Measurement 118 (2018) 23–28

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Online monitoring and failure detection of capacitive displacement sensor in a Capball device using fractal analysis

X. Rimpault*, E. Bitar-Nehme, M. Balazinski, J.R.R. Mayer

Department of Mechanical Engineering, Polytechnique Montréal, 2900 Édouard-Montpetit Blvd., Montréal, QC H3T 1J4, Canada

ARTICLE INFO

Keywords:
Sensor failure detection
Capacitive displacement sensor
Online monitoring
Fractal analysis
Machine error

ABSTRACT

Sensor failure may be difficult to detect depending on the nature of the defect. In this study, fractal analysis was used to analyse the raw signal of capacitive displacement sensors in order to detect abnormalities. The fractal analysis of the signals was performed for stationary and dynamic measurements of the target–sensor distance mounted in a Capball device. The fractal results such as fractal dimension and topothesy are found to be effective estimators of the signal characteristics. A sensor failure index, based on a combination of fractal parameters, is proposed herein and is found efficient to detect sensor defects.

1. Introduction

Automation of manufacturing or assembly lines is important to increase productivity. Sensors are increasingly used in order to gather information from such automation lines and to enable machine or process monitoring. A sensor is a device converting a measured quantity (e.g. length, weight) into an electric signal. During its use, a failure might occur due to environmental contamination or due to the reach of the sensor life end [1]. Such failures may be difficult to detect. Firstly, because the failure can impact the output signal in a variety of ways e.g. systematic error, signal drifting or 'random' noise. Secondly, the failure characteristics may appear intermittently in the signal.

Capacitive displacement sensors, such as those used in this study, allow high-resolution measurements of objects position, displacement and vibration. Thanks to their nanometre resolution, applications are numerous, among them CNC machine tool error evaluation [2]. Herein, three capacitive displacement sensors were used in a Capball (depicted in Fig. 1) to estimate machine tool volumetric errors for machine tool monitoring and error compensation purposes [3,4]. The sensor measurements must be reliable and accurate. Hence, sensor failures must be detected.

In conducted experiments, one of the Capball sensors was found unable to give a valid electric signal at times. This failure was hard to detect, even by the specialist, due to the break-down characteristics. The defective signal was apparently caused by a sensor capacity diminishing (the faulty signal is distorted) and/or signal low factor (the faulty signal amplitude is affected but the signal shape remains correct). This malfunction was not always present but was appearing intermittently, increasing the difficulty to diagnose the sensor failure and to detect the malfunction starting point. Fractal analysis could be a useful technique to describe the signal features and shapes and its change vs a defective sensor signal.

In this study, an online monitoring technique is proposed to evaluate the sensor condition. It is based on the fractal analysis of the sensor raw electric signal obtained during a CNC machine volumetric errors measurement test.

2. Methodology and analysis

The machining accuracy of a machine-tool is measured by its ability to accurately position and orient the cutting tool compared to the workpiece being machined. Such positioning and orientation errors of the machine-tool are called volumetric errors. Measuring volumetric errors is crucial for quantifying the CNC machine accuracy.

The Capball is a device developed in-house at Polytechnique Montréal [3] for measuring the volumetric errors of a five-axis CNC machine-tool. Following the same principle as the R-test device [5], the Capball uses three non-contact capacitive sensors mounted perpendicularly to each other to form an orthonormal frame. It can be installed either at the tool or at the workpiece location, and measures the positional errors of a precision ball mounted at the other location (Fig. 1). The measured errors are then transformed into the machine base frame to assess the CNC machine volumetric errors.

The measurement procedure is depicted in Fig. 2 and in Fig. 3. It consists in continuously moving the machine five axes along a preprogrammed trajectory, with stops at selected points. The nominal positions of the two rotary and three linear axes are shown in Fig. 3. Herein, the Capball is mounted onto the machine work table. The

* Corresponding author.
E-mail address: xavier.rimpault@polymtl.ca (X. Rimpault).

https://doi.org/10.1016/j.measurement.2018.01.006
Received 22 July 2016; Received in revised form 16 October 2017; Accepted 6 January 2018
Available online 08 January 2018

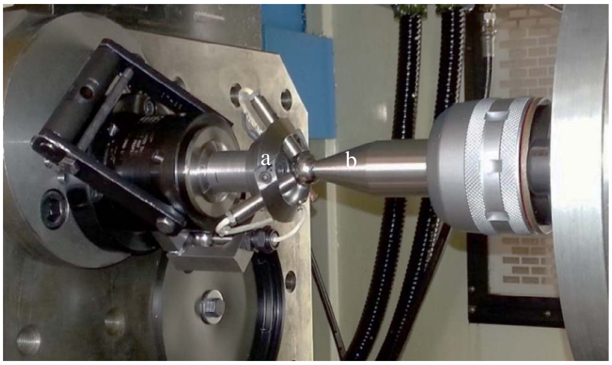

Fig. 1. Capball mounted onto the machine work table (a) and the master ball mounted onto the spindle head (b).

