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Feed-hopper level estimation and control in cone crushers

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ABSTRACT

This paper describes a novel feed-hopper level estimation and control scheme for addressing the known problem of unreliable and occasionally corrupted feed-hopper level measurement in a cone crusher. The approach involves estimating the feed-hopper level with an adaptive time-variant state estimator. The proposed adaptive scheme delivers asymptotically unbiased feed-hopper level estimates, despite using an inherently biased state estimator with biased measurement(s) and/or model, and therefore addresses the common pitfall of state estimators.

The paper details the entire control system design procedure, from the fundamental theory, through dynamic modeling and estimator/controller tuning, to the design validation and control performance evaluation. The performance of the proposed scheme is evaluated through extensive full-scale tests in various production scenarios, including process start-up, level setpoint changes, and mass flow disturbance rejection.

The full-scale tests revealed a number of benefits compared to the straightforward level control implementation. These benefits include the possibility of recovering from a temporary loss of measurement signal, smaller control effort, and increased system robustness due to an increased ability to withstand measurement errors. Therefore, the proposed scheme will enable more consistent size reduction and provide protection against performance degradation and process down-time.

1. Introduction

Crushing is an essential high-volume processing stage in the aggregates, mining and cement industries. The sheer amount of yearly worldwide production is immense: 40.2 billion tons of construction aggregates (2012), 1.57 billion tons[1] of iron and ferroalloys (2013), 86 million tons[1] of non-ferrous metals (2013), 29,000 tons[1] of precious metals (2013), and 4.3 billion tons of cement (2014) were produced to meet the demands of growing infrastructure and evolving society (Freedonia, 2013; Reichl et al., 2015; Cembureau, 2015).

The process control of a modern crushing circuit comprises two principal control tasks:

- Size reduction control
- Mass balance control

The objective of mass balance control is to ensure that sufficient feed material is always available (to be crushed and discharged from the circuit), whereas the size reduction control usually aims to produce desired particle size distribution (PSD). These main control tasks interact with each other. Controlling mass balance affects (acts as a disturbance on) the size reduction, and actions to control the size reduction influence the material distribution (accumulation) and flow rates (proportion of different fractions) inside the circuit. To meet market or downstream demand, it is necessary to ensure both main control tasks are performed sufficiently. This enables the true potential of the circuit.

The most common form of mass balance control is the level control of intermediate buffers such as bins, silos, feeders, and feed-hoppers that are used to prevent the disturbance propagation in the circuit by disconnecting the dynamics between input and output flows. Level control schemes can be roughly divided into averaging level control and tight level control. Averaging level control is used when the buffer level should be allowed to fluctuate (to make full use of available surge capacity), and tight level control when the efficient use of equipment or meeting process targets requires this.

Cone crushers require tight feed-hopper level control because the recommended mode of operating is choke feeding, wherein the crusher inlet is fully covered with feed material (Evertsson, 2000). Failing to provide choke-fed conditions will result in higher crusher peak loads,

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[1] The production of metals often requires large volumes of ore to be processed to yield relatively small quantities of metals.

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erratic power (and pressure) profile, and excessive wear. It has been shown that higher feed rate, and eventually higher feed-hopper level, will result in smaller product size and higher throughput, especially in a Symons-type[2] cone crusher (Whiten, 1984; Herbst and Oblad, 1985; Jacobson et al., 2010). Therefore, the cone crusher feed-hopper level must be regulated if stabilizing the size reduction or maximizing the crusher throughput is of specific interest.

1.1. Need

Sensors are an essential part of the feedback control as the quality of the measurement directly affects the control system performance. Better measurement quality results in more accurate control with less control action. Sensor problems leading to faulty measurement values, excessive measurement noise, or even loss of measurement signal are detrimental to system performance; they force the control system to respond to wrong information that does not reflect the actual process state.

The cone crusher feed-hopper level is typically measured using either ultrasonic or microwave sensors (Parsons et al., 2002). However, the feed-hopper level measurement can be challenging due to the confined feed-hopper shape (causing signal reflections) and falling feed material (interfering with measurement). The problems are more severe with smaller cone crushers in which it is difficult to place the level sensor to simultaneously avoid both the hopper walls and the falling feed material in the sensor detection area. Other known problems include multiple reflections during idling (Lynch, 1977) and loss of measurement signal at certain belt feeder (or feed conveyor) speeds as feed material is thrown into the sensor detection area. This paper presents a full-scale experiment, wherein all of the above-mentioned problems are present.

