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计量型原子力显微镜的位移测量系统

李　伟，高思田*，卢明臻，施玉书，杜　华
（中国计量科学研究院，北京 100013）

摘要：针对纳米结构表征和纳米制造的质量控制需要，中国计量科学研究院设计并搭建了一台计量型原子力显微镜用于纳米几何结构的测量。为了将位移精确溯源到国际单位米，研制了单频 8 倍程干涉仪测量位移，样品表面形貌则由接触式原子力显微镜测量。一个立方体反射镜与原子力显微镜的测头固定，作为干涉仪的参考镜。两个互相垂直的干涉仪用于测量样品与探针在 x-y 方向的相对位置。样品台置于具有三面反射镜的零膨胀玻璃块上，由压电陶瓷位移台驱动。另外两台干涉仪测量样品与探针在 z 方向的位移，探针针尖位于干涉仪光束的交点以减小 Abbe 误差。由于光学器件的缺陷产生的相位混合会引起非线性误差，采用谐波分离法拟合干涉信号来修正误差，修正后干涉仪测量误差减小为 0.7 nm。

关　键　词：原子力显微镜；纳米计量；位移测量；多倍程干涉仪；非线性
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Position measuring system in metrological atomic force microscope

LI Wei, GAO Si-tian*, LU Ming-zhen, SHI Yu-shu, DU Hua

(*National Institute of Metrology*, *Beijing* 100013, *China*)
* *Corresponding author*, *E-mail*: *gaost@nim.ac.cn*

Abstract: For characterizing the nanostructure and controlling nano-manufacturing quality, a metrological Atomic Force Microscope(AFM) was designed and constructed in National Institute of Metrology. To trace the displacement to the SI unit, the relative position of sample and AFM probe is measured with homodyne 8-pass interferometers and the surface topology of the sample is measured by AFM at a contact mode. A cube with mirrors is fixed on the probe as the reference mirror of interferometers, so that the relative displacement of probe in the x-y direction to the sample is measured by interferometers. The sample stage is fixed on a corner block with mirrors on three sides and driven by a piezoelectric motion stage. Two interferometers is used to measure the displacement of sample and probe in z direction. The probe tip is positioned in the intersection of the interferometers in 3 directions to minimize the Abbe error. As the phase mixing from the defect of optical element will cause the nonlinear error, a harmonic separation method is introduced to fit the inteferometric signals and to correct the error. The measured results show that the nonlinear error has been reduced to 0.7 nm,

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which demonstrates this system has better performance.

Key words: atomic force microscope; nanometrology; displacement measurement; multi-pass interferometer; nonlinearity

1 Introduction

With the development of semiconductors industry and material research, metrological Scanning Probe Microscopes (SPMs) with high accuracy are increasingly demanded for characterization of nanostructure and quality control in nano-manufacturing. SPMs with metrological ability are developed and several national metrological institutes have begun to develop large range SPMs with metrological ability as standards[1-6]. A large range metrological Atomic Force Microscope (AFM) has been established in National Institute of Metrology.

Metrological SPMs are usually used to feature traceable position measurement. The displacement in SPMs can be measured by a capacity sensor that has been calibrated or interferometers. To trace the displacement to the SI directly, most of the metrological SPMs use interferometers to measure the displacement. To improve the resolution of interferometers, multi-pass methods and subdivision are applied.

Accurate topography needs to measure the relative displacement between sample and probe. Physikalish-Technische Bundesanstalt (PTB) set up a large range metrological AFM with commercial interferometers[7]. For sample scanning AFMs, the sample is moved, the probe position is stationary. Only the sample movements in 3 directions are measured. The interferometer has fixed reference mirrors in these metrological systems. For large range AFM in National Institute of Metrology (NIM), the probe also scans in small range. As a result, both the probe and sample positions require detecting simultaneously to obtain the relative displacement. A customized interferometer is suitable for the special purpose.

In this paper, the position measuring system for the large range AFM in NIM is introduced including the design and arrangement of the interferometers. In addition, a detail description of the interferometers, the nonlinearity correction are given. Then, the position measurement performance of the interferometer is demonstrated.

