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EEMD based pitch evaluation method for accurate grating measurement by AFM

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ABSTRACT

The pitch measurement and AFM calibration precision are significantly influenced by the grating pitch evaluation method. This paper presents the ensemble empirical mode decomposition (EEMD) based pitch evaluation method to relieve the accuracy deterioration caused by high and low frequency components of scanning profile during pitch evaluation. The simulation analysis shows that the application of EEMD can improve the pitch accuracy of the FFT-FT algorithm. The pitch error is small when the iteration number of the FFT-FT algorithms was 8. The AFM measurement of the 500 nm-pitch one-dimensional grating shows that the EEMD based pitch evaluation method could improve the pitch precision, especially the grating line position precision, and greatly expand the applicability of the gravity center algorithm when particles and impression marks were distributed on the sample surface. The measurement indicates that the nonlinearity was stable, and the nonlinearity of *x* axis and forward scanning was much smaller than their counterpart. Finally, a detailed pitch measurement uncertainty evaluation model suitable for commercial AFMs was demonstrated and a pitch uncertainty in the sub-nanometer range was achieved. The pitch uncertainty was reduced about 10% by EEMD.

1. Introduction

The pitch and its uniformity have great effect on the quality of various devices, such as optical encoder [1], optical disk [2,3] and hard disk [4]. The pitch measurement plays a vital role in controlling their fabrication process and assessing their quality. Moreover, both one-dimensional gratings and two-dimensional gratings are widely used for the calibration of AFM horizontal scales [4]. The pitch evaluation method has great effect on the pitch measurement and AFM calibration precision. They can be divided into space domain methods and frequency domain methods. The gravity center [4–7], zero-crossing point [7] or the autocorrelation function [8,9] was calculated to obtain the pitch in the space domain, which are susceptible to the roughness, surface waviness and particle contamination on the sample and noise and low frequency artifacts originated from measurement. The gravity center method is the most widely used and recognized one among them. Its thresholding will fail if the amplitude of the low frequency component is big enough. Even if the thresholding succeeds, the precision of the gravity center position will be reduced by the low frequency component because the data volume used to calculate the gravity center becomes smaller for certain grating lines. So the profile should be filtered to eliminate the influence of noise, roughness and low frequency components [10]. But it is very hard to determine the filtering parameters that depend on the specific data. The frequency domain methods are much more stable for these artifacts because the pitch was calculated from the reciprocal of peak spatial frequency of amplitude spectrum [5] or PSD [5] (power spectrum density) calculated by FFT, but the frequency resolution of FFT is limited by the measurement range and sampling number. The spectrum can be greatly refined by the FFT-FT method combining FFT and continuous Fourier transform [10], but its ultimate accuracy was also limited by the measurement noise and low frequency artifacts. In order to achieve more accurate measurement of grating pitch, the EEMD based pitch evaluation method is proposed, and its application on pitch uncertainty evaluation and AFM nonlinearity study will be described in this paper.

2. The EEMD based pitch evaluation method

Empirical Mode Decomposition (EMD) [11] decomposes the data according to its own scale characteristics, so no priori basis

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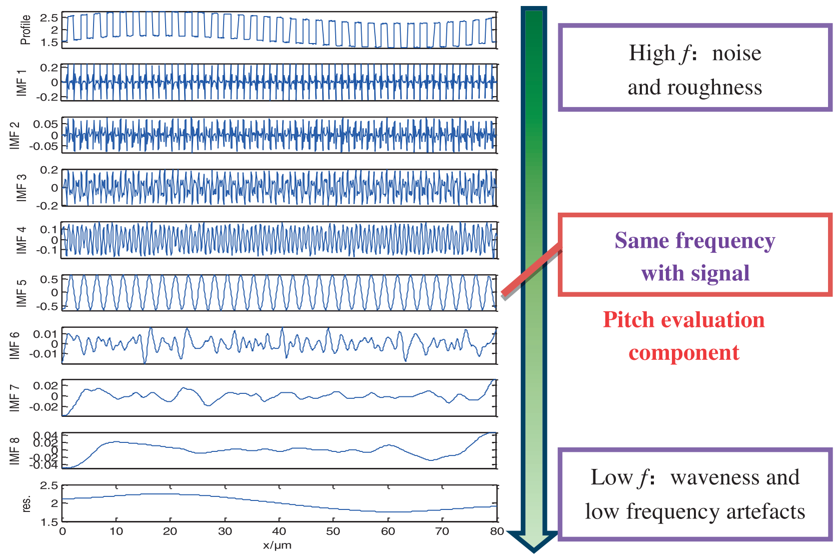

Fig. 1. The schematic diagram of the EEMD based pitch evaluation method.

functions are presumed, which is different from the Fourier Decomposition and Wavelet Decomposition in essence. This feature makes EMD very suitable for the processing of non-stationary and nonlinear signal. Using the EMD method, any complicated data set can be decomposed into a finite and often small number of components which are referred to as intrinsic mode functions (IMF). However, the EMD method is suffered from mode mixing originated from the signal's intermittent. It means that the signal in one scale is decomposed into multiple IMFs, or one IMF contains information of multiple scales. In order to reduce the mode mixing, a white noise assisted method named EEMD was proposed [12].

