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Probability density function of bubble size based reagent dosage predictive control for copper roughing flotation

Jianyong Zhu [a,b], Weihua Gui [a], Chunhua Yang [a,*], Honglei Xu [a,c], Xiaoli Wang [a]

[a] School of Information Science and Engineering, Central South University, Hunan 410083, China
[b] Nanchang Campus, JiangXi University of Science and Technology, Nanchang 330029, China
[c] Department of Mathematics and Statistics, Curtin University, Perth, WA 6845, Australia

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ABSTRACT

As an effective measurement indicator of bubble stability, bubble size structure is believed to be closely related to flotation performance in copper roughing flotation. Moreover, reagent dosage has a very important influence on bubble size structure. In this paper, a novel reagent dosage predictive control method based on probability density function (PDF) of bubble size is proposed to implement the indices of roughing circuit. Firstly, the froth images captured in the copper roughing are segmented by using a two-pass watershed algorithm. In order to characterize bubble size structure with non-Gaussian feature, an entropy based B-spline estimator is hence investigated to depict the PDF of the bubble size. Since the weights of B-spline are interrelated and related to the reagent dosage, a multi-output least square support vector machine (MLS-SVM) is applied to depict a dynamic relationship between the weights and the reagent dosage. Finally, an entropy based optimization algorithm is proposed to determine reagent dosage in order to implement tracking control for the PDF of the output bubble size. Experimental results can show the effectiveness of the proposed method.

1. Introduction

Froth flotation is the most important method to separate valuable minerals from ore by means of the physical and chemical properties of mineral surfaces. Generally, flotation reagents to improve or decrease mineral's flotability are added to make effective separation of valuable minerals. In fact, the reagent dosage has a critical influence on successful flotation. On one hand, less reagent dosage decreases valuable mineral's flotability, and results in lower concentrate grade and recovery of the plant. Excessive reagent dosage, on the other hand, is likely to lead to worse grade (or recovery) and cause the product deficit. In addition, an increase of 1–2% in recovery or grade is economically remarkable in copper flotation plants. Therefore, the reagent dosage control is a very important aspect of the flotation strategy in commercial plants.

In recent years, the reagent dosage control has attracted great interest of both academic and industrial researchers. In Hodouin, Bazin, Gagnon, and Flament (2000) a feedforward and feedback prediction control algorithm was developed to control the reagent dosage. The reagent addition is determined according to the ore amount and property by using a feedforward control strategy, and is then moderately adjusted by feedback control. It also shows that optimization and control of mineral processing could not be performed without a minimum amount of information on the input disturbances, the process states, and the final product quality. In Naik, Reddy, Vibhuti, and Misra (2005) a regression model is established to predict the grade and recovery of combustible material for different reagent conditions by quantifying the effect of sodium meta silicate, collector and frother with factorial experiment data. In Suichies, Leroux, Dechert, and Trusiak (2000) a generalized predictive control (GPC) algorithm is presented and has been applied to many sulfide flotation circuits in the Brunswick mining concentrator. It has proved that the GPC controller performs well on the flotation circuits. Although MPC seems to be the ideal solution for high quality control, Bergh and Yianatos (2011) indicates that the benefits of MPC should not be lost without the actual plant constraints.

In practice, the operators of flotation plant monitor and optimize reagent additions of the flotation process mainly by observing froth appearance characteristics such as bubble size and color owing to the lack of testing equipments such as X-ray fluorescence analyzers. Conventionally, the reagent dosage control heavily depends on the frequent inspection of froth views and manipulation of experienced operators, which often causes serious delayed responses. In Kaartinen, Hätönen, Hyötyniemi, and Miettunen (2006), the correlations between recovery and froth appearance characteristics are

* Corresponding author. Tel.: +86 13975894807; fax: +86 731 88836876.
E-mail address: ychh@csu.edu.cn (C. Yang).

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established and subsequently a rule-based feedback control strategy is designed. It is shown that the image-based reagent dosage control strategy is possible to achieve considerable financial benefits in terms of improved recovery.

As one of the dominant visual features, bubble size structure has a great effect on the probability of collision between mineral particles and bubbles, as well as the adhesion of the particles to the bubbles (Aldrich & Feng, 2000). Flotation kinetics shows that the transfer processes of mineral particles take place in the pulp phase (from the pulp phase to the froth phase) and in the froth phase (from the froth phase to the concentrate launder) by particle–bubble attachment. All of these sub-processes depend strongly on bubble size. If the bubble size is too large, the bubbles easily burst, and the valuable mineral particles attached the burst bubbles will fall into the tailings, resulting in the reduction of recovery, and vice versa. As an effective indicator of bubble stability, bubble size structure is believed to be closely related to flotation performance since the bubble size reflects the extent of bubble coalescence. Many researchers have investigated the relationship between the bubble size and water recovery, froth recovery, etc. For example, Neethling, Lee, and Cilliers (2003) show that bubble size determines water recovery with an inverse squared relationship.

