Measurements of Two-dimensional Gratings Using a Metrological Atomic Force Microscope with Uncertainty Evaluation

Jong-Ahn Kim[1,#], Jae Wan Kim[1], Chu-Shik Kang[1] and Tae Bong Eom[1]
1 Length/Time Group, Korea Research Institute Standards and Science, 1 Doryong-dong, Yuseong-gu, Daejeon, South Korea, 305-340
Corresponding Author / E-mail: jakim@kriss.re.kr, TEL: +82-42-868-5683, FAX: +82-42-868-5608

KEYWORDS : Metrological atomic force microscope, Nanometrology, 2-D grating, Uncertainty analysis

---

The pitch and orthogonality of two-dimensional (2-D) gratings were measured using a metrological atomic force microscope (MAFM), and the measurement uncertainty was analyzed. Gratings are typical standard devices for the calibration of precision microscopes. Since the magnification and orthogonality in two perpendicular axes of microscopes can be calibrated simultaneously using 2-D gratings, it is important to certify the pitch and orthogonality of such gratings accurately for nanometrology. In the measurement of 2-D gratings, the MAFM can be used effectively for its nanometric resolution and uncertainty, but a new measurement scheme is required to overcome limitations such as thermal drift and slow scan speed. Two types of 2-D gratings with nominal pitches of 300 and 1000 nm were measured using line scans to determine the pitch measurement in each direction. The expanded uncertainties ($k = 2$) of the measured pitch values were less than 0.2 and 0.4 nm for each specimen, and the measured orthogonality values were less than 0.09° and 0.05°, respectively. The experimental results measured using the MAFM and optical diffractometer agreed closely within the expanded uncertainty of the MAFM. We also propose an additional scheme for measuring 2-D gratings to increase the accuracy of calculated peak positions, which will be the subject of future study.

Manuscript received: December 18, 2007 / Accepted: December 31, 2007

1. Introduction

Nanometrology, a key component of nanotechnology, deals with dimensional metrology in which the critical dimension is less than 100 nm. Measurement techniques in nanometrology rely mainly on precision microscopes and require nanometric resolution along with a measure of the uncertainty.[1,2] Precision microscopy plays an important role in biotechnology, in which objects are frequently the size of cell. Scanning electron microscopy (SEM), transmission electron microscopy (TEM), and scanning probe microscopy (SPM), which all use typical precision microscopes in biotechnology, have nanometric resolution, but they must be calibrated to measure dimensional values with high accuracy. Precision displacement sensors such as laser interferometers or capacitive sensors can be used to increase accuracy, but this is difficult and costly. Therefore, this type of work is most often performed in the National Measurement Institute such as NIST and PTB, while industries generally choose indirect methods using calibrated standard objects such as gratings and step height specimens.

Grating specimens are widely used to calibrate the lateral magnification of precision microscopes.[3,4] They can be classified as one-dimensional (1-D) and two-dimensional (2-D) gratings with periodic structures in one or two axes. Most precision microscopes measure 2-D images so their magnification in two axes and the orthogonality between the two axes must be calibrated. Hence, to improve microscope performance, it is important to establish a calibration system for 2-D gratings with metrological traceability.

Two-dimensional gratings are usually calibrated using an optical diffractometer (OD)[5,6] or a metrological atomic force microscope (MAFM).[7-9] The OD has very high precision but measures only the average pitch value. The MAFM can obtain average and individual pitch values as well as the surface profile of the specimen. Therefore, these methods can complement each other in the calibration of 2-D gratings.

In this paper, we present a new measurement scheme for 2-D gratings tailored to the performance and limitations of the MAFM. This required adding a precision rotational stage and a peak search process to the MAFM. We measured two types of 2-D gratings and evaluated the measurement uncertainty. We verified the validity of the proposed method by comparing the results with values measured by an OD.

