Diagnostic Methods for Industrial Systems: A Case Study of Rotary Kilns in Cement Manufacturing

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Abstract. With the continuous increase in complexity in industrial systems and the growing importance of maintaining their safety, numerous research efforts have aimed to develop various methods for detecting, locating, and identifying system anomalies as early as possible. In this context, we present existing diagnostic methods and use the rotary kiln in cement manufacturing as a case study for this analysis. Because of the kiln's large volume and the high temperatures involved, this complex structure is subjected to stress and deformation during its operation. Therefore, this study proposes a new solution for processing spatial data using a mathematical method based on the geometric parameters of the kiln shell structure. This study can be used to develop control tools for rotary kilns, particularly in data collection.

1 Introduction

The diagnostic phase remains a significant challenge for industries due to the frequent use of complex systems in various industrial applications. The goal is to detect, locate, and identify the causes of a set of observed symptoms that indicate a degradation in the performance of certain elements, resulting in a modification or abnormal behavior of the system.

The diagnostic process is carried out in three stages. The first phase is fault detection, which determines the presence or absence of a fault and identifies the time of its occurrence. The second phase involves fault localization, which identifies the defective element and determines its type. The final phase is fault identification, which assesses the temporal evolution of the faults and determines their characteristics (e.g., amplitude, depth, size)[1].

The development of diagnostic methods to achieve these three phases has been the focus of numerous research efforts. This article is structured as follows: after the introduction, Section 2 focuses on existing diagnostic methods. Section 3 presents the mathematical model for measuring the eccentricity of the kiln's actual axis, along with the measurement procedure proposed in this article. It also highlights the results obtained and validates the performance of the proposed method by comparing these results with those obtained from the prototype we developed and the three-dimensional machine. Finally, Section 4 presents the conclusion.

2 Review of Diagnostic Methods

The presence of defects (mechanical, electrical, thermal, etc.) significantly disrupts the system's operation and dynamic behavior. In this context, numerous diagnostic methods have been proposed. These methods primarily contribute to preventive maintenance, which aims to predict defects as early as possible to ensure safety, maintain operational continuity, and avoid severe consequences such as machine downtime and reduced production.

The application of diagnostic methods in industries depends first on the nature of the data collected about the system's operation and second on the availability of system modeling. Two main categories of information acquisition are distinguished: analytical redundancy and hardware redundancy [1,2].

2.1 Hardware redundancy

The concept of hardware redundancy relies on the use of sensors to detect the presence or absence of faults. This approach is primarily employed in high-risk systems, such as nuclear power plants and aircraft. The primary advantage of this method lies in its simplicity and reliability. However, the high cost associated with the use of redundant sensors limits its range of applications.

According to research, to reduce the amount of redundant equipment, hardware redundancy can be supplemented by using analytical relationships between the system's inputs and outputs, known as analytical redundancy [2].

2.2 Analytical redundancy

The principle of this method involves developing a mathematical model of the physical system to be monitored and comparing the system's actual operation with the operation estimated by the model. [3].

System modeling can be based either on the fundamental laws of physics, a combination of these laws, or on phenomenological knowledge of the process that describes the system's normal and abnormal states.

Analytical redundancy is traditionally divided into three categories:

1- **Model-based diagnosis:** The general principle of this method is based on comparing the system's actual operation with the estimated operation obtained from a model [3,4].
2- **Signal processing diagnosis:** Signal-based methods rely on measured signals rather than mathematical models for fault diagnosis. System faults are reflected in the measured signals, from which relevant features are extracted, and a diagnostic decision is made based on the analysis of these symptoms [4].
3- **Data-driven diagnostic methods:** These methods rely on generating residuals (indicators of faults) from the measured inputs and outputs of the system. Fuzzy logic and neural networks are among the most commonly used techniques for diagnosis [5].

3 Case Study: Cement Rotary Kiln

In the industrial field, particularly in the cement industry, the essential part of the manufacturing process is the production of clinker, which is obtained through the firing process using a rotary kiln[6,7].

This complex structure is subjected to stresses and deformations during operation. Under these conditions, it is essential to regularly conduct control measurements to ensure compliance with fundamental geometric parameters [8]. The rotary kiln consists of a steel cylinder, called a shell, which is internally lined with refractory brick to protect the shell and reduce heat loss. It is rotated by electric motors. The cylinder is inclined at a 4% slope to facilitate material flow, and the kiln's rotation is controlled by a control unit, a drive pinion, and a gear ring fixed to the shell. [9 ,10].

