Measurement of large step structure with a speed-variable scanning technology

Lei Lihua, Li Yuan, Cai Xiaoyu, Wei Jiasi, Fu Yunxia, Shao Li

(Shanghai Institute of Measurement and Testing Technology, Shanghai 201203, China)

Abstract: A white light interference system was developed with a speed-variable scanning technology to improve signal utilization precision and short measuring time for a large step structure measurement. A Fourier transform and unilateral step evaluation algorithm were performed for processing the scanning interference images. A calibrated standard step height of 9.976±0.028 μm was measured by the white light interference system using the speed-variable scanning method, the measuring time was 35 s, which was much shorter than a conventional measuring time of 222 s. A 10-times-repetitive-measurement shows a result of 9.971 μm with a standard deviation of 0.007 μm, illustrates that the system has accuracy and high-efficiency in the measurement of large step structure.

Key words: white light interference; speed-variable scanning; standard step height

CLC number: O435 **Document code:** A **DOI**: 10.3788/IRLA201746.0717003

基于变速扫描技术的大尺寸台阶测量

雷李华,李 源,蔡潇雨,魏佳斯,傅云霞,邵 力

(上海市计量测试技术研究院,上海 201203)

摘 要:为了提高大尺寸台阶结构的单边测量精度、缩短测量时间,基于变速扫描技术,并利用傅里叶变换提取法及单边台阶评价算法进行扫描干涉信号的处理,提出并搭建了具有变速扫描功能的白光干涉测量系统。并且利用该系统对标称值为 9.976±0.028 μm 的台阶标准样板进行了测量,10次重复性测量结果为 9.971 μm,标准偏差量为 0.007 μm,测量时间仅为 35 s,远小于常规扫描方法的 222 s,大大缩短了测量时间,因此说明了该系统在大尺寸台阶结构测量中,具有较高的精确性与高效性。

关键词:白光干涉; 变速扫描; 台阶标准样板

收稿日期:2016-11-15; **修订日期**:2016-12-19

基金项目:国家重大科学仪器开发专项(2014YQ090709)

作者简介:雷李华(1985-),男,博士,主要从事微纳米几何测量技术方面的研究。Email: leilh@simt.com.cn

通讯作者:邵力(1960-),男,教授,主要从事精密计量测试方面的研究。Email: shaol@simt.com.cn

0 Introduction

Rapid development in several high-tech industries, such as: semiconductor, photonics, micro electro mechanical system (MEMS), communications, micro-processing etc, has significantly increased the need for more complex three-dimensional (3D) information and larger surface regions with a nano-meter resolution [1]. There are several optical measurements methods, for example, grating projection with phase shift, moire with phase shift, confocal and white light interferometry [2-3]. In which, the white light interferometer allows generally surface profiling with high accuracy and can effectively avoid phase ambiguity errors, this means that the light interferometer is more suitable for the increased dimensional micro- and nano-metrology compared with other methods, a significant effort has been improved for the measuring range and measuring efficiency[4-6].

In this manuscript, a speed-variable scanning technique is introduced to improve the measuring efficiency of the white light interferometry. A Fourier transform method is used to process the interference images due to its advantage of high precision, and a unilateral step evaluation is performed for a large step height. A developed white light interference system based on nano-positioning and measuring machine (NMM) with a large scanning range is constructed in this manuscript. Micro scale standard step height and a 3D number pattern on the ink box are measured using the system.

1 Principle of white light interference

Using a broadband white light source, the unambiguous range of the output signal is no longer limited within half of a fringe, and an absolute phase measurement over a large operating range can be achieved. In addition, white light interference technique can effectively avoid phase ambiguity in phase-shifting interferometry and extend measurement range[7].

It is known that, in the output fringe pattern of such a system, the zero-order interference fringe is a bright fringe with maximum visibility [8]. Based on a two-beam interference method, zero-order interference fringe appears when there is no optical path difference between measurement and reference light[9-10]. The light intensity can be expressed as:

$$I(z)=I_1+I_2+2\sqrt{I_1I_2}\exp\left\{-\left[(z-h_0)\left(\frac{2\pi}{l_c}\right)\right]^2\right\}\cos\left[\frac{4\pi}{\lambda_c}(z-h_0)\right] \quad (1)$$

Where I_1 and I_2 are reference and background light, respectively. The intensity of background is denoted as $I_{bg}=I_1+I_2$ and fringe visiblity is denoted as $\gamma=2\sqrt{I_1I_2}/(I_1+I_2)$. The Gaussian envelope of white light interference is denoted as $g(z-h)=\exp\left\{-\left[(z-h)(2\pi/l_c)\right]^2\right\}$.