2 Experiment and method

2.1 Metrological frame

The metrological frame is constructed to measure the displacement between sample and probe in three directions by interferometers, so that the position is traced to SI. For both the sample and probe are scanning parts in the instrument and the metrological system is designed to measure the relative displacement of the sample and the probe. Specifically, the probe and sample displacements in z direction relative to the frame are measured respectively from top and down. And x and y displacement are measured relative to each other in a differential mode.

Figure 1 shows the arrangement of the interferometers of the metrological frame. The

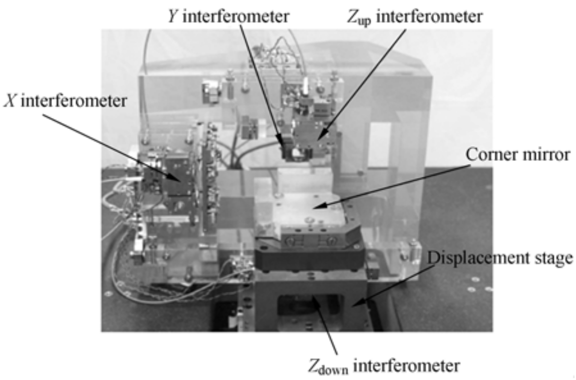


Fig. 1 Photo of metrological frame with interferometers

metrological frame is made from Zerodur and the mechanical parts of interferometer are made from Invar to reduce the thermal fluctuation.

The AFM probe is driven by a piezostage in three orthogonal directions. A cube with mirrors on three sides is fixed to the probe and scans with the probe as a whole. The sample stage is mounted on a corner mirror with high reflectivity on three sides. The mirror is driven by a nano-stage in x-y direction. The nano-stage is mounted on an air bearing 2-dimensional displacement stage with a displacement range of 50 mm×50 mm.

The displacement of the probe in z direction is measured by the z_{up} interferometer. The cube with three-side mirrors serves as a measuring mirror of the interferometer. To measure the relative displacement of probe in the x and y directions to the sample, the x and y interferometers use fold mirrors to direct the reference laser beam to the corner mirror. The sample displacement in z direction is measured by the z_{down} interferometer. The interferometers are mounted on the frame and supported with screws. All the measuring beams of the four interferometers are adjusted to construct a Cartesian coordinate system. The probe tip is positioned in the intersection of the interferometers to minimize the Abbe error.

2.2 Interferometers

All the interferometers use multi-pass schemes as shown in Fig. 2. The laser delivered from a polarization maintaining fiber is split into two linear polarized beams by a Palarizing Beam Splitter(PBS) and directed to the measurement and reference mirrors respectively. After passing quarter wave plates, the laser is changed to circular polarized. The laser beams are reflected back from the mirrors pass the wave plate again with the polarization rotated 90° and then combine at the PBS. Then the laser is reflected back to the PBS by right angle prism and then splitted again. The beams are directed to the mirrors. The paths repeat 4 times, and the incident points on the mirrors are 12 mm from the previous one.

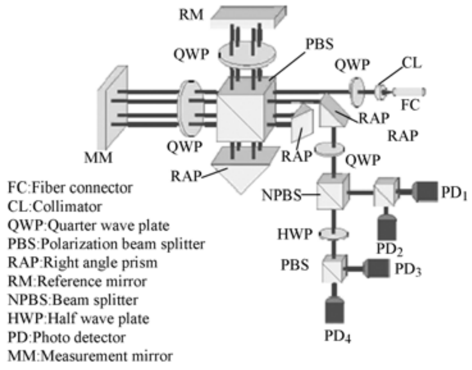


Fig. 2 Schematic of multi-pass interferometer

The output beam is detected by quadrate detection[8]. The beams pass a quarter-wave plate and are divided by a beam splitter into two channels. In the first channel, the beams are splitted by PBS and interfere on detectors PD_1 and PD_2. In the second channel, the phase difference of the two beams is shifted 90° by a half wave plate. Then the beams are splitted by the PBS and detected by PD_3 and PD_4. The signals of the 4 detectors have 90° phase delay with each other, and the signals can be expressed as follows:

