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High definition metrology enabled three dimensional discontinuous surface filtering by extended tetrolet transform

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ABSTRACT

Surface topography is of great importance for the functional behavior of a part, and filtering is a key step in achieving topography analysis. The traditional filtering methods such as Gaussian and spline filter have been effectively applied in the continuous surface, but most parts have a great quantity of crucial discontinuous surfaces in engineering practice. A new filtering method based on extended tetrolet transform is proposed for the three dimensional (3D) discontinuous surface in this paper. The proposed filtering method consists of 3D discontinuous surface measurement and point cloud conversion, edge detector generation, extended tetrolet transform and 3D characterization parameters evaluation. It overcomes the drawback of edge effect which occurs in the discontinuous surface using traditional filtering methods. The 3D discontinuous surface is measured by high definition metrology that can generate millions of data points representing the entire surface. To verify the effectiveness of the extended tetrolet transform, it is compared with the areal Gaussian filter and areal spline filter both for the simulated continuous and discontinuous surface. The low frequency and high frequency components of engineering surfaces are separated exactly, and these results demonstrate that the proposed method is effective for the 3D discontinuous surface filtering without edge distortions.

1. Introduction

Over the past 30 years, there has been an increasing interest in the relationship between surface topography and mechanical manufacturing. Surface topography is a vital link between a part generated by manufacturing process and the functionality that is expected of it [1]. To satisfy tighter tolerances and higher performance standards, there is a need for engineers to go beyond specifying sizes, shapes, and peaks and move toward specifications of various surface functional attributes. Surface can be considered as the linear superposition of flaws, form error and surface texture which contains waviness and roughness [2]. Moreover, surface can be separated into different frequency components from smaller scale to larger scale, such as roughness, waviness, and form. This separation scheme had been recognized from surface texture measurement at the early stage. The motivation for such classification comes from the fact that these surface features in different scales have different origins and affect part functionality in different ways. They can be used to reflect different functions of workpieces, such as vibration, tool wear, chatter and seal [3–5]. Malburg et al. presented a novel method for the analysis of surface profiles in contact with comfortable properties of components such as gaskets, seals and bushings in many engine and hydraulic applications [6]. Bottiglione et al. [7,8] proposed a method where surface topography parameters, the applied load and the geometry of the seal were the major factors which affected leakage mechanism contained leak path formation and leakage calculation.

Surface filtering is a process to partition a surface profile into form, waviness and roughness, which is a crucial aspect of surface topography analysis. Up to now, surface filtering has been widely employed in surface metrology and a relatively mature system has been developed. An areal spline filtering technique has been proposed for 3D surface in these studies [9,10]. Wavelet transform was adopted to engineering surface texture analysis and different wavelet bases were compared by Fu et al. [11]. The applicability of wavelets was highlighted through the multi-resolution analysis on surface profiles. Jiang et al. [12] proposed a lifting wavelet representation for characterization of surface topography. Raja et al. reviewed the common filter techniques which contained traditional methods and advanced methods, such as 2RC, Gaussian, spline, morphological, wavelet, regression filters and robust regression filters [13].

Most surface filtering researches concentrate on the continuous surface, but it exists a great quantity of crucial discontinuous surfaces in

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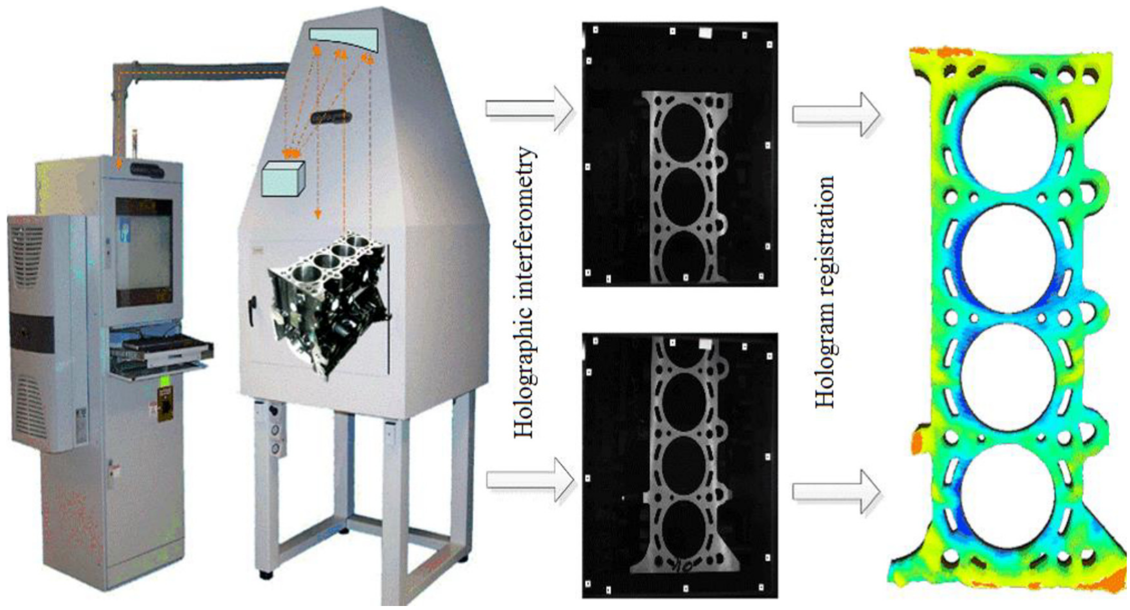

