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Combined fuzzy based feedforward and bubble size distribution based feedback control for reagent dosage in copper roughing process

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ABSTRACT

A combined fuzzy based feedforward (FBF) and bubble size distribution (BSD) based feedback reagent dosage control strategy is proposed to implement the product indices in copper roughing process. A fuzzy theory based feedforward compensator will be used to calculated the reagent dosage in advance to eliminate the influence of large disturbances according to ore grade and handling capacity. Since the bubble size is believed to be closely related to flotation performance and responds to changes in the reagent dosage, using BSD based feedback predictive control calculates the reagent dosage to stabilize the flotation running. Instead of simple statistic feature, the bubble size with non-Gaussian feature is characterized to be probability density function (PDF) by using B-spline. A multi-output least square support vector machine (MLS-SVM) based is then applied to establish a dynamical relationship between the weights of B-spline and the reagent dosage since the weights are interrelated and related to the reagent dosage. A multiple step based optimization algorithm is finally proposed to determine the reagent dosage. Experimental results can show the effectiveness of the proposed method.

1. Introduction

Froth flotation is an important approach to extract valuable minerals from ore according to physical and chemical properties of mineral surfaces. In this process, the chemical reagent which improve or decrease mineral's flotability is capable to implement effective separation of valuable minerals. In practice, the reagent dosage has very important influence on successful flotation. Less or excessive reagent dosage easily deteriorates flotation performance and results in product deficit. Therefore, control strategy for reagent dosage has paid close attention of both academic and industrial researchers. In Naik et al. (2005) a regression model is established to predict 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 [1]. A generalized predictive control algorithm is presented according to sulfide flotation circuits in the Brunswick mining concentrator [2]. 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, the benefits of MPC should not be lost without the actual plant constraints [3].

However, the workers monitor and optimize reagent dosage mainly by observing froth appearance characteristics in China, It is due to lack of testing equipment such as X-ray fluorescence analyzers in a lot of Chinese flotation plants. It heavily depends on frequent inspection and expert experience of the operators. To overcome the shortcomings of manual operation, image-based control and optimization research has been carried out extensively. Aldrich et al. think that the features of the surface froths of flotation cells can be used to monitor and control flotation running by use of machine learning techniques [4]. Kaartinen et al. establish the correlations between recovery and bubble features and subsequently propose a rule-based feedback control strategy [5]. In order to establish more effective control models for flotation, froth image based control should be integrated with operating variables [6]. For example, bubble image based control method for reagent dosage can achieve great economical benefits in reference to improved recovery.

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As one of the dominant visual features, the bubble size has a very important influence on probability of collision and adhesion between mineral particles and bubbles [7]. Flotation kinetics indicates that collection of mineral particles depend strongly on bubble size in transmission processes of mineral particles. As an effective indicator of bubble stability, bubble size is believed to be closely related to flotation performance since the bubble size reflects the extent of bubble coalescence [8]. However, the bubble size strongly linked to the operation parameters such as airflow rate, impeller speed, pulp level, reagent dosage [9]. Since the impeller speed and the airflow rate of Wemco's flotation cell with self-aspirating aeration mechanisms only change slightly, they will have less effect on bubble size during flotation running [10]. Compared to the slurry level, the reagent dosage has more important influence on the bubble size. Generally, the frother influences bubble size by reducing bubble coalescence, and the phenomenon of bubble coalescence will be entirely prohibited when the concentration of the frother exceeds the critical coalescence concentration (CCC) in a flotation system [11]. In addition to the frother, the collector also has an effect on bubble coalescence and evaporation by interacting with the frother.

Since the bubble size is found to be non-Gaussian distribution, single statistical feature such as variance hardly characterize the distribution effectively [12]. Some researchers investigate random distribution control algorithms in order to implement control and diagnosis of variables with non-Gaussian distribution [13–16]. The PDF of bubble size based fault detection technology for flotation process is designed, where the PDF is depicted by kernel method [17]. Recently, the dynamic PDF of bubble size is utilized to evaluate operating status of reagent dosage in copper flotation process [18]. A novel bubble size distribution based reagent dosage predictive control algorithm is proposed to implement the product indices in copper roughing circuit. Compared with manual operation, the proposed method can effectively achieve reagent dosage control [19].