The AFM scanning profile could be decomposed into a collection of IMFs from high frequency to low frequency by EEMD, as shown in Fig. 1. The noise and surface roughness were decomposed into the first few IMFs, and the low frequency components originated from surface waviness and measurement artifacts were corresponding to the last few IMFs and the residue signal. As shown in Fig. 2, the low frequency components calculated by EEMD coincided with the real one pretty well. The IMF with the largest peak amplitude in its amplitude spectrum had the same pitch with the scanning profile, and this unique IMF is referred to as pitch evaluation component in this paper. We can conclude from Fig. 3 that only the frequency corresponding to the grating pitch was preserved in the pitch evaluation component.

Based on the above analysis, the EEMD based pitch evaluation method has many advantages. First, because of the self-adaptive property of the decomposition, we do not need determine the filtering parameters for removing of low frequency components and high frequency roughness and noise, which is necessary for gravity center method to realize the thresholding procedure. Second, the threshold line for gravity center method is naturally existed in IMF obtained by EEMD. At any point of IMF, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero, which means $Z_{Th} = Z_{Top} - (Z_{Top} - Z_{Bottom}) \times 50\% \approx 0$, where Z_{Top} is the local maximum, and Z_{Bottom} is the local minimum. So the line $Z = 0$ is very close to the middle line [6] which is commonly used as the threshold line. EEMD can avoid calculating Z_{Top} and Z_{Bottom} which are usually pretty difficult. Finally, the pitch precision of the FFT-FT method may be further improved by reducing the low and high frequency components.

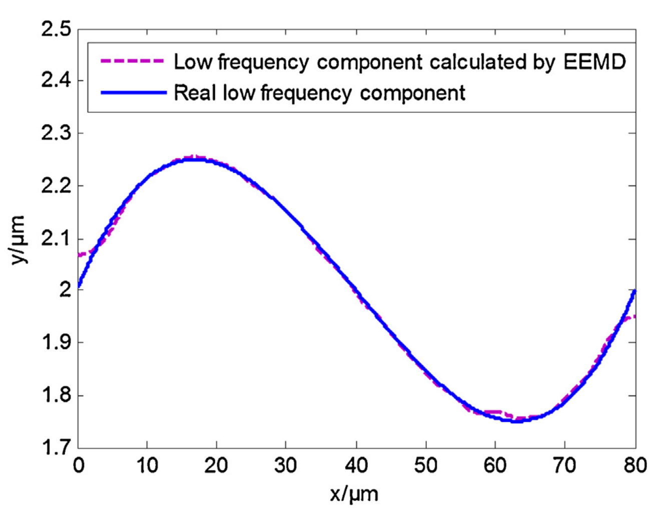

Fig. 2. The real and calculated low frequency artifact component.

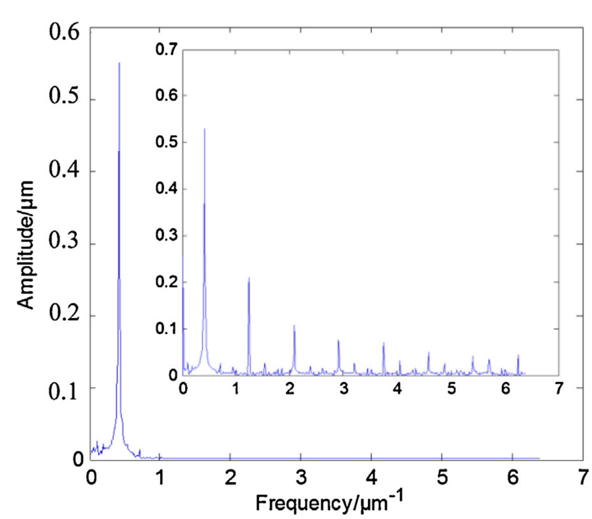

Fig. 3. The amplitude spectrum of the fifth IMF. The inset is the amplitude spectrum of the signal.