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# Switching cyclones to increase product particle size range for ore milling circuits.

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**Abstract:** A commonly used continuous grinding mill circuit model is expanded to a hybrid model which contains both continuous and discrete dynamics. The discrete dynamics in the grinding mill circuit are as a result of switching individual cyclones in a cluster of cyclones. With the additional discrete dynamics an investigation was conducted to establish whether the switching of cyclones can be used as an additional manipulated variable. A nonlinear model predictive controller was implemented using the hybrid grinding mill model. Through simulations it is shown that the switching of cyclones can be used to extend the range of control for the product particle size. When applying a substantial disturbance it was found that certain setpoints could not be reached by the NMPC controller, however by switching in an additional cyclone the particle size setpoint could be reached. Simulation results are given to show that the discrete switching of hydrocyclones can be considered as a manipulated variable for hybrid model based controllers to achieve additional controller benefits.



*Keywords:* hydrocyclone cluster, grinding mill, hybrid modelling, model predictive control

## 1. INTRODUCTION

A run-of-mine (ROM) ore milling circuit is primarily used to grind incoming ore, bearing precious metals, to within specification size (le Roux et al., 2013). The optimal operation of the downstream processes from the grinding mill rely on the size of the particles discharged by the milling circuit to be consistently within specification (Chen et al., 2007). However, a consistent product specification is difficult to maintain because of the nonlinearities in the circuit, the long time delays, the strong loop interactions, unmeasurable disturbances and parameter variation (Coetzee et al., 2010).

The controller objectives are to improve process stability, increase throughput, increase quality and reduce power consumption (Wei and Craig, 2009). However an inversely proportional relationship exists between the milling circuit product particle quality and the product throughput: a higher throughput leads to a decrease in quality (Craig and MacLeod, 1996). The ideal situation is to increase product quality while increasing product throughput. But, because the control objectives of product quality and throughput are coupled, trade-offs are required when designing a controller (Hodouin, 2011). Prioritising controller objectives is important as an increase in throughput results in a monetary benefit, whereas the recovery rate of the valuable metals from the discharged particles will be significantly lower if the product quality fluctuates (Craig and MacLeod, 1996).

Many strategies have been implemented to attempt to achieve the controller objectives. In Coetzee et al. (2010) a robust non-linear model predictive controller was successfully implemented. The controller maintained product quality in the presence of large disturbances, but at the cost of deviation of throughput from its desired value. Various studies have aimed to achieve additional control over the circuit, by including new manipulated variables. In Craig et al. (1992) the range of control for the product particle size estimation (PSE) was increased by independent control of the water added to the mill. More recently in Naidoo et al. (2014) it was illustrated that if a mill is fitted with a variable speed drive, the speed of the mill could be used as an additional manipulated variable (MV) to reduce the power consumed by the mill.

The work presented in this article investigates the possibility of individually switching cyclones in a cluster of cyclones as an additional MV for a ROM-ore milling circuit. The aim is to increase the range of product quality control. A nonlinear model predictive controller was implemented and the performance of the controller evaluated when the number of active cyclones was altered. The results indicated that by switching in additional cyclones the upper constraint on the cyclone feed flow rate can be increased, and as such the range of control for PSE is increased. The switching in of additional cyclones can therefore be used to counter the effect of disturbances or large setpoint changes such that a desirable steady state condition can be maintained.

## 2. CIRCUIT AND MODEL DESCRIPTION

### 2.1 Process Description

A closed single-stage grinding mill circuit with a cyclone cluster is shown in Figure 1. The circuit consists of a mill, sump and hydrocyclone. The mill receives four different inputs: mined ore ($MFS$), water ($MIW$), steel


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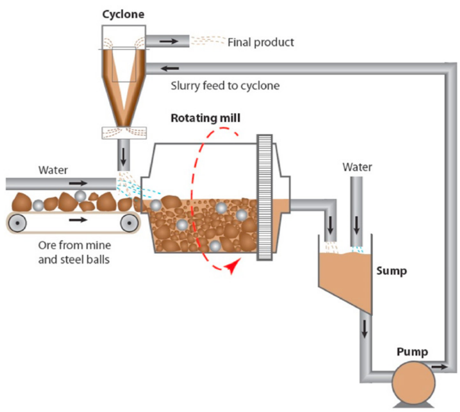


Fig. 1. A single-stage grinding mill circuit.

balls ($MFB$) and underflow from the hydrocyclone. The fraction of the mill filled with charge is represented by $JT$. A slurry mixture of ground ore and water is discharged by the mill directly into the sump through an end-discharge-screen. The slurry in the sump is diluted with water before it is pumped to the hydrocyclone. The level of the slurry in the sump and the flow-rate of slurry pumped to the cyclone is represented by $SVOL$ and $CFF$ respectively. The fine particles are discharged from the cyclone overflow as final product ($PSE$), while the course particles are recycled through the cyclone underflow back to the mill for further grinding (Napier-Munn et al., 1999).

In this section the reduced complexity nonlinear model in le Roux et al. (2013) is briefly described and the model for the cyclone is expanded to allow for the switching of cyclones using activation variables. The variables of the grinding mill circuit, and those used in the model are given in Table 1. With the adapted model, the model will be able to accurately describe dynamics of the system in Figure 2, where the cyclone cluster can have any number of cyclones.