However, it is noted that the long flotation process leads to large delay, and limits the control effects. If slurry properties change greatly, the unstable state of flotation running is likely to emerge after some time. When the changes act on the flotation, we hardly adjust the reagent dosage in response to the changes promptly only by bubble characteristics. It is clear that the feedback control methods cannot obtain the changes of slurry property in advance such that it needs more time to adjust the reagent dosage to achieve steady state of flotation running. From a control systems point of view, the fluctuations of slurry property act as disturbances which the closed-loop controller needs to reject. This is commonly known as disturbance feedforward control. Feedforward control can be very effective in improving control performance, especially if the disturbances can be measured. Further improvements are possible if the disturbance is known ahead in time. The feedforward control does not use observations from the actual plant response. Instead, this is left to the "feedback" component which monitors the actual response and makes appropriate adjustments.

Combined feedforward and feedback control is applied in many fields. For example, an application of combined feedback–feedforward control to the wind turbine collective pitch and torque control problem in full-load operation is presented [20]. A mixed feedforward/feedback (FFB) based adaptive fuzzy controller design for a class of multiple-input–multiple-output (MIMO) uncertain nonlinear systems is proposed [21]. A position tracking control system is developed for a rotorcraft-based unmanned aerial vehicle using robust integral of the signum of the error feedback and neural network feedforward terms [22]. In flotation system, a feedforward and feedback prediction control algorithm is developed to control the reagent dosage [23]. The reagent addition is determined according to ore amount and property by using a feedforward control strategy, and then the dosage is 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.

Considering poorly modeled flotation systems and operation experience, a combined feedforward and feedback (FFB) based control scheme of reagent dosage is presented to implement tracking for PDF of the desired bubble size. Instead of using feedback cancelation, a FFB-based control scheme of reagent dosage is firstly introduced for copper flotation. Here a fuzzy based feedforward compensator is developed to closely compensate the disturbances. Based on the previous works [13–16,19], a PDF of bubble size based feedback predictive control is used to track for the given PDF and assure the stability of bubble size distribution during transient state.

The rest of the paper is organized as follows: a copper flotation process is described and reagent dosage control modeling is discussed in Section 2; Section 3 proposes the proposed control model in detail. 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

A concise flow diagram of a copper flotation process can be shown in Fig. 1. Raw ore is firstly grinded into powder with a suitable particle size (i.e. less than 0.074 mm) by a ball mill, and the powder is mixed with water to form pulp slurry according to special proportion. The pulp slurry is then directly pumped to the hydro cyclone so that the mineral particle in the pulp slurry will be screened to meet particle size for flotation. Eligible slurry from the hydro cyclone is subsequently fed into an agitated tank I, where the valuable mineral particles are selectively coated with hydrophobic chemicals. After being fully agitated, the slurry flow into the flotation cell with self-aspirating aeration mechanisms, where air is cut to a large number of tiny bubbles by the impeller, and then the bubbles carry the valuable mineral particles according to collision and adhesion probability mechanism and float the top of the cell to form a froth layer due to buoyancy. Finally, the bubbles carrying valuable mineral particles overflow from the froth layer, and the remaining slurry will be discharged through the outlet channel of the flotation cell.

The copper flotation process consists of three flotation circuits, namely, a roughing circuit, a scavenging circuit and a cleaning circuit. In order to improve recovery, the concentrate of the scavenging and the tailing of the cleaning need to be regrinded for re-flotation. Each circuit is used to separate the specific mineral particles from slurry and has an individual 'role'. For example, the roughing circuit carries out as far as possible easily floated valuable mineral particles from the gangue by adding Z200. The scavenging circuit separates hard-flotation valuable mineral particles from the gangue by adding butyl xanthates and BC. Therefore, the recovery is more important than the grade in the two circuits. The cleaning circuit, on the other hand, produces the final product, and therefore the grade of the concentrate becomes more important than the recovery. In sum, these circuits allow multistage treatment of the slurry to meet high product indices in the final product.

2.2. Modeling analysis

According to expert experience, the reagent dosage control for the copper roughing has a very significant and direct impact on