2. Instrument and Procedures

2.1 Metrological AFM

Our MAFM consists of an AFM head module, nanoscanners, a two-axis laser interferometer, and a control/data-processing module (Fig. 1). The tube-type scanner of the commercial AFM head module was replaced by flexure nanoscanners to improve the metrological capabilities, and the displacement of the x-y

nanoscanners was measured using a two-axis laser interferometer with a resolution of 1.24 nm. The measurement range of the MAFM is 100 × 100 × 12 μm ($x \times y \times z$) and the expanded uncertainty ($k = 2$) in the measurements of the lateral displacement L is $\sqrt{(4.2\,\mathrm{nm})^2+(2.8\times10^{-4}\times L)^2}$ with a confidence level of approximately 95%.[9]

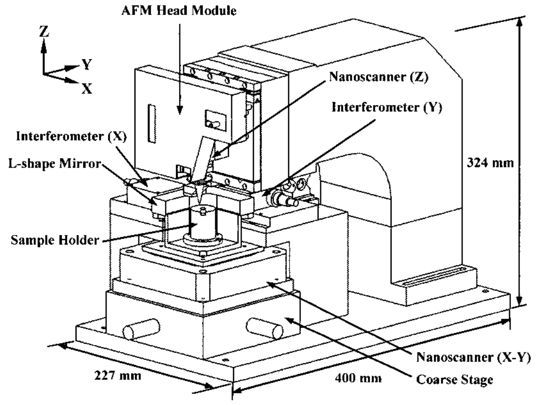

Fig. 1 Schematic diagram of the MAFM at the Korea Research Institute of Standards and Science (KRISS)

2.2 Measurement of Two-dimensional Gratings

The parameters of interest in the measurement of 2-D gratings are the average pitch values in the x- and y-axis directions (p_x, p_y), and the orthogonality between the two pitch directions (α), as shown in Fig. 2. We consider two types of measurement methods for 2-D gratings. One uses a 2-D scan profile and 2-D data-processing algorithm. The other uses a 1-D line scan profile and a procedure similar to that used in measuring a 1-D grating. The choice of measurement method is closely related to the performance of the measurement instrument being used.

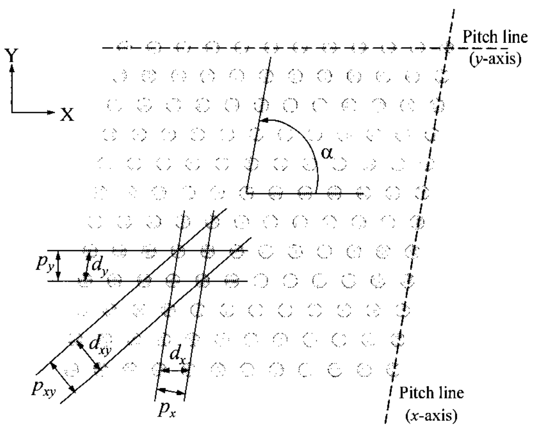

Fig. 2 Two-dimensional grating measurement parameters

The 2-D fast Fourier transform (FFT) is a typical 2-D processing algorithm, which requires a 2-D scan profile acquired at uniformly spaced positions for the calculation of the measurement parameters. However, since the calculation accuracy is affected by the amount of data involved in the calculation, increasing the scan range and number of data points also increases the measurement time. The MAFM should have high thermal stability and scan speed to reduce the thermal drift during a 2-D scan process.

Our MAFM has a drift of 1.6 nm/min, and its scan speed should be limited to about 2 μm/s to minimize image distortion.[9] When a 2-D scan image is acquired over 40 x 40-μm area at a resolution of 2048 x 2048, the total measurement time is about 680 min and the drift of the measured displacement in the slow scan axis is more than 1 μm. If the scan range and number of data points are increased for higher accuracy, the measurement time and drift increase accordingly.

Therefore, we chose the second method for the measurement of 2-D gratings, the method similar to that used in the measurement of 1-D gratings.

Several other considerations and preprocessing steps are involved. Because a 2-D grating has two perpendicular pitch lines as shown in Fig. 2, the rotational angle of the grating and the start point of each scan line must be adjusted precisely so that the MAFM scans can follow the peak positions of each pitch line.