Considering an additional reflection phase, h represents the actual height of test sample, the white light interference output is written as:

$$I(z)=I_{bg}\left\{1+g(z-h)\gamma\cos\left[\frac{4\pi}{\lambda_c}(z-h)+\alpha_{\text{add}}\right]\right\} \quad (2)$$

One can observe from Eq.(2) that a white light interference signal is a cosine signal modulated by Gaussian function and the intensity of zero-order interference fringe reaches a maximum value. Based on white light interference principle, the coherent fringe position information represents just the corresponding data points of the test surface for the relative height information.

2 Fourier transform method

The zero-order interference fringe identification algorithm is a key for a white light interferometer to position the center of a bright fringe with maximum visibility. The positioning accuracy of test surface height information is directly decided by the processing algorithm of zero-order interference fringe. So far, the white light signal demodulation techniques can be basically categorized into two main groups: spatial domain algorithm and frequency domain algorithm. As a frequency domain algorithm of white light signal demodulation techniques, Fourier transform can perform the surface characterization with a higher resolution and precision compared with spatial domain algorithms, in which, the normalized output pattern of the white light interferometer is a cosine function modified by a Gaussian visibility profile. Fourier transform method is used in precision evaluation for the standard height steps and/or surfaces spatially isolated from one another with less evaluation data in this manuscript.

Actually , Eq. (2) can be expressed using the Fourier transform method[10] as shown,

$$FT[I(z)]=$$

$$2\pi I_{bg}\delta(k)+\frac{\gamma}{2\pi}\ FT[g(z-h)]*FT\left\{\cos\left[\frac{4\pi}{\lambda_0}(z-h)+\alpha_{\rm add}\right]\right\}=$$

$$2\pi I_{bg}\delta(k)+G(k)e^{-hkj}\gamma*$$

$$\left[\frac{1}{2}e^{\alpha_{\rm add}j-\frac{4\pi h}{\lambda_0}j}\delta\left(k-\frac{4\pi}{\lambda_0}\right)+\frac{1}{2}e^{-\left(\alpha_{\rm add}j-\frac{4\pi}{\lambda_0}j\right)}\delta\left(k+\frac{4\pi}{\lambda_0}\right)\right] \quad (3)$$

Where $\delta(k)$ is impulse function, $G(k)$ is the Fourier transform result of $g\ (z-k)$, * is symbol of convolution and spatial angle frequency is $k=2\pi/z$, $4\pi/\lambda_0$ represents the signal carrier angle frequency.

The positive frequency section of Eq. (3) is extracted and moved back to center of amplitude-frequency curve, after inverse Fourier transform, the positive frequency interference signal is expressed as:

$$IFT\left[\frac{\gamma}{2}e^{\alpha_{\rm add}j}G(k)e^{-khj}\right]=\frac{\gamma}{2}e^{\alpha_{\rm add}j}g(z)*\delta(z-h)=$$

$$\frac{\gamma}{2}e^{\alpha_{\rm add}j}g(z-h) \quad (4)$$

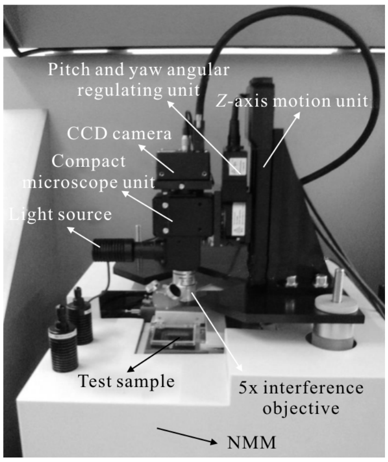
It can be seen that the envelope curve of white light interference is directly proportional to amplitude in Eq.(4). The correlation peak position is obtained by using Gaussian curve fitting for interference signal.