Table 1. Description of circuit variables

| | |
|---|---|
| | *Manipulated Variables* |
| $MIW$ | flow-rate of water to the mill [m$^3$/h] |
| $MFS$ | feed-rate of ore to the mill [t/h] |
| $MFB$ | feed-rate of steel balls to the mill [t/h] |
| $SFW$ | flow-rate of water to the sump [m$^3$/h] |
| $CFF$ | flow-rate of slurry to the classifier [m$^3$/h] |
| | *Controlled Variables* |
| $JT$ | fraction of the mill filled [-] |
| $SVOL$ | volume of slurry in sump [m$^3$] |
| $PSE$ | product particle size estimate [-] |
| | *Additional Output Variables* |
| $P_{mill}$ | Power draw of the mill motor [kW] |
| $THP$ | Throughput [t/h] |
| $CFD$ | Cyclone feed density [t/m$^3$] |

The values for the steady state variables, as well as the parameters given for each of the milling circuit modules are those given in le Roux et al. (2013).

Table 2 gives a description of each of the symbols and their respective subscripts as used in the Hulbert model described in le Roux et al. (2013). In Table 2 the variable $V$ denotes volumetric flow-rate in m$^3$/h and $X$ denotes the states of the model as volume of material in m$^3$. The nomenclature for the model is given in Table 3.

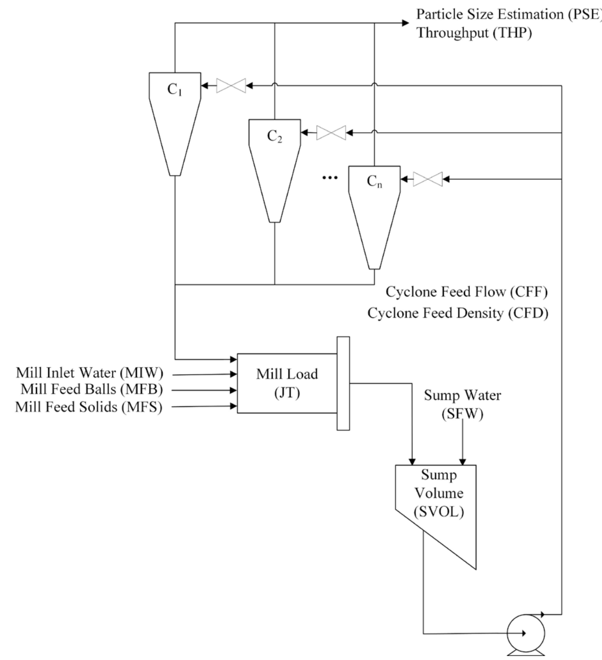


Fig. 2. Adaption of the single stage grinding mill circuit to contain a cyclone cluster.

Table 2. Description of subscripts

| Subscript | Description |
|---|---|
| $X_{\Delta -}$ | f-feeder; m-mill; s-sump; c-cyclone |
| $X_{-\Delta}$ | w-water; s-solids; c-coarse; f-fines; r-rocks; b-balls |
| $V_{--\Delta}$ | i-inflow; o-outflow; u-underflow |

### 2.2 Mill Module

The mill is modelled by incorporating the effects of mill power draw and slurry rheology in the calculation of the mill load and breakage power functions. The model uses five states to represent the constituents of charge in the milling circuit. The states are rocks, solids, fines, balls and water. Rocks are ore too large to be discharged from the mill, whereas solids are ore that can be discharged from the mill. The solids consist of the sum of fine and coarse ore, where fine ore is smaller than the product specification size and coarse ore is larger than the product specification size. All of these states are present within the mill and therefore continuous time state-space description of the grinding mill is given as

$$\begin{aligned}
\dot{X}_{mw} &= MIW - \frac{V_V \varphi X_{mw} X_{mw}}{X_{ms}+X_{mw}} + V_{cwu} \\
\dot{X}_{ms} &= \frac{MFS}{D_S}(1-\alpha_r) - \frac{V_V \varphi X_{mw} X_{ms}}{X_{ms}+X_{mw}} + V_{csu} + \\
&\quad \frac{P_{mill}\varphi}{D_S \phi_r}\left(\frac{X_{mr}}{X_{mr}+X_{ms}}\right) \\
\dot{X}_{mf} &= \frac{MFS}{D_S}\alpha_f - \frac{V_V \varphi X_{mw} X_{mf}}{X_{ms}+X_{mw}} + V_{cfu} + \frac{P_{mill}}{D_S \phi_f} / \\
&\quad \left[1+\alpha_{\phi_f}\left(\frac{X_{mw}+X_{mr}+X_{ms}+X_{mb}}{v_{mill}} - v_{P_{max}}\right)\right] \\
\dot{X}_{mr} &= \frac{MFS}{D_S}\alpha_r - \frac{P_{mill}\varphi}{D_S \phi_r}\left(\frac{X_{mr}}{X_{mr}+X_{ms}}\right) \\
\dot{X}_{mb} &= \frac{MFB}{D_B} - \frac{P_{mill}\varphi}{\phi_b}\left(\frac{X_{mb}}{D_S(X_{mr}+X_{ms})+D_B X_{mb}}\right)
\end{aligned} \tag{1}$$

where $X_{mw}$, $X_{ms}$, $X_{mf}$, $X_{mr}$ and $X_{mb}$ are the volume of water, solids, fines, rocks and balls within the mill respectively. $V_{cwu}$, $V_{csu}$, and $V_{cfu}$ are the flow rates of the water, solids and fines at the underflow of the cyclone