Fig. 1. Measurement by HDM.

engineering practice, such as engine block faces with cylinder holes, bolt holes and cooling holes. Conventionally, most surfaces are measured by the widely-used coordinate measuring machine (CMM). However, with the low-density sampling, the measurement result of CMM cannot represent the entire surface topography. Therefore, a full-inspection and high-density sampling measuring instrument is necessary for large and discontinuous surfaces. Recently, a novel measuring instrument called non-contact high definition metrology (HDM) has been developed [14]. Coherix ShaPix (ShaPix® Surface DetectiveTM, Ann Arbor, MI) is the device for HDM measuring process. It is a new laser holographic interferometry measurement that can measure entire surface height of discontinuous objects with holes and empty zones instead of a local area. Millions of data points are generated on an area of 300 mm × 300 mm within seconds to represent the entire measured surface with 150 µm lateral resolution in x–y direction and 1 µm accuracy in z direction. Fig. 1 shows the HDM device and a measured engine block face. Based on HDM, some researches such as 3D surface topography evaluation [15], filtering [16,17], classification [18,19], forecasting [20] and monitoring methods [21–24] have been developed for the pre-control of the manufacturing process.

However, few filtering researches had been conducted on the discontinuous surface using HDM. Zhang et al. [25] utilized a Gaussian (DoGs) filter bank to achieve the classification of workpiece surface by extracting features from HDM data. Liao et al. [26] presented a method of utilizing biorthogonal wavelets to decompose 3D surface into multi-scale subsurface and also demonstrated the relationship between wavelet scale and surface features. For the discontinuous surface, edge distortion is usually caused by holes and boundaries in the surface. To be specific, edge distortion is the pattern of manifestation of the singularity. The edge distortion belongs to the point singularity in the two dimensional discontinuous surface, and it is corresponding to the line and surface singularities in the three dimensional discontinuous surface. The discrete wavelet transform (DWT) has been one of the most popular tools in image processing due to its promising properties for point singularity analysis that can solve edge distortion. But the DWT fails to achieve geometric features with line and surface singularities, and its basis functions are fixed on the horizontal, vertical and diagonal directions without adapting the image geometric structures. Therefore, it is necessary to develop an optimal filtering technique for the 3D discontinuous surface.

A latest academic discipline called multi-scale geometric analysis (MGA) has been developed in harmonic analysis. The major goal of MGA is to explore the optimal representation of high dimensional data, and it can be extended to surface filtering. Tetrolet transform is the latest MGA method, which is a non-redundant adaptive geometric wavelet transform [27,28]. Due to small support, symmetry and orthogonality, tetrolet does not suffer from pseudo-Gibbs artifacts while preserving the anisotropic edges and features. It provides a simple but enormously fast and effective approach for image processing and compression of real data arrays. However, the standard tetrolet transform can represent the original surface well, but it lacks the representation for the decomposed and reconstructed subsurface. In order to adapt to the discontinuous surface filtering, the tetrolet transform need to be extended. Therefore, the limitations of current methods are summarized as follows:

- Surface topography directly related to mechanical properties and functional attributes, and different surface components reflect different functions of workpieces, such as vibration, tool wear, chatter and seal [3–5].
- Filtering is a key step to extract surface components. Traditional filtering methods such as Gaussian and spline filter are only appropriate for continuous surfaces, they cannot be used for discontinuous surfaces due to boundary distortion or end effects problems.
- Many discontinuous surfaces exist in engineering practice, such as the engine block faces, the engine desk faces and automatic transmission valve joint surfaces. It is necessary to propose a filtering method for discontinuous surfaces.

Meanwhile, to the best knowledge of the authors, there is no tetrolet transform based filtering method for the discontinuous surface using HDM. Benefitting from the development of measurement, the main contribution of this paper is to present a novel filtering method for the discontinuous surface based on extended tetrolet transform. The proposed filtering method overcomes the drawback of edge effect which occurs in the discontinuous surface using traditional filtering methods. The low frequency and high frequency components of discontinuous engineering surfaces are separated exactly without edge distortions. Once the exact surface components are obtained, they can indicate the machining process and the function of the part properly.

The paper is organized as follows: The basic idea of tetrolet

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