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On the current state of flotation modelling for process control

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Abstract: Despite significant effort in modelling and simulating flotation circuits, comprehensive model based control and optimisation implementations on industrial circuits remain scarce. In this paper, the factors preventing more widespread implementation of model-based control and optimisation applications are investigated by focussing on three aspects. Firstly, the critical variables required in a simplified flotation model are identified. Models that are currently used in control, optimisation and supervisory applications are thereafter analysed to determine to what extent the required variables are modelled. Finally, online instrumentation available to support these models are investigated, also including instrumentation that is still under development and not commonly available in commercial applications. Although models used in control applications tend to focus on subsections of the flotation process, there seem to be a good agreement between the required and modelled variables. Model fitting however often relies on extensive sampling campaigns that will need to be repeated regularly to maintain model accuracy. A number of online measurements of sufficient accuracy are still not available to support these models, compromising the long term reliable use of models in online applications. The fact that flotation processes are in many instances not extensively instrumented, constrains online maintenance and adaption of model based solutions further.

Keywords: Flotation modelling and identification, process control and optimisation, model based control

1. INTRODUCTION

The origins of froth flotation can be traced back to the 1880s (Gaudin, 1957) while column flotation was patented in the early 1960s (Finch & Dobby, 1990). Froth flotation has been modelled extensively to include factors such as the chemical reactions (King, 1982), how different size classes participate in the process (Lynch, et al., 1981) and the physical processes such as particle-bubble collision (Finch & Dobby, 1990). Collaboration between industry and academia as part of programmes such as AMIRA P9 focussed efforts, and significant progress has been made during the past 25 years in understanding the intricacies of the froth flotation process. As a result, many of the principles described earlier have been integrated into a comprehensive simulator (Schwarz, et al., 2006).

Despite the rich modelling framework available, the number of successful industrial implementations of model based control and optimization strategies (other than basic level control as described by Schubert et al. (1995)) remain scarce (Shean & Cilliers, 2011). Reasons for this include a lack of instrumentation, lack of reliable dynamic models and inadequate regulatory control (Bergh & Yianatos, 2011). The issues of the lack of suitable dynamic models and insufficient instrumentation to interface with these models cannot be separated and need to be addressed simultaneously.

Model based implementations often fall into disuse after some time due to the models not being robust over a large range of operating conditions (Shean & Cilliers, 2011). The use of empirical models fitted over a limited operating range has similar limitations, and require frequent recalibration when the operating points shift (Bouchard, et al., 2009). In the absence of online measurements to recalibrate these models, or at least alert the operator of the need for recalibration, these strategies are bound to fail.

The aim of this paper is hence to identify the key variables required in flotation control applications, determine if existing models take these variables into account, and consider to what extent online measurements required by these models are commonly available on froth flotation plants, or are being developed and can potentially be made available on industrial sites in future. The focus is on long term industrial implementations rather than short term pilot plant campaigns.

2. MODEL REQUIREMENTS

2.1 Structure

The motivation to develop many of the existing flotation models, is to model different circuit configurations and operating practices with high accuracy, in order to recommend changes that would improve operation. Examples of such activities are described by Schwarz et al. (2006). Under these circumstances a detailed sampling campaign can often be justified to provide the data to fit a comprehensive set of model parameters. Where models are to be used online, manual sampling campaigns are not viable on an ongoing basis, and online measurements would have to be used to maintain model integrity. A model for continuous control applications would

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thus need to be structured in such a way that available online measurements provide the stimuli to the process and are also used to maintain model integrity by estimating parameters where possible.

Basic froth flotation models are typically extended with the aim of characterising some behaviour that cannot be explained by existing models. While more detailed modelling is essential in improving model accuracy and in advancing knowledge about the process, it does result in a significantly larger set of parameters to be fitted initially and updated regularly to maintain model consistency. For control purposes, some accuracy may be sacrificed in exchange for fewer parameters. The direction of change and relative magnitude is generally of more importance than the absolute value of a variable, as measurement feedback can correct for model inaccuracies. While the decision on which interactions to ignore are not trivial, a reliable model would have to be based on a significantly reduced parameter set, to ensure that model accuracy is not degraded by the use of estimates based on parameters that cannot be updated dynamically.

Despite the requirement of minimising the set of parameters, the model needs to be able to estimate process dynamics required for control with sufficient accuracy. It must also be able to model non-linear phenomena such as peak air recovery (Hadler & Cilliers, 2009) and discrepancies between mass-pull and recovery (Hadler, et al., 2010) that currently receive research interest, with sufficient accuracy.

While laboratory and pilot-plant scale applications show some benefit of deriving empirical models (Bouchard et al., 2009), the long-term reliability of these models in the presence of changing operating conditions is a concern. Phenomenological models should thus take priority. Bouchard et al. (2009) however also commented that empirical models should not be dismissed completely, as all models as well as sensors require calibration.

2.2 Variables

A number of authors listed the key variables required in the control of froth flotation processes, for example Finch & Dobby (1990), Lynch et al. (1981), Bergh & Yianatos (2011) and Laurila et al. (2002). There is to a large extent agreement on the set of variables required, and a summary follows:

As inputs, or manipulated variables, the following variables can be used to drive the process in a desired direction:

- Reagent additions
- Pulp level setpoints
- Air flow rate setpoints
- Froth wash water rate (particularly in columns)

Lynch et al. (1981) also included addition points for reagents and collection points for concentrate, but these form part of circuit design parameters rather than online control parameters.

Depending on the circuit configuration, feed characteristics are either considered as disturbances or as manipulated variables, as indicated by Lynch et al. (1981). Bergh & Yianatos (2011) considered slurry flow as a manipulated variable rather than a disturbance, which would also be the case in integrated grinding and flotation control and optimisation applications (Conradie *et al.*, 2003). The following feed properties can be classified as manipulated variables or disturbances:

- Pulp density
- Volumetric flowrate
- Fineness of grind

The main outputs of the process relate to its economic performance, and are grade and recovery. Lynch, et al. (1981) also included concentrate density and flowrate in the outputs referred to as "performance variables", as the total production also affects profitability.

A number of process states has a direct influence on the economic outputs of the process, and are typically affected by the manipulated variables and disturbances. The following states, also referred to as "intermediate variables" by Lynch, et al. (1981) are listed:

- Froth depth
- Gas holdup
- Bias superficial velocity (mostly columns)
- Air superficial velocity
- Feed, tailings and concentrate flow rates
- Mineral concentrations in all intermediate streams (grades)
- Densities of all streams

The largest discrepancy between the variables described by the authors, is in the variables considered disturbances. Bergh & Yianatos (2011) only included the first 3 disturbances listed below, while the full list is described by Laurila et al. (2002).

- Feed size distribution
- Feed grade (minerals concentration in feed)
- Feed density
- Feed mineralogy (fineness of crystallisation, minerals)
- Electrochemical potentials (Eh, pH)
- Particle properties (size distribution, shape, degree of liberation)
- Froth properties (speed, bubble size distribution, stability)

The fact that Bergh & Yianatos (2011) managed to explain 92% of variance with a reduced parameter set model, using only 6 latent variables obtained through principle component analysis, indicates that a model with a small parameter set may still provide sufficient accuracy for control purposes, but the complexity required is likely to be process dependent (Laurila et al., 2002). Shean & Cilliers (2011) confirmed that all these variables are not necessarily required to obtain good control performance, but that their impact needs to be considered. Simplifying assumptions, for example that the feed distribution and density would not vary significantly if the grinding circuit control is effective have been proposed (Wills & Napier-Munn, 2006) and can potentially be used to simplify models without degrading controller performance.