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An approach to in-process surface texture condition monitoring

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ABSTRACT

Surface textures formed in the machining process have a great influence on parts' mechanical behaviours. Normally, the surface textures are inspected by using the images of the machined and cleaned parts. In this paper, an in-process surface texture condition monitoring approach is proposed. Based on the grey-level co-occurrence matrices, some surface texture image features are extracted to describe the texture characteristics. On the basis of the empirical model decomposition, some sensitive features are also extracted from the vibration signal. The mapping relationship from texture characteristics to texture image features and vibration signal features is found. A back propagation neural network model is built when the signal features and the texture conditions are respectively inputs and outputs. The particle swarm optimization is used to optimise the weights and thresholds of the neural network. Experimental study verifies the approach's effectiveness in monitoring the surface texture conditions during the machining process. The approach's accuracy and robustness are also verified. Then, the surface texture condition can be monitored efficiently during the machining process.

1. Introduction

The term "surface texture" is used to describe surface patterns on the parts [1]. It defines the spatial relation of surface irregularities and is different from the statistical profile parameter "surface roughness" [2]. Surface texture is formed in the machining process and has a great influence on parts' mechanical behaviours, including friction coefficient [3], lubrication [4], wear condition [5], and so on. It also has a significant effect on the accuracy and performance of components or products. In fact, surface texture is affected by the cutter geometry parameters [6] and cutting parameters, including cutting speed [7] and feed rate [8]. In addition, some dynamic factors, such as the cutter runout, tool wear condition, tool orientation, vibration, temperature, cooling and lubrication, contribute to surface texture conditions too [9].

Normally, surface textures can be inspected directly by using 2D images of the machined surface [10]. Then, some surface texture inspection methods have been developed based on the image descriptors [11], such as autocorrelation function [7], statistics of intensity difference, grey-level co-occurrence matrix [2], spectrum features, and so on. Although these methods were proved to be effective enough, the texture images could only be captured from the machined and cleaned surfaces. The illumination condition affects the surface texture evaluation results greatly [10]. If the surface texture could be monitored during the machining process, great effort and time could be saved. Although experienced engineers can judge it by considering the sound, the chips and other symptoms, it is always too arbitrary to get a reliable and objective result.

After all, it is very difficult to implement a direct in-process surface texture condition mode based on machine vision technology [10]. Obscured by the cutting flood and chips, a high quality photo cannot be captured prior to the necessary cleaning operation. However, machined surface images carry the information about the cutting tool conditions as well as the machining conditions [12]. Then, the surface texture could be measured by using multiple sensors [13]. Moreover, cutting vibration had a great effect on the topography of the resulting surface [14]. A certain degree of relative vibration reduced the quality of surface texture [15]. Based on these findings, the surface texture conditions may be evaluated indirectly by using vibration signals acquired in the machining process. Then, this paper aims to investigate the approach to in-process surface texture condition monitoring based on vibration signals.

The rest of this paper is organized as follows. Section 2 presents a brief review of literature related to surface texture monitoring. Section 3 proposes the overall in-process surface texture condition monitoring procedure. In Section 4, surface texture image feature extraction and correlation analysis with vibration signal features are discussed in detail respectively. In Section 5, a back propagation neural network model for in-process surface texture monitoring is built. An experimental study is demonstrated in Section 6, which is followed by concluding remarks in Section 7.

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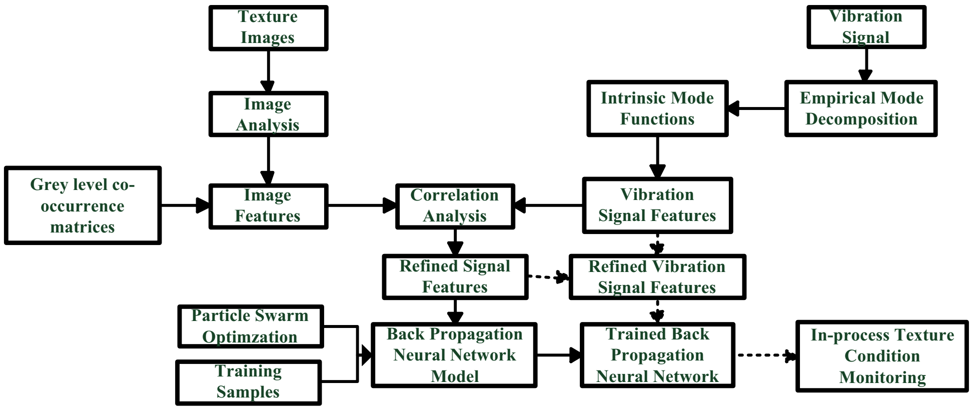

Fig. 1. The in-process surface texture condition monitoring procedure.