$$\begin{aligned} U_1 &= R(1+\sin\theta) \\ U_2 &= R(1+\cos\theta) \\ U_3 &= R(1-\sin\theta) \\ U_4 &= R(1-\cos\theta) \end{aligned}, \qquad (1)$$

where R is the detector response, and θ is the phase difference between reference beam and measuring beam. The phase angle can be derived from the measured signals as

$$\theta = \arctan\frac{U_1 - U_3}{U_2 - U_4}. \qquad (2)$$

Then the difference of optical path length ΔL is obtained by $\Delta L = \theta\lambda/2\pi$. As the laser is frequency stabilized He-Ne laser, for eight-pass interferometer the cycle is $\lambda/8$, corresponding to 79 nm.

2.3 Signal processing electrics circuit

The ideal quadrate signals have the same amplitude with 90° phase delay. However, in practice, for the imperfect of the PBS, wave plate, and the alignment of the optics, the interference signals are not simply as those shown in Equ. (1). For these reasons, the signals have different amplitudes R, non-zero offsets p, and phase angles α, causing nonlinear errors. The distorted signal is pressed as:

$$\begin{aligned} U_1 &= p_1 + R_1 \sin(\theta + \alpha_1), \\ U_2 &= p_2 + R_2 \cos(\theta + \alpha_2), \\ U_3 &= p_3 - R_3 \sin(\theta + \alpha_3), \\ U_4 &= p_4 - R_4 \cos(\theta + \alpha_4). \end{aligned} \tag{3}$$

The nonlinearity of interferometer is one of the dominant errors. For single pass interferometers, Heydemann used elliptical equation to fit the quadrate signal and get the nonlinear coefficients, then the corrected phase was obtained[9]. However, the fitting procedure is time consuming. To derive the phase angle θ from signals above, gain adjustments are performed to correct nonlinear errors[10]. We used an analog circuit to correct the nonlinearity to eliminate the errors as shown in Fig. 3.

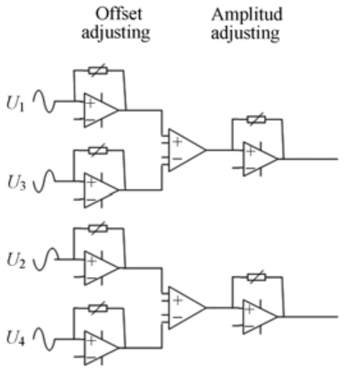


Fig. 3　Gain adjusting circuit of interferometer

Assuming k_i is the gain of the ith channel, the adjusted signals are expressed as

$$\begin{aligned} U_1' &= k_1 U_1 = k_1 R_1 \sin\theta \cos\alpha_1 + k_1 R_1 \cos\theta \sin\alpha_1 + k_1 p_1 \\ U_3' &= k_3 U_3 = -k_3 R_3 \sin\theta \cos\alpha_3 - k_3 R_3 \cos\theta \sin\alpha_3 + k_3 p_3. \end{aligned} \tag{4}$$

From Equ. (4), the DC offset can be eliminated by adjusting the gain when the conditions $k_1 p_1 = k_3 p_3$ and $k_2 p_2 = k_4 p_4$ are satisfied.

In our system, the signals are corrected by adjusted gain potentiometers in the circuit manually while monitoring the Lissajours figure of the signal to be a circle. By adjusting the gain of the interferometer signals with operation circuit, the DC components are eliminated and the signals are orthogonal and have equal amplitudes. The signal correction can also be implemented in real time.

For an ideal condition, the reference and measuring beams are separated in the interferometers and combined in the detector part. In multi-pass interferometers, the signals have components with different orders. In practical, the beams mix for the imperfect of the PBS and wave plate. The reference beam will leak to the measuring beam. And the optical path length is different from the single pass interferometers.