1.2. Approach

To address the problem of unreliable and possibly corrupted feed-hopper level signal, this paper proposes an approach to estimate the true value of the feed-hopper level using a state estimator. A state estimator is a system that combines the available knowledge using the fusion of dynamic process model, measurements y, and control inputs u to provide the most accurate estimate of the process state (Lewis et al., 2008). State estimators have been previously used in comminution, for example, by Herbst and Oblad (1985) and Herbst and Rajamani (1989).

A state estimator is an unbiased estimator that provides unbiased state estimates, but only if both the model and the measurement(s) are unbiased. To overcome this requirement, the paper proposes adapting the process model parameters online to guarantee asymptotical decay to the zero-mean steady-state estimation error. This approach makes it possible to achieve unbiased state estimates, despite biased measurement(s) and/or model (a common pitfall of state estimators).

1.3. Benefits

Using a state estimator offers a possible remedy for known feed-hopper level measurement challenges detrimental to the cone crusher feed-hopper level control system and crushing circuit performance. The benefits of the proposed approach include the possibility of recovering from a temporary loss of measurement signal, more consistent level control with less control effort (as a result of decreased sensor noise), and increased system robustness due to increased ability to withstand measurement errors.

[2] That is, a cone crusher without the top bearing.

1.4. Structure of the paper

Section 2 describes the operating principle and the manipulated variables of a cone crusher, explains the fundamentals of state estimation and feedback control, and finally reviews the previous work on cone crusher feed-hopper level control. In Section 3, the theory of state estimators and possibilities for their tuning are discussed. Section 4 presents the dynamic modeling for the cone crusher feed-hopper level control system. Section 5 details the full-scale setup to test the proposed estimation and control scheme. The results are discussed in Sections 6, and 7 concludes the paper.

2. Background

2.1. Cone crusher

Fig. 1 illustrates the operating principle and the main components of a cone crusher. A cone crusher basically comprises two bell-shaped manganese crushing liners placed inside each other. The concave is attached to the crusher frame, and the mantle is attached to the eccentric main shaft, which sways around the geometric center point at the eccentric speed[3] ω. The size reduction takes place in the volume between the crushing liners (crushing cavity). The mantle movement exposes feed material to the successive compression and free fall/sliding cycles in the gravity-driven downward movement inside the crushing cavity (Evertsson, 2000).

Crushing liners are subject to wear; regular replacement and wear compensation are required. To provide maximum throughput, reduce wear, and minimize the crusher stresses, a mode of operation wherein the crusher inlet is fully covered with feed material (choke feeding) is recommended (Evertsson, 2000).

Cone crusher size reduction can be affected by three possible manipulated variables (MV):

1. Closed side setting (CSS), governing the volumetric capacity of a crusher;
2. Eccentric speed (ω), governing the number and intensity of crushing events;
3. Feed rate/feed-hopper level (q_{in},h), governing the material density inside the crushing cavity.

CSS is the most commonly used variable to control the size reduction (Kellner and Edmiston, 1975; Lynch, 1977; Whiten, 1984; Moshgbar and Parkin, 1994; Svensson et al., 1996; Hulthén, 2010; Itävuo et al., 2011; Itävuo et al., 2012; Itävuo et al., 2013; Airikka, 2013). However, out of the two main cone crusher types (Hydrocone crusher and Symons crusher) only the Hydrocone crusher is capable of CSS changes during crushing. This is performed by hydraulically moving up/down a piston supporting the main shaft (and thus the mantle). The second option is to manipulate the crusher eccentric speed ω (Hulthén, 2010; Itävuo et al., 2012; Jacobson and Lamminmäki, 2013; Itävuo et al., 2013; Atta et al., 2013; Atta et al., 2014). The Symons crusher has proven to be more responsive to the eccentric speed changes than the Hydrocone crusher (Ruuskanen, 2006). The third option is to regulate the size reduction with the crusher feed rate (trickle fed crusher) and eventually with the feed-hopper material level (choke fed crusher) (Borisson and Syding, 1976; Manlapig and Watsford, 1983; Whiten, 1984; Grujic, 1996; Sbarbaro, 2005). There are indications that higher feed rate and higher feed-hopper level will result in smaller product size and higher throughput, especially in a Symons crusher (Whiten, 1984; Herbst and Oblad, 1985; Jacobson et al., 2010).

[3] Eccentric speed ω is proportional to counter shaft speed, motor speed, and variable speed drive (VSD) frequency. For simplicity, symbol ω is used also for VSD frequency.