2. Literature review

In fact, surface texture is different from surface roughness [16]. As a statistical profile parameter, surface roughness cannot be used to distinguish the difference of topological properties, including regularity, similarity, homogeneity and smoothness. On the contrary, surface texture explains the presence of specific surface geometry organization. The concept of texture was introduced in tribology and surface metrology [17]. It defines the spatial relation of surface irregularities [18] and describes surface patterns on parts [19]. Basically, the concept of texture combines the notions of treatment and irregularity directions. It gives the opportunity to get the invariant presentation of surfaces for contact problems of tribology [2].

Surface texture conditions were visually displayed by the machined surface images. The surface texture's direction, density, periodicity, smoothness and other characteristics, were investigated by using the methodology of the image analysis and co-occurrence matrices [20]. Some sensitive image features, including energy and entropy, were extracted from these co-occurrence matrices. The surface texture conditions were judged on the basis of these features and computing intelligence methods. Moreover, the crystallographic orientation or anisotropy also had a significant effect on the texture evolution on the machined surfaces. Then, based on the Viscoplastic self-consistent model and the machining process mechanics model, both analytical and numerical models for the orthogonal cutting process were built to predict texture evolution during machining of aluminium alloy AA-7075-T651 [21].

In addition, the surface texture inspection results could be referred for the subsequent machining quality and condition evaluation, including the cutting tool wear condition monitoring. For example, the Voronoi tessellation and the discrete wavelet transform were used to decompose the turned surface images. By using the grey level co-occurrence matrix (GLCM) technique, eight features, including the root mean square (RMS) and energy, were extracted as the highly repeatable descriptors [22]. Prediction of cutting tool flank wear has also been performed by using these eight features and linear support vector machine (SVM) based regression technique [12]. The size and number of cracks and distortions in the surface texture varied with respect to the applied cutting parameters [23]. Specific surface textures were designed and created to improve cutting performance by enhancing lubricant availability at the contact point, reducing the tool-chip contact area, trapping wear debris [24], friction and tool wear [25].

Moreover, surface texture condition was closely related to cutting tool conditions and the machining conditions [12]. Surface texture could be measured by using multiple sensors [13]. Some obvious surface defects and malfunctions, such as cracks, could be found when the in-process acoustic emission signals were acquired [26]. Scanning electron microscope (SEM), optical microscopy, x-ray computed tomography (CT), Raman spectrometry, etc., were used to measure the texture features of additively manufactured parts [27]. Moreover, cutting vibration had a great effect on the topography of the resulting surface [14]. A certain degree of relative vibration reduced the quality of surface texture [15]. However, the approach to surface texture condition monitoring based on vibration signal is still rare.

According to above discussion, surface texture defines the spatial relation of surface irregularities. Surface texture conditions could be inspected directly on the basis of images of machined and cleaned surfaces [10]. Although the vibration signal may be a clue to in-process surface texture condition monitoring [14], there are very limited studies on this topic. To fill this gap, new approaches should be introduced and studied.

3. The overall in-process surface texture monitoring procedure

In order to evaluate surface texture conditions during the machining process, an approach to in-process surface texture monitoring is put forward. The overall in-process surface texture monitoring procedure is shown in Fig. 1. Its main steps are listed as follows.

1) Acquiring the vibration signals in the machining process.
2) Decomposing the acquired vibration signals and extracting signal features on the basis of the empirical mode decomposition (EMD) method.
3) Capturing the surface texture images and extracting image features on the basis of grey level co-occurrence matrices.
4) Doing correlation analysis between signal features and image features, and refining signal features.
5) Training the back propagation neural network (BPNN) model by using the training samples and the particle swarm optimization.
6) In-process surface texture condition monitoring based on the trained BPNN model and the refined vibration signal features.

To enable the whole procedure, the surface texture image feature extraction method, the correlation analysis between vibration signal features and texture image features, and the improved BPNN-based surface texture condition monitoring are key issues. Detailed discussions about them are given in the following sections.

4. Surface texture image feature extraction and correlation analysis

4.1. Surface texture characteristics

In general, the contact between cutter and work piece makes some regular textures. Little difference lies between adjacent textures. The same machining parameters make similar texture characteristics. Variable machining parameters make different texture patterns. Due