We added a precision rotation stage to align the 2-D grating with the MAFM scan lines (Fig. 3).

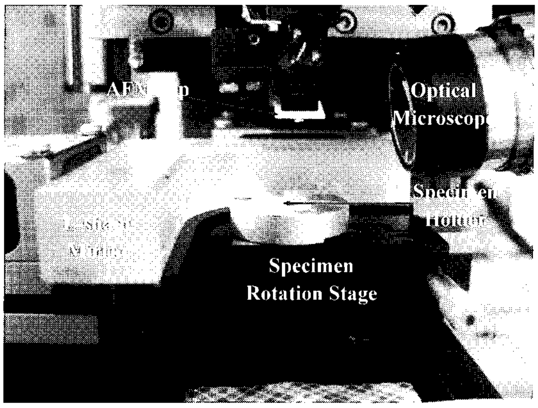

Fig. 3 Precision rotation stage for the rotational alignment of specimens

The precision rotation stage is composed of a micrometer and a flexure hinge structure designed so that the center of rotation is coincident with the tip of the MAFM. The adjustment range of the stage is ±5° and its resolution is less than 0.016°. The required accuracy in rotational angle alignment increases according to the scan range increment and the decrease in the grating pitch, since the scan line should not deviate from one pitch line. For example, when a 2-D grating with a nominal pitch of 300 nm is measured using a line scan of 100 μm, the limit angle alignment error can be calculated geometrically as 0.16°, which is the maximum error before a scan line deviates from one pitch line. However, the alignment error should be much less than this limit to obtain an accurate surface profile.

To determine the start position of the scan line, we require a search process for the peak position of the periodic structures making up the pitch lines. This is determined from a 2-D scan image of a small area that includes at least one periodic structure in the central area. The peak position can be determined using a 2-D peak-finding algorithm such as the center of gravity method, and this position is assigned to be the start position of a scan line.[10]

2.3 Average Pitch

The average pitch value of the 2-D grating was calculated by analyzing the surface profiles of the specimen, which were obtained from line scans along each pitch direction. As noted above, the fine alignment of the rotational angle of the specimen and the start position of line scan are necessary to measure the surface profile accurately. The procedure for calculating the rotational angle and the preprocessing to determine the average pitch were the same for the 1-D grating.[10] However, in case of the 2-D grating, the average pitch value obtained using the line scan profiles is the average distance between periodic structures consisting of each pitch line as shown in Fig. 2. Therefore, the average distance (d_x, d_y) is slightly different from the actual average pitch (p_x, p_y) due to the deviation of orthogonality (α) from 90°, and their relationship can be expressed as

$$\begin{aligned} p_x &= d_x \sin\alpha \\ p_y &= d_y \sin\alpha \end{aligned} \tag{1}$$

Considering this relationship, the average pitch value p in each direction is calculated as[10]

$$p = \frac{1}{M}\sum_{i=1}^{M}\frac{L_i}{N_i}C_sC_t\sin\alpha = \frac{1}{M}\sum_{i=1}^{M}\frac{L_i}{N_i}\frac{\cos\theta_z}{\cos\theta_y}\left[1-\alpha_m(t-20)\right]\sin\alpha \tag{2}$$

where M is the number of measurement positions, L_i is the displacement between the first and the last peak positions at the ith measurement position, N_i is the number of pitches included in the ith scan line profile, C_s is the compensation coefficient for the cosine error, C_t is the compensation coefficient for the temperature deviation, θ_z is the rotation angle of the specimen, θ_y is the inclination angle of the specimen, α_m is the thermal expansion coefficient of the specimen, and t is the temperature of the specimen.[10]

2.4 Orthogonality

The average distance between periodic structures in the diagonal direction (d_{xy}) is also required to calculate the orthogonality using the 2nd cosine law (Fig. 2). The measurement procedure for d_{xy} is similar to the other pitch directions, and three average distances (d_x, d_y, d_{xy}) are used in Eq. (3) to obtain the orthogonality of the 2-D grating:

$$\alpha = \cos^{-1}\left(\frac{d_x^2 + d_y^2 - d_{xy}^2}{2d_xd_y}\right) \tag{3}$$

where α is the orthogonality of the specimen and d_x, d_y, and d_{xy} are the average distance between periodic structures in the x-, y-, and diagonal directions, respectively.