The gain correction method is suitable for single pass interferometers to eliminate the nonlinearity though the low order nonlinearities caused by multi-pass interferometers still exist.

2.4　Harmonic separation methods

In eight pass interferometers, the optics mixing results in harmonic components of different orders in the signal. The elliptical fitting is not applicable to the high order error. The harmonic separation is proposed to address the error of signal and to get the real phase difference[11].

The interferometer signal is expressed as summations of Fourier expansion as shown below:

$$\begin{cases} u_1 = a_{10} + \sum_{m=0}^{M/4} [a_{1(m+1)} \sin(\frac{\theta}{2^m}) + b_{1(m+1)} \cos(\frac{\theta}{2^m})] + \sum_{n=1}^{N} \{c_{1n} \sin[(n+1)\theta] + d_{1n} \cos[(n+1)\theta]\}, \\ u_2 = a_{20} + \sum_{m=0}^{M/4} [a_{2(m+1)} \sin(\frac{\theta}{2^m}) + b_{2(m+1)} \cos(\frac{\theta}{2^m})] + \sum_{n=1}^{N} \{c_{2n} \sin[(n+1)\theta] + d_{2n} \cos[(n+1)\theta]\}. \end{cases} \tag{5}$$

where a_{10}, a_{20} are constant term, M is the optical pass number. The second summation is the harmonic components of low frequency and the third term is that of high frequency.

The coefficients are determined by least square fitting after the optical configuration is fixed. Then from the model of the harmonic error components, the correct signals can be obtained. Instead of calculating the arctangent, the phase angle is interpolated by a look up table. It is noted that Heydemann correction only considers the DC offset and base frequency component in the harmonic components in Equ. (5).

3 Results

The performance of the interferometer is tested to investigate the nonlinearity correction methods. The sample stage is driven by the piezostage.

The output signals of detectors are distorted by nonlinear errors as shown in Fig. 4. The Lissajous figure of the detected signal without correction is ellipse and center of the ellipse is biased because of the DC components in signal. By using analog circuit operation, the offset and amplitude are adjusted so that the two signals are orthogonal and the offset is removed. The Lissajous figure becomes a circle centered at the zero point after correction.

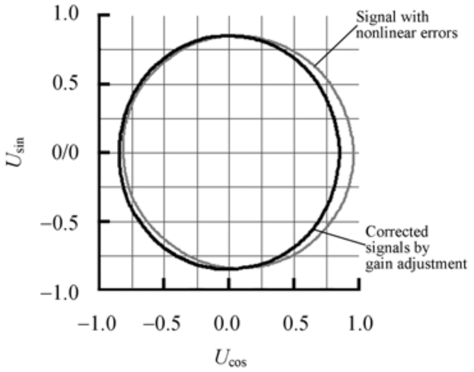
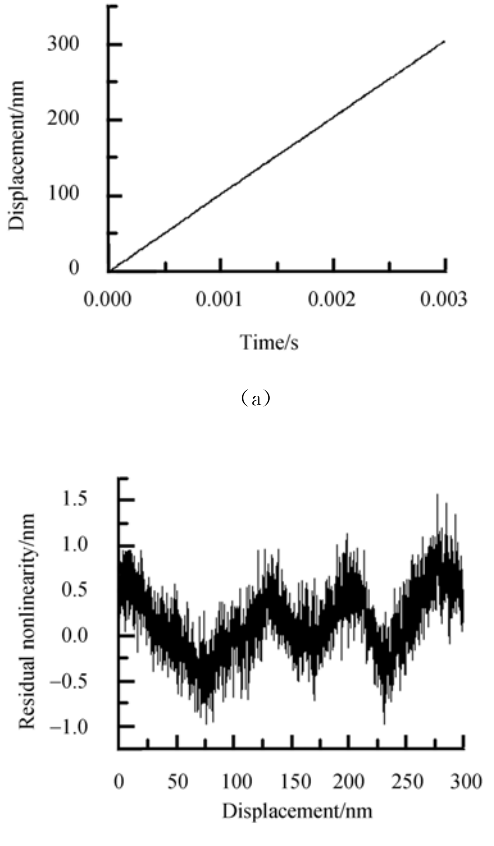


Fig. 4 Lissajous figures of interferometer signal U_{sin} and U_{cos}.