3 Measuring system setup

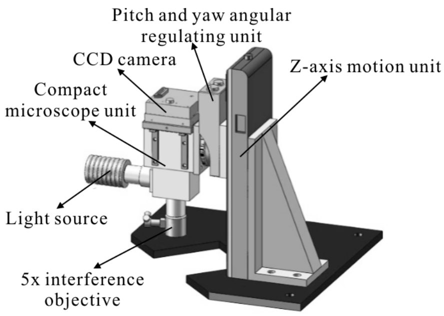
Figure 1(a) shows a newly developed white light interference system with large range. A white light interference probe works as a fixed surface-sensing probe, a nano-measuring machine (NMM, SIOS NMM-1) works as a scanning and measuring platform to drive the test sample in the whole measuring process[11-12]. Z-axis motion unit is used in the coarse position for an adjustment before the measurement. The vertical measuring range of the measuring system is only limited to the working distance of the motion driving platform and interference objective focal plane distance. Combined with a high precision, large range of scanning and measuring platform, the measurement system is more suitable for a high step standard and complex three-dimensional (3D) structure[13].

A white light interference probe is showed as Fig.1(b), which consist of a light source, a CCD camera (Basler A102 k, frame rate is 14.8-75 FPS, pixel size is 6.45 μm×6.45 μm with 1 392 pixel×1 040 pixel), a compact microscope unit (Nikon CM-30 A), 5 x Michelson interference objective (Nikon, 0.13 NA), Z-axis motion unit and angular unit used in the coarse position adjustment before the measurement. The white light interference probe allows fast parallel data collection using a CCD camera with an approximately two million points for a precise 3D information of semiconductor, photonics, MEMS. The white light interference probe can offer a non-destructive, non-contact, high density lateral resolution with extremely high sensitivities to the surface in the Z-direction, all of which are essential requirements for high volume manufacturing [14]. The lateral resolution is limited to 0.5-1 μm determined by the optical magnification, and CCD camera number and dimensions of pixels.

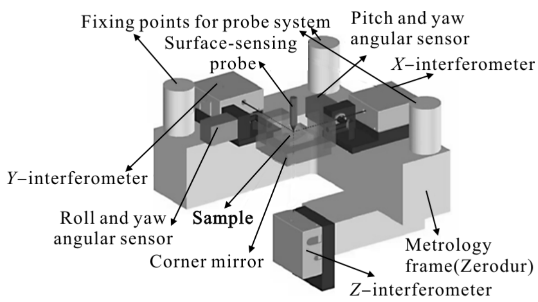
In order to have a high-speed, accurate and large range scanning and measuring, the NMM with a motion resolution of less than 0.1 nm, positioning uncertainty less than 8 nm for a measurement range of 25 mm×25 mm×5 mm and speed scanning <5 mm·s^{-1}, is designed as the motion driving and positioning table in the white light interference system[15-17]. As showed in Fig.1(c), a configuration of a zero Abbe offset arrangement with three plane mirror miniature interferometers and two adjusting angular sensors are used for highly accurate measurement[18]. The three perpendicular laser beams are directed towards a corner mirror on which the object to be measured.



(a) Structure diagram of a white light interference system with large range



(b) Configuration of a white light interference probe



(c) Configuration of positioning table of the NMM

Fig.1 Developed white light interference system

4 Speed-variable scanning method

The con ventional constant scanning method is that the information image is taken by CCD camera at a given scanning length while the test surface fixed in a short time, then the test surface is motioned again by the motion unit, another image is taken, and so on. Because complete measuring time is cumulated by the image sampling period, so the larger vertical scanning dimension the more consuming time.

To analyze the white light interference measurement process, the zero-order interference fringe area just appear in the images taken around the test sample top surface and bottom surface, while there is a large range with no interference fringe along the scanning direction.

The principle of a speed-variable scanning technology with preset areas mode is shown in Fig.2, there are three scanning phases with different rate along the scanning direction for a speed-variable scanning method. First of all, a range of zero-order interference fringe area of the top test surface as a start test surface needs to be recorded with white light interference measurement system. Then, the first scanning phase is a top fine scanning process using a low rate with a given step, and an image is taken by a CCD camera with time-lapse photography to eliminate th e position jitter. The top fine scanning area L_1 is set to be larger than the recorded range of zero-order interference fringe area for restoring the

