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An adaptive threshold estimation scheme for abrupt changes detection algorithm in a cement rotary kiln

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HIGHLIGHTS

- The developed adaptive threshold detects with accuracy the occurrence of a real fault.
- False alarms are completely avoided in a cement rotary kiln system.
- The developed technique uses a two dimensional plot for large-sized multivariate data.
- Adaptive thresholding technique based on the computing of confidence regions.
- The confidence region helps overcome difficulties of uncertainties quantification.

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ABSTRACT

This work deals with a major problem that arises when searching for a reliable, accurate and easily exploitable adaptive threshold based fault detection technique to indicate with great accuracy the presence of a fault in a cement rotary kiln system. The adaptive threshold estimation scheme for detection of faults is developed through the mean and variance of the measured signals. Squared radii, which represent the sum of squares of these statistical parameters, are obtained. This fault detection index is calculated using several repeated experiments under the same operation conditions. At each sample time and for all the experiments, the confidential interval of instantaneous squared radii is closely related to its estimated probability density function. *Jarque–Bera* hypothesis testing is performed at a typical error risk level and confirms the obtained probability distribution law. Several significance levels are considered where the limitations of fixed thresholding and the performance of the proposed adaptive thresholding procedure are demonstrated respectively through the rate of false alarms. The proposed adaptive threshold is compared with the fixed threshold by evaluating the detection performance across various types of faults in a cement rotary kiln system.

1. Introduction

Industrial rotary kilns, large scale pieces of sintering equipment, are widely used in chemical, metallurgical, cement industries [1]. Due to the complex dynamic, multivariable nature, nonlinear reaction kinetics, long time delays and variable

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raw material feed characteristics, the rotary kiln process is inherently difficult to model [2]. So far, to the authors knowledge, there is no mathematical model that adequately describes the process behavior. Moreover, the product quality of industrial rotary kilns is usually measured after the clinker has cooled down which adversely limits the online supervision. Furthermore, the product quality is greatly affected by the high and fluctuating combustion temperature (up to 1500 °C) in the rotary kiln; in particular the maximum sintering temperature whose accurate measurement is also difficult due to a heavily dusty environment. Therefore, only a few successful industrial applications of the kiln process diagnosis are reported in the literature [3].

A great deal of effort has been put into the development of monitoring approaches for such faults within rotary kiln systems [4]. Makaremi et al. used an identification model for abnormal operation detection in a cement plant. A locally linear neuro-fuzzy model is used for the plant normal operating conditions. The detection of faulty operations occurrence is based on the discrepancy between the actual output and the model output [5,6]. In conjunction with the development of models-based diagnosis, Subbaraj employed fuzzy based classification for fault detection and diagnosis of possible faults in pneumatic actuator for cooler water spray system in cement industry [7]. He also developed a neural network model for various operating conditions of the cooler spray system for the purpose of improving the model sensitivity in detecting and classifying different faults [8]. These fuzzy and neural approaches allow the discrimination between a faulty mode and the effect of noise and disturbance on the output that may be taken for a faulty one.

On the other hand, the theory of sequential statistical tests offers interesting alternatives and can usefully complement model-based fault detection approaches [9,10]. This theory proposes robust tools to deal with rates of both false alarms and fault non detection. An alarm is activated when the used index of fault detection exceeds a threshold which is computed based on statistical tests. Substantial effort has been devoted to the design of adaptive thresholds [11,12]. Armengol et al. developed adaptive thresholds by generating envelopes based on interval techniques of the modal interval analysis. This approach characterizes the measurement inaccuracy and model parameter uncertainties [13]. Wang et al. proposed a statistical approach based on the study of the residual signal statistics for monitoring complex industrial processes. The robust model-based monitoring is achieved through a recursive partial least squares regression technique [14,15].

In industrial processes, the application of the model-based techniques for fault detection is quite restricted because of inaccuracies stemming from the neglected higher order terms during linearization of the nonlinear model which remains valid for that specific operating point only. Any change of the operating point will therefore become a source of modeling errors. In the present work, a statistical procedure for thresholding is proposed. The developed threshold is based on a circle defined by its radius and center coordinates in a mean and variance graphical representation of the measured signals. Some statistical properties for circle parameters are obtained through an adequate number of experiments carried out under healthy mode of operating conditions of a cement rotary kiln. For each sample time, the confidence interval of a given squared radius, which is closely related to the probability density function estimation, is determined. *Jarque–Bera* hypothesis testing is performed at a given significance level and confirmed the obtained probability distribution law with acceptable *p*-value. Several significance levels are considered where the limitations of fixed thresholding and the performance of the proposed adaptive thresholding procedure are demonstrated through the rate of false alarms. The proposed adaptive threshold is compared with the fixed threshold by assessing the detection performance for various types of faults occurring in a cement rotary kiln at Ain El Kebira Cement Plant in eastern Algeria.

In Section 2 of the paper is given a brief description of the cement rotary kiln. In Section 3, the fundamentals of model-based fault detection are reviewed and the factors that effect model accuracy highlighted and the limitations of fixed threshold fault detection schemes described. In Section 4, the adaptive threshold techniques based on an adequate statistical analysis of circle parameters that use a mean and variance plot for recorded data are described. The main emphasis will be given to the computation details of the adaptive threshold design using statistical methods.

Experimental results presented in the final section of the paper will assess the effectiveness of the proposed thresholding approach in reducing false alarms and improving detection capability for different types of faults in comparison with the fixed thresholds technique; this is followed by a conclusion stating that the developed thresholding approach is a reliable, accurate and powerful fault detection technique.

2. Description of a cement rotary kiln

At the heart of a cement plant is the rotary kiln, a huge slightly inclined cylinder of typically 80 m length and 5 m diameter, which slowly rotates on its axis. A mixture of limestone and clay finely milled is fed in at the upper end and the rotation of the kiln causes it to gradually move downhill to the other end of the kiln while being heated to sintering temperature up to 1450 °C to obtain the clinker which in turn is milled with some additives to make the cement (Fig. 1). Two 250 kW squirrel cage induction motors spin the kiln at a speed of 2 r.pm. The material flux feeds the kiln after being preheated at 900 °C in the preheat tower made up of four floors of cyclones which are mounted in two parallel vertical positions. Each of them is separately fed by a dry craw material feeder with a capacity of 150 ton/h. The raw material made up of a mixture of limestone, marl and iron according to some adequate proportions is separately milled. A tower burner system, which uses natural gas as a combustion fuel, is fixed at the end of the rotary kiln. The kiln output material is fed to a post-kiln called the cooler. It consists of many fans that blow the stream of matter moving on a mobile grid in order to cool it down to less than 100 °C.