After the gain adjustment, the displacement of the stage is calculated from the phase angle θ measured by interferometers

$$x=\frac{\lambda\theta}{2\pi M}, \tag{6}$$



(a)

(b)

Fig. 5 Nonlinearity errors of interferometer in scanning

The displacement of the stage is linear during the scanning as shown in Fig. 5(a). The stage is driven at a speed of 0.1 mm/s and the speed measured from the displacement is consistent. Figure 5(b) shows the periodic residual nonlinearity with peak-to-peak amplitude of 2 nm. This is caused by the optical mixing of the interferometer mentioned above. The 80 nm pe-

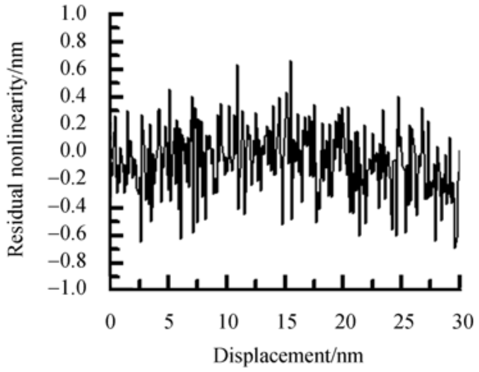


Fig. 6 Residual error of interferometer with harmonic separation correction

riod components is the main nonlinearity. To reduce the error, the harmonic components of different orders are separated. After correction by fitting the signal to Equ. (5), the harmonic coefficients are obtained. As shown in figure 6, the residual errors are reduced to peak-to-peak amplitude of 0.7 nm by harmonic separation methods. The periodic noise is eliminated and the error is a white noise.

4　Conclusions

A position measuring system is constructed as the metrological frame of a large range metrological AFM to measure the displacement of the sample stage and probe tip. Four interferometers establish a coordinate system and the relative displacements are measured in the differential mode. For multi-pass interferometers, the details of the nonlinearity are analyzed and harmonic separation method is adopted to correct the nonlinearity. By adjusting the gains of the signal and harmonic separation method, the nonlinear errors of interferometers are reduced to 0.7 nm.

In future work, the AFM measuring head will be used to scan samples and the metrological frame will measure the displacement of probe of the AFM and sample to detect the surface profile.

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Authors' biographies:

LI Wei, Ph. D. He was born in Shanxi province in 1981 and received the PhD degree in Department of Physics from Tsinghua University in 2010. He is currently a post doctor in National Institute of Metrology. His research interests include nanometrology and precision measurement. E-mail: liwei@nim. ac. cn

GAO Si-tian, PhD, research fellow at National Institute of Metrology (NIM). He received his MS degree from Xi'an Jiaotong University and his PhD degree from Tianjin University in 1984 and 2008 respectively. He worked at Physikalisch-Technische Budesanstalt as a visiting scholar from 1995 to 1997. He had been with Division of Length and Precision Engineering in National Institute of Metrology since 1984. Now he is a research fellow at NIM and also an Adjunct Professor at Beijing Institute of Technology. His current research interests include length metrology, nanotechnology and nanometrology. E-mail: gaost@nim. ac. cn

LU Ming-zhen, PhD. He received his PhD degree in 2010 in Department of Precision Instruments & Mechanology from Tsinghua University. He is an associate research fellow at National Institute of Metrology. His current research interest includes nanometrology. E-mail: lumzh@nim. ac. cn

SHI Yu-shu, He received his MS from China Jiliang University in 2008, and now is a research assistant in National Institute of Metrology. His research interests include length metrology, interferometry, and nanometrology. E-mail: shiys@nim. ac. cn

DU Hua, Senior Engineer. His research interests include geometry metrology and precision measurement. E-mail: duh@nim. ac. cn