Optics and Lasers in Engineering 100 (2018) 71–76

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Improved zero-order fringe positioning algorithms in white light interference based atomic force microscopy

Chi Hu, Xiaojun Liu, Wenjun Yang, Wenlong Lu*, Nengguo Yu, Suping Chang

State Key Laboratory of Digital Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan 430074, China

ARTICLE INFO

Keywords:
White light interference
Atomic force microscopy
Zero-order fringe positioning
Hilbert transform

ABSTRACT

In white light interference based atomic force microscopy (WLIAFM), the vertical displacement of the probe is obtained by zero-order fringe positioning on the probe cantilever, so the accuracy of zero-order fringe positioning will affect directly that of the WLIAFM. However, due to non-uniform distribution of light intensity and photoelectric noises, accurate zero-order fringe positioning becomes a problem. In this paper, two algorithms are proposed to improve the zero-order fringe positioning accuracy. In the first algorithm which is called improved maximum algorithm, multi-row maximum positions of the interference fringes are obtained and error theory is applied to eliminate erroneous maximum positions, then the average of remaining maximum positions is used as the zero-order fringe position. Another is called phase evaluation algorithm, in which wavelet transform is applied to eliminate effects from disturbances mentioned above and Hilbert transform is used for phase evaluation to obtain the zero-order fringe position. The practicability and accuracy of the two algorithms have been verified by series of experiments. The experiment results indicate that both two algorithms are suitable in this condition and the phase evaluation algorithm has higher accuracy while the improved maximum algorithm has higher processing speed.

1. Introduction

White light interference based atomic force microscopy [1] is a novel atomic force microscopy (AFM) different from those based on optical beam deflection (OBD) [2]. Compared with AFM based on OBD, the vertical measurement range of open-loop contact mode of WLIAFM is much larger and the measurement speed can be greatly improved especially for 3D measurement with large vertical height. And the measurement result of WLIAFM can be traceable to optical wavelength, which can reach higher accuracy. In WLIAFM, the vertical displacement of the probe is obtained by analysis of white light interference fringes formed on the probe cantilever, and the accuracy of zero-order fringe positioning will affect directly that of the vertical displacement measurement of the probe and then the AFM measurement.

Maximum method [3], centroid method [4] and envelope fitting method [5,6] are common methods for zero-order fringe positioning in white light interference. Maximum method takes advantage of the characteristic of white light interference pattern that the light intensity is strongest at the zero-order fringe position. By directly extracting gray level of a row of the interference pattern, the position with maximum gray level is taken as the zero-order fringe position. Since it needs less calculation, the speed of the method is high. But the positioning accuracy can be greatly influenced by noise disturbances.

The ideal white light interference pattern is symmetrical relative to the zero-order fringe, so in centroid method the centroid position of the extracted gray curve from the interference pattern can be taken as the zero-order fringe position. Centroid method is fast since it needs a small amount of calculation and the positioning accuracy can be up to sub pixel, but it is sensitive to the noise and requires high symmetry of the interference patterns.

In envelope fitting method, envelop of the extracted gray curve of the interference pattern is solved by Hilbert transform, Fourier transform or wavelet transform, and the maximum position of the envelop curve is taken as the zero-order fringe position. The positioning accuracy of envelope fitting method can reach sub pixel, but the calculation error will be much larger when the interference patterns are asymmetric, and the speed is much lower since envelope fitting needs a large amount of data operation.

In current WLIAFM to obtain the vertical displacement of the probe, a row of interference signal is extracted from the white light interference pattern on the probe cantilever for zero-order fringe positioning. Since the probe cantilever is always deflected in the measurement process, the light distribution on the probe cantilever is non-uniform, and high fre-

* Corresponding author.
E-mail address: hustwenlong@mail.hust.edu.cn (W. Lu).

http://dx.doi.org/10.1016/j.optlaseng.2017.07.010
Received 7 November 2016; Received in revised form 6 July 2017; Accepted 25 July 2017
0143-8166/