It is symmetrically supported on both sides by a metallic banding system mounted on rollers. The banding's role is to guide the kiln's rotation through shims and rings installed at their interfaces. The purpose of the rings is to prevent axial movement of the banding during kiln operation.

3.1 Method and procedure to measure rotary kiln cylinder running axis

In this context, this contribution proposes a new technique for measuring the eccentricity of the kiln axis. The calculation principle is defined as follows:

- Calculate the eccentricity**:** It is necessary to determine the actual center of the circular section's geometry. We used three sensors, oriented towards the cylinder section, to measure the distances (d1, d2, d3) for each angle of rotation (Fig. 1).
- After developing the mathematical model based on the geometry, we determined the geometric coordinates of the kiln axis.

Referring to (Fig.1) that illustrates the principle of the new method for calculating the eccentricity of the rotary kiln axis, three sensors (point A, point B, and point C) are employed and directed towards the cylinder section (shell). These sensors measure the distances (d1, d2, d3) and the position of each sensor, determined by the orientation angles (α1, α2, α3). Additionally, we calculate the coordinates of the position points (A, B, C) and the coordinates of the midpoints of the segments M and M', respectively of [AB] and [BC]. By determining the bisector lines of [AB] and [BC], the point of intersection between these two lines is identified as the true center of the circular section (ferrule). The equations of the bisector lines of the segments [AB] and [BC] then allow us to determine the coordinates of the point of intersection (x', y'), representing the true center of the ferrule section.

$$x' = \frac{\frac{d_2^2 - {d_1}^2}{2\left(d_2 \sin sin(\alpha_2) - d_1 \sin sin(\alpha_1)\right)} - \frac{d_3^2 - {d_2}^2}{2\left(d_3 \sin sin(\alpha_3) - d_2 \sin sin(\alpha_2)\right)}}{\frac{d_2 cos(\alpha_2) - d_3 cos(\alpha_3)}{d_3 \sin sin(\alpha_3) - d_2 \sin sin(\alpha_2)} - \frac{d_1 cos(\alpha_1) - d_2 cos(\alpha_2)}{d_2 \sin sin(\alpha_2) - d_1 \sin sin(\alpha_1)}}$$

$$y' = \frac{d_1 cos(\alpha_1) - d_2 cos(\alpha_2)}{d_2\, sin\, sin(\alpha_2) - d_1\, sin\, sin(\alpha_1)} \times \frac{\frac{d_2^2 - {d_1}^2}{2\left(d_2\, sin\, sin(\alpha_2) - d_1\, sin\, sin(\alpha_1)\right)} - \frac{d_3^2 - {d_2}^2}{2\left(d_3\, sin\, sin(\alpha_3) - d_2\, sin\, sin(\alpha_2)\right)}}{\frac{d_2 cos(\alpha_2) - d_3 cos(\alpha_3)}{d_3\, sin\, sin(\alpha_3) - d_2\, sin\, sin(\alpha_2)} - \frac{d_1 cos(\alpha_1) - d_2 cos(\alpha_2)}{d_2\, sin\, sin(\alpha_2) - d_1\, sin\, sin(\alpha_1)}} + \frac{d_2^2 - {d_1}^2}{d_2\, sin\, sin(\alpha_2) - d_1\, sin\, sin(\alpha_1)}$$

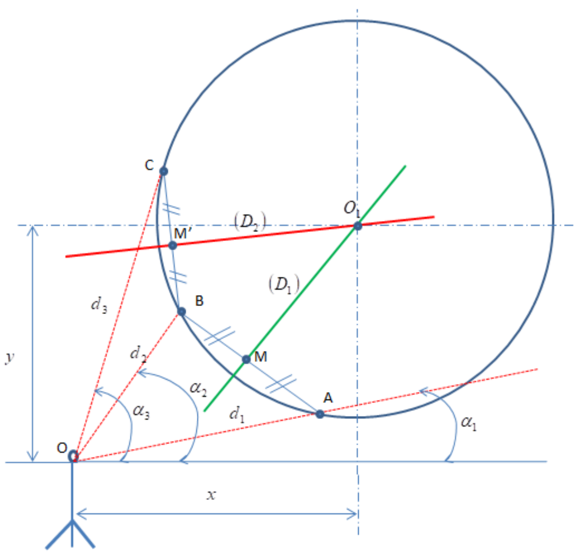

Fig. 1. the position of the device in relation to the section and the principle for calculating the eccentricity of the rotary kiln axis

3.2 Validation and Results

To validate the new method presented, a prototype was designed and manufactured based on a simple model that facilitates the creation of the prototype. We modeled the kiln shell as a small cylinder with a diameter of 300 mm. This prototype is controlled by Arduino and is capable of measuring and storing information about the cylinder's geometry, which can be analyzed later, the results obtained by the prototype are compared with the results obtained using the three-dimensional measurement machine.