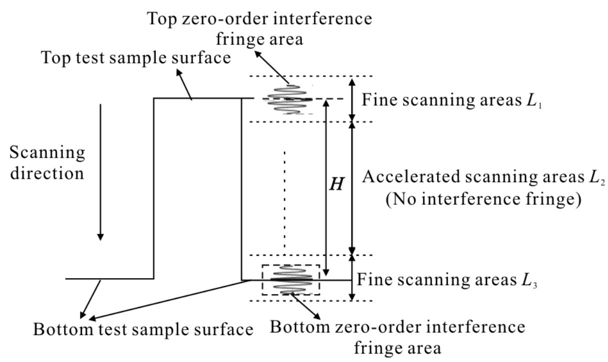


Fig.2 Principle of a speed-variable scanning technology for a large step height measurement

top test surface. The different length fine scanning area is set on a basis of the test surface roughness, tilt and objective magnification in the actual measurement process. The second scanning process without the interference fringe, is set to be an accelerated scanning process for a rapid motioning to the bottom fine scanning area, the accelerated scanning area L_2 is set to be smaller than a nominal step height. The third scanning process is a similar process with the first scanning phase. The zero-order fringe position of the bottom test surface is analyzed based on the images of bottom fine scanning areas L_3. Generally, L_3 is set to be larger length than L_1, because there are several uncertain factors and accumulated errors (such as surface parallelism error, calibration value error). The start and stop of each phase is controlled by the upper and lower limit of preset scanning areas length with a feedback motioning control of the NMM.

Nevertheless, because three scanning preset areas L_1, L_2, L_3 need to be set based on the range of zero-order interference fringe area and the height value of test sample, the speed-variable scanning method is main used in accurate repeatability measurement experiment with the uniform measuring parameters.

With a speed-variable scanning method, the scanning process is divided into the fine scanning process for acquiring the zero-order interference fringe information and accelerated scanning process, which is an effective way to improve the efficiency of measurement. Because the measurement time of the conventional constant scanning method are mainly consumed in the scanning process of the step side structure, the larger step height of measurement object can show the more prominent advantage of efficiency in practical measurement with the speed-variable scanning method[19]. And the more measuring precision is possible because the shorter measurement time means the lesser environment influence in the milli- and micro-meter measurement. Nevertheless, because the limitation of three scanning areas L_1, L_2, L_3 need to be set based on the preset recorded range of top zero-order interference fringe area and the nominal step height of test sample, the speed-variable scanning method is main used in large dimension structure in vertical direction and accurate repeatability measurement experiment with the uniform measuring parameters.

5 Unilateral step height evaluation

A larger vertical step height means a wider horizontal groove in step height structure with the limit of depth-to-width ratio. In a large step height measurement, the CCD cannot acquire the bilateral information image meeting the bilateral step height evaluation due to the CCD, hence, a unilateral step height evaluation needs to be developed for the evaluation of a unilateral step height structure. In our discussion, a unilateral step height evaluation is developed from the ISO 5 436-1-2 000, in which the step height value is constant, and the slop of fitting lines for the top and bottom of a standard step are identical and single.

The standard step height H of each profile can be deduced by the least squares method[20], in which,

$$y=\alpha x+\beta+\delta H \tag{5}$$

Where α is the slop of fitting line, β is constant. With unknowns α, β, H, is fitted by the method of least squares to a profile equal in length to two times the width of the groove. The variable δ takes the values +1 in region A and the value -1 in region B with the method of least squares as shown in Fig.3.

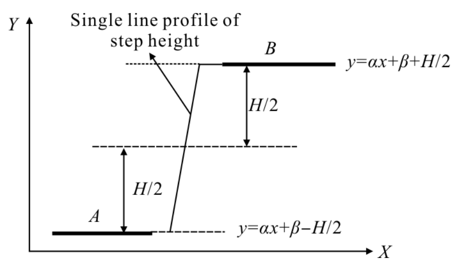


Fig.3 Schematic of a unilateral step height evaluation

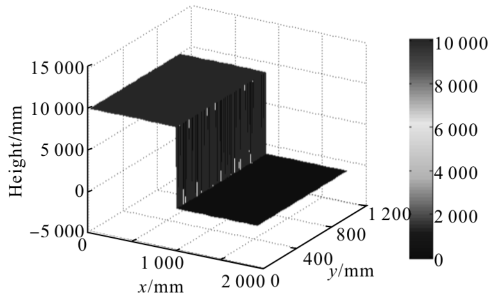
To avoid the influence of any rounding of the corners, the top and the bottom surface on sides of the groove shall be ignored for a given length. The portions to be used for assessment purposes are those shown at *A* and *B* in Fig.3. There are several profiles in a measurement area with the white light interference system. The step height value is average over the results of separate step height value for each profile is evaluated with the unilateral step height evaluation.