It is noticed that the observable bubble size is really the film bubble size on the top of the froth. The bubble size in the collection zone named 3D bubble size is hardly measured in industrial flotation machine, but is capable to be observed and measured in laboratory flotation machine. Wang and Neethling (2009) explored the relationship between the film bubble size and the 3D bubble size and proved that the difference between film bubble size distribution and 3D bubble size distribution are not remarkable such that the mentioned bubble size distribution in the paper is really the film bubble size distribution.

It is beyond doubt that the bubble size is a key parameter in froth flotation. Bubble size closely relates to the operation parameters such as airflow rate, impeller speed, pulp level, reagent dosage (Grau & Heiskanen, 2005). Little changes of the impeller speed and the airflow rate will have less effect on bubble size for Wemco's flotation cell with self-aspirating aeration mechanisms (Girgin, Do, Gomez, & Finch, 2006). Among them, the reagent dosage has very important influence on bubble size. It is commonly believed that the bubble size decreases with an increase in the froth concentration owing to a decrease in the surface tension induced by the addition of surfactants, and at a particular concentration, the bubble size levels off. In Cho and Laskowski (2002) the researchers suggest that the frothers control bubble size by reducing bubble coalescence in the cell and that coalescence can be entirely prevented at concentrations exceeding the critical coalescence concentration (CCC) in a dynamic system. In addition to the frothers, the collectors also have an influence upon coalescence and evaporation of bubbles by interacting with the frother.

Bubble size presents characteristics of random distribution in flotation process. And it is worth noticing that the PDF of bubble size has been found to be non-Gaussian distribution (Yang, Xu, Gui, & Du, 2009). Generally, the researchers tend to focus on singular statistical features of bubble size such as mean, standard deviation, kurtosis and skewness to characterize bubble size structure. However, it is well known that the features are incapable to represent the entire profile of bubble size distribution with non-Gaussian feature.

Except the well-developed minimum variance control, LQG and mean value control, some researchers explore other random variable distribution control algorithms in order to implement control and diagnosis of variables with non-Gaussian distribution. Wang (2000) adopted B-spline expansions are developed to model PDF of variables with non-Gaussian and subsequently a BSD based control algorithm is constructed to track the given PDF. In Guo and Wang (2010) further innovative and systematical work on modeling and system analysis is conducted including the structure controller design and fault detection and diagnosis for non-Gaussian distribution. In Forbes, Guay, and Forbes (2004) the Gram–Charlier based PDF parameterization method is proposed and regulatory control synthesis techniques for shaping the PDF of the stochastic process is developed. Weight dynamic model built in Wang (2000), Guo and Wang (2010), and Forbes et al. (2004) is limited to precise linear systems, so these methods are not suitable for the flotation process with highly nonlinear and complex mechanism. In Yang, Guo, and Wang (2009), a constrained proportional-integral (PI) tracking control for probability distribution of the output variable is proposed based on two step neural networks. Although the dynamic relationship between the control input and the weights is built by using dynamic neural network in Yang et al. (2009), the method which is applied to a linear system is difficult to be directly used for the flotation process. In Xu et al. (2012) a flotation process fault detection system based on output PDF of bubble size distribution is designed, where the distribution is described by a kernel estimation method. Recently, in Liu et al. (2013) dynamic bubble size distribution is used to recognize operate state of reagent addition in the copper flotation process.

This work aims to develop bubble size PDF based reagent dosage control for roughing flotation of copper flotation plants. Based on PDF modeling work using B-Spline estimator (Wang, 2000; Guo and Wang, 2010; Yang et al., 2009; Forbes et al., 2004), an entropy based B-Spline estimation technique is investigated to depict the PDF model according to bubble size extracted from froth images of copper flotation. Based on the analysis of the flotation process, PDF of the bubble size based reagent dosage predictive control method is firstly proposed to implement the indices of the roughing flotation. The method abundantly takes advantage of the fact that bubble size structure closely relates to the indices and responds to changes in the reagent dosage. The novelty of this proposed approach is that the method is using PDF of bubble size rather than a concentrate grade or recovery as a target variable. In addition, instead of using flotation mechanism, the proposed reagent dosage control method is built by integrating machine vision, random distribution control and predictive control principle. As such, a MLS-SVM model is firstly proposed to establish the relationship between the reagent dosage and bubble size. In order to implement the tracking of the targeted PDF, an entropy based optimization algorithm is then proposed to calculate the reagent dosage.

The rest of the paper is organized as follows: a copper flotation circuit of a copper flotation plant is described in Section 2; Section 3 proposes the bubble size PDF based reagent dosage predictive control to implement PDF tracking of the output bubble size. Experimental results and discussions are presented in Section 4. Section 5 illustrates the conclusion and directions for future research.

2. Process description and modeling analysis

2.1. Process description of copper flotation

A concise flow diagram of the copper flotation process can be shown in Fig. 1. Raw ore is firstly conveyed to the ball milling. Next, the ball milling breaks the feeding ore into pulp slurry with a suitable particle size (minerals size should be under 200 mesh, i.e., less than 0.074 mm). Eligible slurry from ball milling is then fed into an agitated tank, where the valuable mineral particles are selectively coated with hydrophobic chemicals. After being fully agitated, the slurry is fed into flotation cells with self-aspirating aeration mechanisms, where air together with frothing reagents produces a large number of stable bubbles, which travel to the