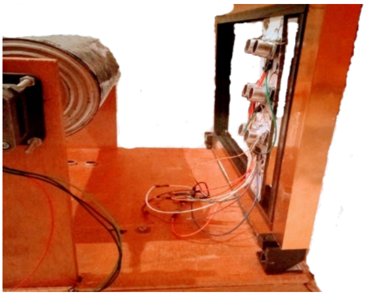


Fig. 2. the prototype and the three-dimensional measurement machine

The following figure (fig.3) shows the measurement results obtained by the three-dimensional measurement machine and the prototype

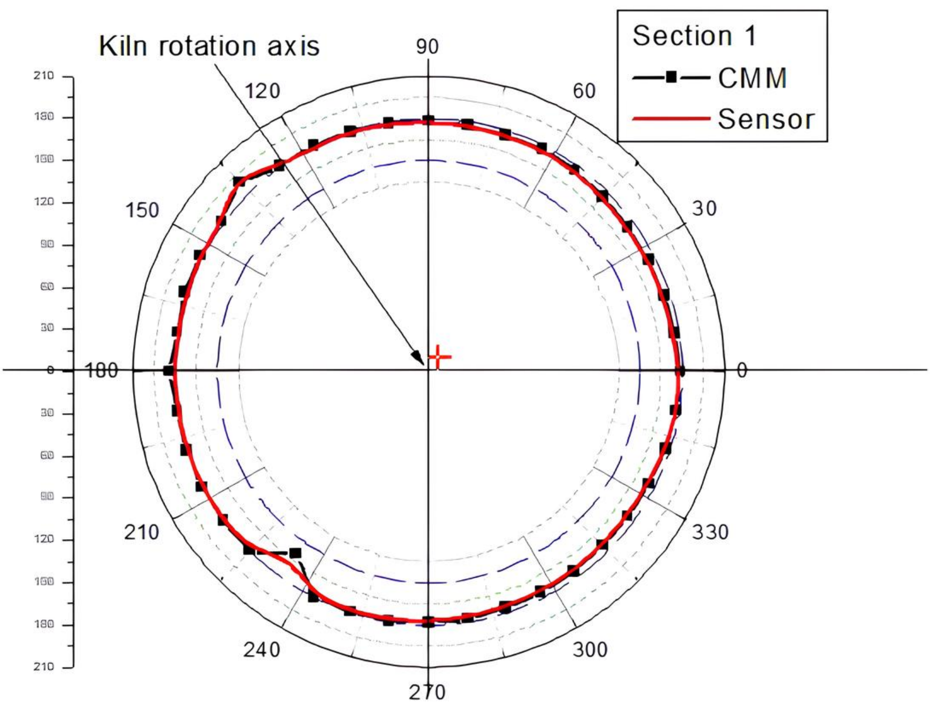

Fig. 3. Result of the measurements obtained by the coordinate measuring machine and the prototype

4 Conclusion

In this study, we have proposed a state-of-the-art classification of diagnostic methods for dynamic systems, according to the nature of the data used. This classification is mainly divided into two main categories: analytical redundancy and hardware redundancy.

In the context of material redundancy, a new measurement method and a mathematical model, derived from the cylinder geometry of a rotary kiln, are presented in this article.
The primary goal of this method is to analyze the data collected by measuring instruments in order to accurately determine the coordinates of the cylinder's real axis and its ovality. This is aimed at reducing downtime and reducing spare parts costs. The effectiveness of the proposed method is evaluated by comparing the results obtained from the designed prototype with those provided by a coordinate measuring machine.
The measurement results show that the proposed method accurately determines the coordinates of the rotation axis, ensuring a precise evaluation of eccentricity and ovality. These results are consistent with previous comparisons between measurements obtained from the sensors and those provided by the coordinate measuring machine (CMM).
In the future, we plan to focus on applying the new model in various domains and conducting additional experiments to validate the proposed method. This will involve exploring practical industrial contexts in more in-depth research

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