6 Experimental results

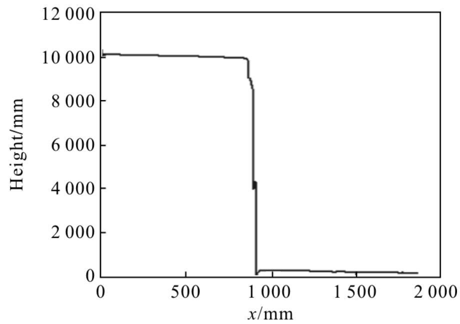
A 10 μm standard step height with a calibration value of 9.976 μm ±0.028 μm by PTB is measured using the white light interference system. Based on the proposed speed-variable scanning technology with preset areas mode, the scanning area of the 10 μm standard step height is divided into a top fine scanning area of 0.5 μm containing the whole zero-order interference fringe area of about 0.3 μm, an accelerated scanning area of 9.5 μm and a bottom fine scanning area of 1.0 μm.

In a fine scanning process, a scanning time is 0.5 s for a scanning step of 50 nm with a scanning rate of 0.1 μms^{-1}, and a time-lapse photography is 0.5 s, so an image sampling period is 1s. Hence, the top fine scanning process needs 10 s for 10 images, and the bottom fine scanning process needs 20 s for 20 images. The accelerated scanning process needs about 5 s without image taken using a canning rate of 2.5 μms^{-1} [21]. Based on the above calculation, it will need 35 s to take 30 images using the speed-variable scanning method for the analysis of the top and bottom zero-order fringe positions of the test standard step height surfaces. However, the time is 222 s with 220 images using a conventional scanning method [10,17] for a measurement length of 11.0 μm. The mean height of 10 times repetitive measurements is 9.971 μm with a standard deviation of 0.007 μm using the speed-variable scanning method, while the result is 9.984 μm with a standard deviation of 0.010 μm using the conventional constant scanning method.

It is obvious the speed-variable scanning method has a similar result with a conventional scanning method, however, the speed-variable scanning method reduces the consuming time largely. The results show that the white light interference system with speed-variable scanning technology will improve the measurement efficiency for a large step structure measurement [22]. The 3D structure and profile of a 10 μm standard step height are as shown in Fig.4.



(a) 3D topography reconstruction of standard step height



(b) Single profile of standard step height

Fig.4 Measurement result of the 10 μm standard step height

However, When the measured structures are continuous change with height or curved surface, the speed-variable scanning cannot be used in the measurement process. A number pattern '242' on the surface of ink box is measured to verify the ability of measuring complex micro/nano scale devices, and Fourier transform is adopted. As shown in Fig.5, the surface of ink box is not a flat area but a concave surface. This means a high precision, non-contact measurement and 3D surface reconstruction are achieved by the developed white light interference system.

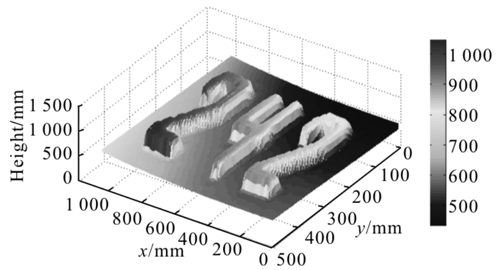


Fig.5 3D topography reconstruction of number on ink box

7 Conclusions

A white light interference system with speed-variable scanning technology has presented to improve signal utilization and reduce measuring time for a large step structure measurement, the Fourier transform and unilateral step height evaluation have adopted for processing the images acquired by CCD. The measurement results show that a measuring time of 35 s, which is much shorter than a measuring time of the conventional constant scanning method of 222 s, and a 10-times-repetitive-measurement of 9.971 μm with a standard deviation of 0.007 μm for a standard step height of 10 μm. This means the measurement with a speed-variable scanning method can short the measuring time largely with a high precision, compared with a conventional constant scanning method.

Acknowledgements

This work was financially supported by national key scientific instrument and equipment development projects of China (2014YQ090709).

References:

[1] Manske E, Jager G, Hausotte T, et al. Recent developments and challenges of nanopositioning and nanomeasuring technology[J]. ***Measurement Science & Technology***, 2012, 23 (7): 074001.