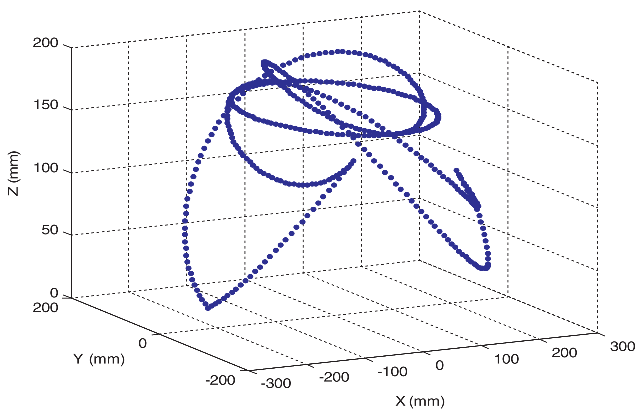

Fig. 2. Trajectory of the measurement routine.

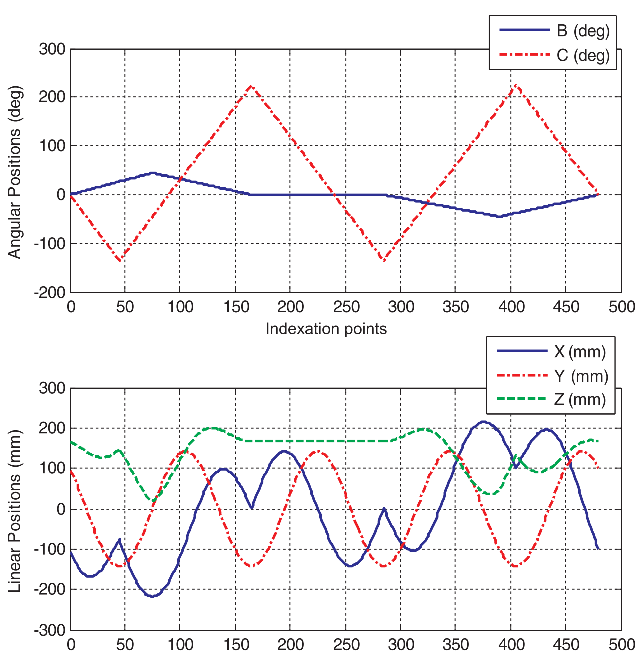

Fig. 3. Programmed measurement routine; (a) angular positions (A and B around X- and Y-axis), (b) linear positions (for X-, Y-and Z-axis).

machine program nominally places the center of the spindle ball at the Capball frame origin.

The Capball capacitive sensor characteristics are a −58 µm/V output sensitivity and a ± 10 V output range. Zero volt is returned at a nominal distance of 800 µm from the ball surface. The sampling frequency rate was set to 1 kHz.

Fig. 4 shows the raw data of two routine samples from the defective sensor before and after the intermittent fault is observed. From the comparison of two routine samples, the faulty–signal follows the signal at the beginning of the signal. Then, the faulty signal includes a low factor (signal amplitude reduced) combined with a diminishing performance (signal distorted) in comparison with the signal measured before the failure.

For each indexation of the CNC machine coordinate, there is a displacement of the linear and rotatory axes of the machine and a stop – a stationary period. This stop allows to measure the distance between the sensor and the target based on a point average during 200 ms, while the machine is relatively stabilized. The values obtained from each Capball's sensor are utilized to evaluate the volumetric errors. This stationary period is called 'static plateau'. Each plateau was timed at 300 ms. Plateaus are considered static even though the machine may be still vibrating due to the active machine position control.

Those sensor measurements must be reliable because the estimation of the volumetric errors is based on the plateaus mean values of the displacement sensor signal.

3. Fractal dimension

Fractals were first introduced by the mathematician Benoit Mandelbrot to characterize Britain's coastline length [6]. Fractal dimensions were initially used to depict irregular geometries which topologic lengths are different depending on the scale of observation. Nowadays, fractals are seen as an object which owns a self-affine pattern or singularity [7]. 'Rough' surfaces were found to have a self-affine behavior, and fractal dimension is used to estimate the surface complexity. Even though this technique is known to have an excellent capability to describe the complexity of a surface or a curve, the use of fractal analysis and its fractal parameters is rare in fault detection monitoring.

Evaluating the fractal dimension of an object or a curve is a rather difficult task to perform. Numerous techniques can be used to estimate the fractal dimension from a profile, signal or curve.

In this study, the regularization analysis was selected due to its relative robustness. This technique had already been used to evaluate gear damage using accelerometer signals [8]. The regularization analysis consists in estimating fractal parameters such as fractal dimension using convolutions of the signal 's' with different kernels g_a with a width of 'a' [9,10]. Each convolution product s_a can be written as:

$$s_a = s * g_a \tag{1}$$

The kernel g_a, which was used in our calculation with a width of 'a', was the Gaussian kernel which is the first derivative of the 1-D Gaussian function. Then, the hypothesis that the convolution product s_a has a finite length called l_a, for the size of 'a', is set.

The fractal dimension estimated herein also known as the regularization dimension D can be calculated using:

$$D = 1 - \lim_{a \to 0} \frac{\log l_a}{\log a} \tag{2}$$

The limit, in the Eq. (2), is usually estimated as the slope value when 'a' values are close to 0, and when the linear regression R^2 of the part of the curve is close to 1. Fig. 5 depicts examples of fractal dimension evaluation graphs for different static plateaus from a valid sensor signal. From preliminary computations of those log–log curves, a determination range was selected – identified in Fig. 5 by dash lines. This range corresponds to the highest frequency range in the acquired signal (25–140 Hz) so for 7 to 40 acquisition points. In this range, the slope and y–intercept slope offset of the linear regression was estimated for each curve. According to fractal theory, the offset corresponds to the topothesy of the analysed curved. The topothesy can be described as an index determining the ruggedness of the signal. The slope is related to