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Control oriented modeling of flow and size distribution in cone crushers

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ABSTRACT

This work presents a dynamic model for prediction of flow and output size distribution of cone crushers. The main purpose of the model is for simulation of closed-loop control using the Closed Side Setting (CSS) and the eccentric speed (ω) as manipulated variables. The idea of modeling crushers as cascaded zones is adopted throughout this work. The capacity, the length, the stroke, and the compression ratio of each zone are taken into consideration. Simulation results are presented in the form of the Crusher Performance Map (CPM) and the dynamic response for production of different size classes to steps input in ω and CSS. The simulations also include operation with recycling of oversize output, as well as the input of mixed materials. As an example, closed-loop control of the ratio of the large-size output to the total size output was simulated.

1. Introduction

Cone crushers are a vital stage in the comminution chain in many mineral processing plants, and are used as a secondary, tertiary, and quaternary crushing stage to provide a reduction ratio of maximum 1:10 (Gupta et al., 2006; King, 2001). Traditionally, crushing has received less attention than grinding, but this started to shift recently, partly because of the power consumption of the crusher on its own, but perhaps more importantly, since the crusher is often part of a comminution chain and instrumental in optimizing the behavior of this chain.

The crushing takes place in a cavity called chamber which is formed between a cone shaped mantle and a concave bowl. The mantle is gyrating in an eccentric path to deliver several strokes to the material passing the chamber, which provides the required breakage until it reaches the size that allows it to pass through the controlled small opening in the end (down) of the chamber, as shown in Fig. 1.

Changing CSS and ω on-line may give a significant improvement in crusher operation, and suggestions of control algorithms utilizing this possibility have begun to emerge (Hulthén and Evertsson, 2011; Hulthén, 2010). The purpose of this paper is to formulate a process model for developing and simulating closed-loop strategies by using CSS and ω as manipulated variables.

1.1. Modeling of cone crushers

The main methods for describing size distribution functions are (Lynch et al., 1977) the continuous functions, discontinuous functions, and statistical functions, of which the most widely used is the discontinuous function introduced by Broadbent and Callcott in 1956. This method represents the material distributions as vectors and the operations as matrix multiplications, and is also known as matrix analysis approach (Broadbent and Callcott, 1956). Accordingly, the material are partitioned into size classes $\infty > D_1 > D_2 \cdots > D_m > 0$, and the mass (or the mass flow) size distribution are a vectors on the form $M = [M_1\ M_2\ \cdots\ M_m]$, where M_j represents a mass (or a mass flow) of particles of sizes $[D_{j-1}, D_j]$.

The three main activities that describe the behavior of crushers are: breakage, selection for breakage (or simply selection), and classification. The overall behavior of the crushers is a combination and repetition of these actions, that can be represented as operators if the continuous function approach is adopted, or as matrix multiplication in the case of the discontinuous function approach. In the later case, the matrix is, in most of the cases, the discretized image of the continuous function.

The Breakage Matrix B is a lower triangular matrix, in which the entry $b_{i,j}$ represent the mass proportion of particles from size class i that ends up in size class j, after breakage (Broadbent and Callcott, 1956).

The Selection Matrix S is a diagonal matrix, where each entry $s_{i,i}$ (or s_i for convenience) represents the probability of breakage of a particle in the ith size class.

Finally, the Classification Matrix C is a diagonal matrix, where each entry $c_{i,i}$ (or c_i) represents the fraction (proportion) of

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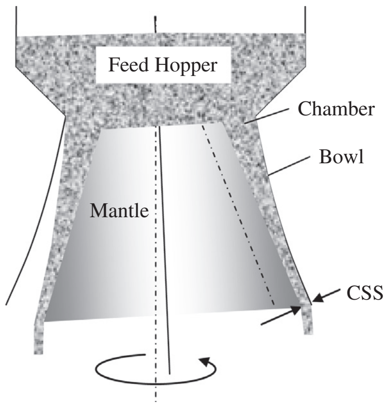

Fig. 1. Cross section of a cone crusher (Johansson, 2009).

material from the ith size class in a particular zone that is prevented from moving to the next zone.

Most of the modern studies divide the crusher into zones and are first-principle in the sense that they are formulated in the classical selection/breakage/classification framework. Each zone is considered as a single stage that has input and output, and the main actions are applied on the material inside it. The material inside these zones is considered to be well-mixed.

One of the earliest works on the modeling of cone crusher was conducted by Gauldie (1953, 1954) who presented a model to predict the throughput of jaw and cone crushers. The crusher is divided into zones, and the material is considered to be sliding until it is crushed between the mantle and the bowl. Also the effect of the eccentric speed on the behavior of the crusher was considered in this work.