[2] Damian V S, Bojan M, Schiopu P, et al. White light interferometry applications in nanometrology [C]//Proceedings of SPIE - The International Society for Optical Engineering, 2009, 7297: 72971H.

[3] Laude B, Martino A D, Drevillon B. Three-dimensional microscopy through white light interferometry [C]// Proceedings of SPIE, 2002, 4621:1-7.

[4] Zhang J W, Belouadah R, Lebrun L, et al. Magnetoelectric phenomena of insulator polymers after corona poling: procedure and experiments [J]. ***Sensors & Actuators A Physical***, 2014, 220: 112-117.

[5] Gurov I, Volynsky M. White-light microscopy for evaluating transparent films using switching model of overlapped fringes [C]//American Institute of Physics, 2010: 295-300.

[6] Dai G, Pohlenz F, Xu M, et al. Accurate and traceable measurement of nano- and microstructures [J]. ***Measurement Science & Technology***, 2006, 17(3): 545-552.

[7] Chen S, Palmer A W, Grattan K T, et al. Digital signal-processing techniques for electronically scanned optical-fiber white-light interferometry[J]. ***Appl Opt***, 1992, 31(28): 6003-6010.

[8] Kino G S, Chim S S C. Mirau correlation microscope [J]. ***Applied Optics***, 1990, 29(26): 3775-3783.

[9] Hart M, Vass D G, Begbie M L. Fast surface profiling by spectral analysis of white-light interferograms with fourier transform spectroscopy [J]. ***Applied Optic***s, 1998, 37 (10): 1764-1769.

[10] Jiang Y. Fourier transform white-light interferometry for the measurement of fiber-optic extrinsic fabry-pérot interferometric sensors [J]. ***IEEE Photonics Technology Letter***s, 2008, 20(2): 75-77.

[11] Lei L, Deng L, Fan G, et al. A 3D micro tactile sensor for dimensional metrology of micro structure with nanometer precision[J]. ***Measurement***, 2014, 48(1): 155-161.

[12] Sun Y, Duthaler S, Nelson B J. Autofocusing in computer microscopy: selecting the optimal focus algorithm [J]. ***Microscopy Research & Techniqu***e, 2004, 65(3): 139-149.

[13] Harasaki A, Schmit J, Wyant J C. Improved vertical-scanning interferometry[J]. ***Applied Optics***, 2000, 39(13): 2107.

[14] O′Mahony C, Hill M, Brunet M, et al. Characterization of micromechanical structures using white-light interferometry[J]. ***Measurement Science & Technology***, 2003, 14(10): 1807-1814.

[15] Kramar J A. Nanometre resolution metrology with the molecular measuring machine [J]. ***Measurement Science & Technology***, 2005, 16(11): 2121.

[16] Schmidt, Hausotte, Gerhardt, et al. Investigations and calculations into decreasing the uncertainty of a

nanopositioning and nanomeasuring machine (NPM−machine) [J]. ***Measurement Science & Technology***, 2007, 18(2): 2026.

[17] Kapusi D, Machleidt T. White light interferometry in combination with a nanopositioning and nanomeasuring machine (NPMM) [C]//Proceedings of SPIE − The International Society for Optical Engineering, 2007, 6616: 661607.

[18] Hoffmann J, Weckenmann A. Traceable profilometry with a 3D nanopositioning unit and zero indicating sensors in compensation method [C]// Journal of Physics: Conference Series, 2005, 13:228.

[19] Subbarao M, Tyan J K. Selecting the optimal focus measure for autofocusing and depth−from−focus [J]. ***Pattern Analysis & Machine Intelligence IEEE Transactions on***, 1998, 20(8): 864−870.

[20] Misumi I, Gonda S, Kurosawa T, et al. Reliability of parameters of associated base straight line in step height samples: Uncertainty evaluation in step height measurements using nanometrological AFM[J]. ***Precision Engineering***, 2006, 30(1): 13−22.

[21] Lei L, Li Y, Deng X, et al. Laser −focused Cr atomic deposition pitch standard as a reference standard[J]. ***Sensors & Actuators A Physical***, 2015, 222: 184−193.

[22] Tibrewala A, Hofmann N, Phataralaoha A, et al. Development of 3D force sensors for nanopositioning and nanomeasuring machine[J]. ***Sensors***, 2009, 9(5): 3228−3239.