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Powder Technology 186 (2008) 31–39
POWDER TECHNOLOGY
www.elsevier.com/locate/powtec

Constrained model predictive control in ball mill grinding process

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Received 27 October 2006; received in revised form 12 July 2007; accepted 26 October 2007
Available online 7 November 2007

Abstract

Stable control of grinding process is of great importance for improvements of operation efficiency, the recovery of the valuable minerals, and significant reductions of production costs in concentration plants. Decoupled multi-loop PID controllers are usually carried out to manage to eliminate the effects of interactions among the control loops, but they generally become sluggish due to imperfect process models and a close control of the process is usually impossible in real practice. Based on its inherent decoupling scheme, model predictive control (MPC) is employed to handle such highly interacting system. For high quality requirements, a three-input three-output model of the grinding process is constructed. Constrained dynamic matrix control (DMC) is applied in an iron ore concentration plant, and operation of the process close to their optimum operating conditions is achieved. Some practical problems about the application of MPC in grinding process are presented and discussed in detail.

Keywords: Model predictive control; Dynamic matrix control; PID control; Ball mill; Grinding process

1. Introduction

Ball mill grinding is a fundamental operation process, and in many respects the most important unit operation in a mineral processing plant. Grinding process represents almost half of the total operating costs associated with the mining operation, and the product particle size greatly influences the recovery rate of the valuable minerals and the volume of tailing discharge in the subsequent processes. Low qualified rate of product particle size can cause unacceptable economic loss and could be harmful for pollution control. For effective concentration or subsequent mineral liberation, grinding process has to maintain the following outputs (or controlled variables) stable, mainly including the product particle size distribution, circulating load and mill solids concentration, etc [1–3].

The control of grinding processes is a challenging problem due to two basic reasons. First, a large number of variables involved have strong couplings among them. If regulating one controlled variable is attempted with one manipulated variable, the other controlled variables will, more likely than not, be influenced in an undesired fashion. Second, the existence of large time delays, time-varying parameters and nonlinearities are some of the other difficulties encountered by the control engineers.

Many research papers have been published on the development of control strategies for grinding process. Traditionally, the grinding processes are controlled by multiple single-input single-output (multi-SISO) PID controllers which are usually decoupled to avoid multivariable interactions [1]. Fig. 1 shows a widely used multi-SISO (two-input two-output) system with two decouplers, namely $D_{12}(s)$ and $D_{21}(s)$.

$$D_{12}(s) = -\frac{W_{12}(s)}{W_{11}(s)} \tag{1}$$

$$D_{21}(s) = -\frac{W_{21}(s)}{W_{22}(s)} \tag{2}$$

where $W_{ij}(s)(i=1,2;\ j=1,2)$ are process models.

One difficulty of this kind of control lies in the choice of the proper input–output pairing. When manipulated variables are not properly selected, interactions between controlled and

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doi:10.1016/j.powtec.2007.10.026

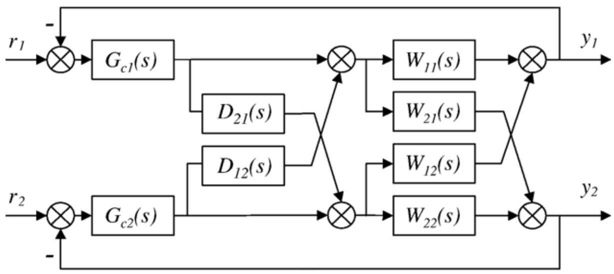

Fig. 1. Multi-SISO system with decouplers.

manipulated variables can result in undesirable control loop interactions, leading to poor control performances [1]. Another difficulty is that static decoupling (based on steady-state gains) is used much more often than dynamic decoupling in practice because the dynamic version may not be physically realizable [4,12]. Therefore, a close control of the process based on conventional multi-SISO PID controllers is usually impossible in real practice for a long time, and the controllers generally become sluggish especially when model mismatch occurs due to great disturbances, such as the changes in ore hardness and fresh ore feed size, etc.

