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Technical note

3D surface form error evaluation using high definition metrology

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ABSTRACT

This paper presents an approach to evaluate 3D surface form error of machined surface using high definition metrology that can measure millions of data points representing the entire surface. A data preprocessing method was developed to convert the mass data into a height-encoded and position-maintained gray image. With the converted image, a modified gray level co-occurrence matrix method was adopted to extract 3D surface form error characteristics, including entropy, contrast and correlation. Entropy measures the randomness of surface height distribution. Contrast indicates the degree of surface local deviations. Correlation could be used to identify different machining techniques. These characteristics can be used with flatness together to evaluate 3D surface form error of large complex surface.

1. Introduction

During the last decade, the evaluation of surface geometric qualities (surface texture and surface form) gradually changes from 2D profile to 3D areal characterization [1]. For example, the evaluation of surface texture has extended from roughness and waviness to 3D surface texture, from 2D-Motif to 3D-Motif, and from 2D material ratio curve to 3D material ratio curve. However, compared with the remarkable evaluation methods on 3D surface texture, there is limited research on 3D surface form error. In general, surface form error is evaluated using surface flatness measured by coordinate measuring machines (CMMs). As CMM measures only a few scattered points or profiles due to economic constraints [2], it cannot sample high-density points describing 3D surface form error in industrial application. Recently, non-contact high definition metrology (HDM) has been adopted for its 3D inspection of the entire surface as HDM can generate a surface height map of millions of data points within seconds [3]. HDM provides possibility to evaluate 3D surface form error in many aspects besides surface flatness. Therefore, the purpose of this research is to develop a proper method to evaluate the 3D surface form error using HDM data.

To begin with, we first discuss the scope of 3D surface form error. In the authors' point of view, 3D surface form error describes relatively long-wavelength deviations from a 3D areal characterization of an entire machined surface. According to the authors' definition, there are differences and similarities between 3D surface form error and 2D surface texture, 3D surface texture, as well as flatness measured by CMM. These four types of surface geometric qualities are classified by a two-dimensional coordinate system (Fig. 1). The horizontal coordinate is the lateral resolution of the corresponding measurement techniques, and the vertical coordinate is the metrology dimension. Therefore, 3D surface form error differs from flatness measured by CMM in metrology dimension and 3D surface texture in lateral resolution. As for similarities, 3D surface form error has the same level of lateral resolution with surface flatness and has the same metrology dimension with 3D surface texture.

As both 3D surface texture and 3D surface form error are based on 3D areal measurement, the evaluation methods for 3D surface texture can be adopted to evaluate 3D surface form error to a certain degree. 3D surface texture is typically measured by areal-topography methods (ATM) such as phase-shifting interferometry, coherence scanning interferometry, and atomic force microscopy [4]. A serious of successful studies such as "Birmingham 14 parameters" [5–8] and international standards on 3D surface texture [9] were achieved. Among these parameters, certain 3D surface texture parameters such as height parameters in ISO 25178-Part 2 [9] can be extended to evaluate HDM data. However, other 3D surface texture parameters are not fit to evaluate HDM data. There are two reasons. The first reason is the measurement continuity. ATM usually measures a simple square area that has no holes or empty zones. Therefore, ATM data are continuously sampled, so the 3D surface texture parameters can be calculated directly. On the contrary, HDM measures the entire surface probably with many holes and empty zones. For instance, engine block faces measured by HDM in Fig. 1 have cylinder holes, bolt holes and cooling

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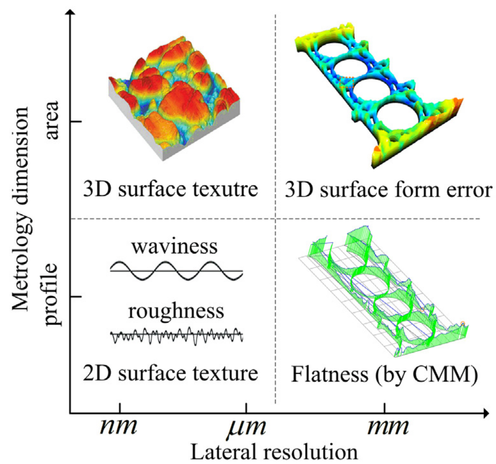

Fig. 1. Classification of surface geometrical qualities.

holes. Therefore, HDM data are not continuously measured, so the 3D surface form error cannot be analyzed directly by using 3D surface texture methods such as 3D frequency filtering. The second reason is the lateral resolution or deviation wavelength between HDM and ATM. ATM measures typically a selected area with an edge of several millimeters with lateral resolution at the scale of micrometer or even nanometer. However, HDM measures the entire surface with an edge of several hundred millimeters at sub-millimeter resolution. Therefore, 3D surface texture parameters, which focus on the short-wavelength, high-frequency deviation of local regions, are not designed for evaluating the long-wavelength, low-frequency deviation of the entire surface. The above two reasons also explain why we assign HDM measurement to the scope of 3D surface form error instead of 3D surface texture.