Whiten presented one of the pioneer studies in modeling cone crushers (Whiten, 1972). This basic model connects the input flow rate and the output flow rate by looking at the crusher as a one stage activity. The material entering this stage can either pass (dropped) or selected to be broken, and then the result of this breakage is again fed into the process.

Lynch extended Whiten's simple model into a dynamic model for comminution processes, that considers the derivative of the material size distribution (Lynch et al., 1977). This model still describes the system as a single unit and connects the input and output size distribution.

Herbst and Oblad (1985) presented a model in which the crusher was divided into three well-mixed zones. A dynamic model was developed to describe the material size distribution in each zone, considering the flow between zones. Models for power consumption were also derived in this work.

Machado presented a crusher model for continuous flow in his work (Machado Leite, 1990). The main idea was to have two modes of breakage, so the classified material that will not pass out, will be classified again in order to decide which mode of breakage will be applied. The model was suitable for both jaw and cone crushers.

Evertsson conducted a detailed study on cone crushers (Evertsson, 1998, 1999, 2000), resulting in models for both flow and size distribution. An investigation on breakage and selection functions was presented. As well as a detailed model describing the motion of material inside the crusher and the total flow. A selection-breakage model was used to predict the size distribution of the output of the crushers.

Nikolov presented a general model for Impact Crushers based on matrix analysis (Nikolov, 2004, 2002), similar to Whiten's model, but with multiple zones. He also presented a new classification function, based on the cumulative Weibull distribution. The relations between different factors that affect the operation were included.

Johansson (2009) developed a model based on the continuous function method to represent the size distribution of the material. The transport behaviour of the crusher was taken into consideration. A logarithmic transformation of the material size density function was proposed to deal with the non-equal spacing of the classes in the classic materials size distribution. This transformation defines a new size variable (λ) that represents the logarithm of the physical size ($D = D_0 e^{-\lambda}$). The crusher model was formulated as a Partial Integro-Differential Equation.

A model proposed by Itävuo et al. (2011, 2013) and Itävuo (2009), is separated into a dynamic linear part, which is a second or first-order system with time delay, and a static nonlinear part, formulated as a neuro-fuzzy network and a log-transformed linear regression model. The model was based on known static behaviour of the crusher. An advanced control algorithm was also presented in this work.

In the proposed model, we have chosen to consider the classification, selection and breakage actions, the volume capacity limitation, the influence of the eccentric speed on the vertical transport of material, and the effect of mixed materials in the input. To the best of our knowledge none of the above models considers all these factors in one model.

2. The proposed crusher model

Consider partitioning the crusher into N zones, as shown in Fig. 2. Please note that the partitioning into zones is not related to the movement of the material but is constant over time (i.e. the horizontal boundaries are fixed relative to the bowl). By using the matrix representation, the output size distribution can be predicted using the inflow to the zone as an input to the model.

Starting from the model developed by Whiten (1972), and by introducing the multi zone approach, and after adding the selection action to the model, we can combine all the actions that are applied to the material inside each zone as shown in Fig. 3.

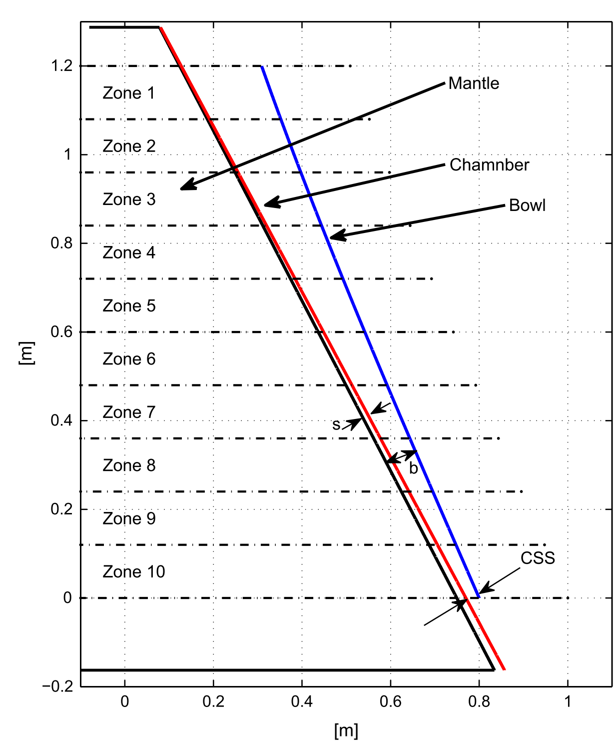

Fig. 2. Cross section showing the zones, CSS, stroke (s), and bed height (b).