Although robust control [5], adaptive control [6], neural control [7] and multivariable control [8] are studied either in simulation level or in experimental level, very few of them currently operate in industry. Moreover, in most of the literatures [1,6–8], two-input two-output model is usually employed for control study. However, two controlled variables are the minimum requirement for a basic grinding process. For the process with high quality requirements, it is often not adequate to meet the production needs if only two controlled variables are considered.

Presently MPC has become the most widely used multivariable control algorithm in the chemical process industries and in other areas [9]. Unlike many other multivariable control strategies, MPC was conceived primarily by industry. Dynamic matrix control (DMC) [10] and model algorithmic control (MAC) [11] are the two powerful MPC multivariable control strategies. While these algorithms differ in certain details, the main ideas behind them are very similar. MPC schemes are popular in multiple variable processes because: (1) MPC can predict the future behaviors of a process with large time delays, (2) it has no variables paring problems in multivariable systems, and (3) it can easily handle constraints imposed on both the manipulated and controlled variables. MPC also has the prominent features such as relatively easy to tune, and less sensitive to model mismatch compared with many other model based advanced control strategies [12].

This paper presents an application of multivariable model predictive control scheme to a ball mill grinding process. The rest of the paper is organized as follows: A three-input three-output model of grinding process is constructed in Section 2. After a brief description of DMC scheme in Section 3, Section 4 presents an industrial application with constrained DMC schemes in an iron concentration plant. Some practical problems about the application of MPC in grinding process are presented and discussed in Section 5. Conclusions are given in Section 6.

2. Process description

2.1. Grinding process

The grinding process studied in this paper operates in a closed loop as shown in Fig. 2, including a ball mill and a spiral classifier. The feed, iron ore (from primary crusher, size ≤14 mm) is fed into the ball mill by swaying feeders.

The tumbling action of the balls within the revolving mill crushes the feed to finer sizes. The slurry containing the fine product is discharged from the mill to a classifier. The slurry is separated into two streams: an overflow stream containing the finer particles and the circulating stream containing the larger particles. The overflow is the desired product. The circulating is recycled back to the ball mill for regrinding. The product particle size is specified as 72% passing 200 mesh screens.

As mentioned above, simpler control variables' pairing was studied by earlier researchers, and the circulating load and the product size were usually taken as controlled variables.

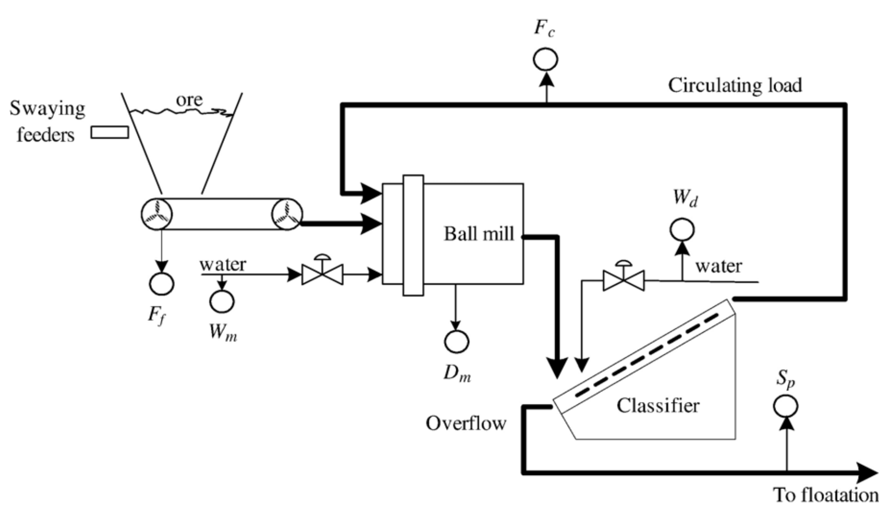

Fig. 2. Process diagram of grinding process.