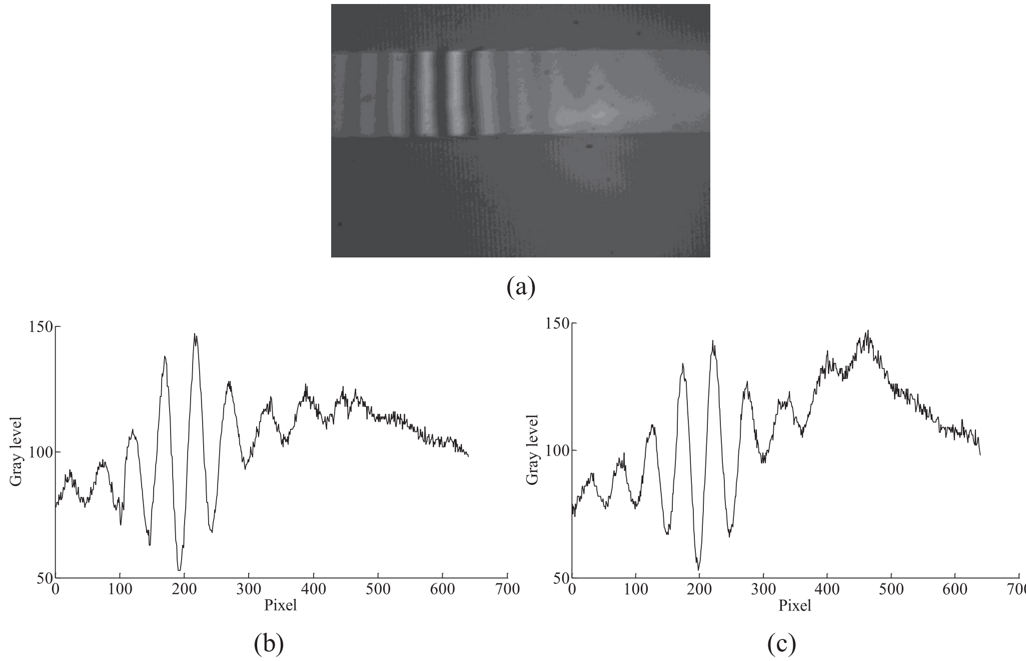

Fig. 1. The white light interference pattern and the extracted interference signals.

quency noises in the interference signals from the photoelectric devices and the miscellaneous light are inevitable. These factors will lead to the distortion of the interference signals and reduce the practicality of the common zero-order fringe positioning methods for WLIAFM.

To improve the zero-order fringe positioning accuracy in WLIAFM, two algorithms are proposed in this paper. One is called improved maximum algorithm. In this algorithm, maximum positions of multi-row interference signals on the probe cantilever are extracted and error theory [7] is applied to eliminate erroneous maximum positions caused by non-uniform distribution of light intensity, then the average of maximum positions excluding erroneous maximum is used as the zero-order fringe position, which can enhance the stability and improve the accuracy of the algorithm. Another is called phase evaluation algorithm, in which wavelet transform [8] combined with soft threshold filtering and homogenization is applied to eliminate the distortion of the interference signal, Hilbert transform is applied to evaluate the phase distribution [9], and then the zero-order fringe position is obtained by solving the zero-phase position. In this algorithm, it is unnecessary for the interference pattern to be symmetric, the influence of noises can be reduced greatly and high accuracy for zero-order fringe positioning can be reached. Series of experiments have been conducted to prove the advantages of the two algorithms.

2. Improved maximum algorithm

In WLIAFM for AFM measurement, zero-order fringe on the probe cantilever should be positioned to obtain the vertical displacement of the probe accurately. In theory, the zero-order fringe position is where light intensity is the maximum, and the zero-order fringe position can be determined according to light intensity distribution. Due to non-uniform distribution of light intensity and photoelectric noises on the white light interference pattern, as shown in Fig. 1, the extracted interference signal is liable to be skew and asymmetric and contains a lot of high frequency noises. So the zero-order fringe position will be wrongly determined by maximum method, which will result in erroneous maximum positions and severe positioning error.

To avoid the effects from erroneous maximum positions, in the proposed improved maximum algorithm, maximum positions of multi-row interference signals are extracted from the interference pattern and among which erroneous maximum positions are identified and eliminated by error theory, and the average of the remaining maximum positions is used as the zero-order fringe position.

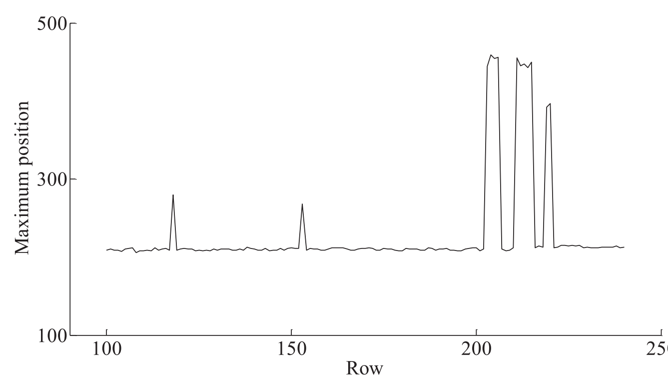

Fig. 2. Maximum positions of many rows of interference signals.

For example, for zero-order fringe positioning of the interference pattern in Fig. 1(a), many rows of interference signals on the probe cantilever are extracted, and by maximum method, many maximum positions x_i are first obtained which are shown in Fig. 2 and their residuals r_i are calculated. The expression for residuals is

$$r_i = x_i - \bar{x}. \tag{1}$$

With error theory applied to these residuals, gross errors are found and maximum positions with gross errors are eliminated. Finally the average of all maximum positions excluding gross errors is obtained as the zero-order fringe position. By the proposed algorithm, the influences of non-uniform distribution of light intensity and noises in the white light interference patterns on zero-order fringe positioning accuracy are suppressed largely, so the positioning accuracy is improved, while high speed is retained.

3. Phase evaluation algorithm

Phase analysis for interference pattern is a high precision measurement method [10]. In white light interference, zero-order fringe position