Recently published research has adopted some characteristic extraction techniques using HDM data for various applications [10–13]. However, the extracted characteristics are inadequate for evaluating 3D surface form error. Because characteristics for surface form error evaluation must have engineering meaning whereas those for surface classification and surface partition do not have to. In a short summary, 3D surface form error information has not been mined and analyzed sufficiently using HDM data.

The evaluation of 3D surface form error should focus on two problems. The first problem is to process raw HDM data into a suitable data type for evaluating the entire surface that has holes or empty zones. The second problem is to extract meaningful characteristics describing 3D surface form error. In this research, an evaluation method for 3D surface form error is proposed to tackle the two problems. First, a HDM data preprocessing method is proposed to convert HMD data into a height-encoded gray image containing all the height and spatial information of entire surface. Gray values and positions of pixels in the image are assigned to height deviations and spatial positions of the measurement points of the surface, respectively. Second, a modified GLCM method is developed to evaluate 3D surface form error of machined surface with complex geometry, which eliminates the influence of the empty zone of the surface. From the modified GLCM, characteristics such as entropy, contrast, and correlation are calculated. These characteristics having engineering meaning complement 3D surface form error evaluation.

The remainder of this paper is organized as follows: Section 2 describes an evaluation method for 3D surface form error, including the HDM data preprocessing method and the modified GLCM method. Section 3 presents a case study to show the effectiveness of the proposed 3D surface form evaluation method in industrial use. Section 4 draws the conclusions and discusses the future research.

2. Proposed method

The proposed method for 3D surface form error evaluation includes two parts: a HDM data preprocessing method and a modified GLCM method, which are illustrated in Sections 2.1 and 2.2, respectively.

2.1. HDM data preprocessing method

In this section, a HDM data preprocessing method is proposed to convert HDM data into a height-encoded and position-maintained gray image. The height information (Z coordinates of HDM data) is converted to pixel gray intensities, and the spatial information (X and Y coordinates) is converted to pixel index. The converted gray image reduces the data size to about one third of the size of raw HDM data and serves as a suitable data type for further analysis. Fig. 2 shows the four steps of the HDM data preprocessing method, including HDM data alignment, grid generation, grayscale converting, and empty zone removing.

The first step is obtaining the orthogonal height deviations from raw HDM data $[x_i y_i z_i]$, where $i = 1, 2, \ldots, N$ is the number of the measurement points. The raw HDM data are relative to the reference plane of HDM. Unless the measured surface is perfectly aligned with the reference plane, raw data will be titled with respect to the measured surface. A least square plane P is fitted to acquire the nominal measured surface:

$$P : ax + by + c - z = 0 \tag{1}$$

The original coordinates $[x_i y_i z_i]$ can be transformed to new coordinates $[X_i Y_i Z_i]$ on the fitted plane P. The orthogonal height deviation Z_i is calculated by:

$$Z_i = \frac{z_i - ax_i - by_i - c}{\sqrt{1 + a^2 + b^2}} \tag{2}$$

The second step is generating a regular grid of height deviation Z_i. A continuous surface is interpolated using coordinates $[X_i Y_i Z_i]$ by Delaunay triangulation [14]. From the interpolated surface, a

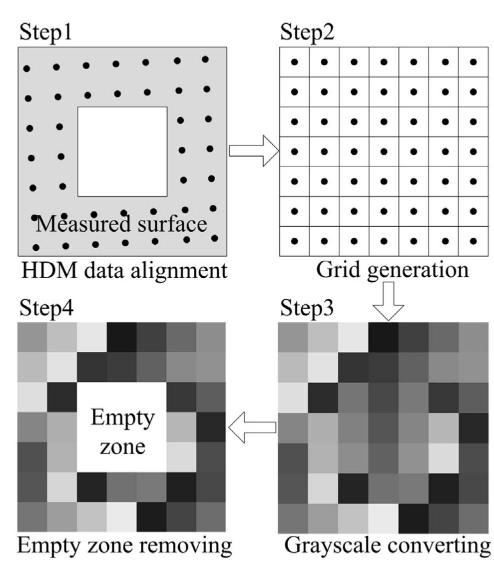

Fig. 2. HDM data preprocessing method.