study aims to illustrate the benefits to be gained from including Q and ρ_Q measurement instrumentation in industrial circuits.

Grinding mills are usually designed with a constant target fractional volumetric filling of balls (J_B) in mind. Because accurate real-time measurements of J_B are not available, J_B is difficult to include in control schemes to manipulate the mill grind and the discharge rate. Although J_B is not