3. Uncertainty Analysis

3.1 Average Pitch

The uncertainty in the measurement of the average pitch was evaluated according to the Guide to the Expression of Uncertainty of Measurement (GUM).[11] If we apply the law of propagation of uncertainty to Eq. (2), which is a mathematical model, the combined standard uncertainty in the average pitch measurement $u_c(p)$ can be summarized as[10]

$$u_c^2(p) = \left(\frac{C_sC_t}{N}\right)^2\left[a^2 + u^2(L_p) + u^2(L_r) + u^2(L_u)\right] + \left[b^2 + \frac{u^2(C_s)}{C_s^2} + \frac{u^2(C_t)}{C_t^2} + \frac{u^2(\alpha)}{\tan^2\alpha}\right]p^2 \tag{4}$$

where a and b are the terms representing the uncertainty in the displacement measurement using the MAFM expressed as $\sqrt{a^2 + b^2L^2}$. The a represents the root mean square of the standard uncertainty components not related to the measured displacement, and b is the root mean square of the coefficients multiplied by L to construct the standard uncertainty components proportional to the measured displacement.[10] These standard uncertainty terms can be explained as follows: $u(L_p)$ is the uncertainty in the peak finding process, $u(L_r)$ is the uncertainty caused by the repeatability of the displacement measurement, $u(L_u)$ is the uncertainty caused by the nonuniformity of the specimen, $u(C_s)$ is the uncertainty of the compensation coefficient for the cosine error, $u(C_t)$ is the uncertainty of the compensation coefficient for the temperature deviation, and $u(\alpha)$ is the uncertainty of orthogonality.

The uncertainty in the measurement of the average distance between pitch structures $u_c(d)$ can be obtained through a similar process as

$$u_c^2(d) = \left(\frac{C_sC_t}{N}\right)^2\left[a^2 + u^2(L_p) + u^2(L_r) + u^2(L_u)\right] + \left[b^2 + \frac{u^2(C_s)}{C_s^2} + \frac{u^2(C_t)}{C_t^2}\right]d^2 \tag{5}$$

3.2 Orthogonality

We use Eq. (3) as a mathematical model and apply the law of propagation of uncertainty to calculate the uncertainty in the measurement of orthogonality.[11]

$$u_c^2(\alpha) = \left(\frac{\partial\alpha}{\partial d_x}\right)^2u^2(d_x) + \left(\frac{\partial\alpha}{\partial d_y}\right)^2u^2(d_y) + \left(\frac{\partial\alpha}{\partial d_{xy}}\right)^2u^2(d_{xy}) \tag{6}$$

The orthogonality is computed using the average distance between pitch structures. Therefore, the uncertainty in the measurement of average distance will be the main source of uncertainty.

4. Experiments

4.1 Experimental Procedure

Two 2-D grating specimens were used in the experiment. One was the 2D300 (Moxtex) and the other was the 2D1000 (Ibsen). Their nominal pitch values are 300 nm and 1000 nm, respectively, with a nominal orthogonality of 90°. The measurement procedure of a 2-D grating is similar to that of a 1-D grating. However, we cannot obtain an accurate scan profile over the entire scan range without precisely adjusting the start position of the line scan and the alignment of the rotational angle of the specimen because the pitch lines of 2-D gratings are not continuous as they are in 1-D gratings.

First, the rotational angle of the specimen was coarsely adjusted using a small area 2-D scan, so that the scan line (x-axis) was parallel to a pitch line. Fine alignment took place using the following procedure. Ten line scan profiles were obtained at intervals of a multiple of the average pitch value in the y-direction. The rotational angle of the specimen was calculated by analyzing the obtained profiles and compensated by adjusting the fine rotational stage.[10] This fine alignment process was repeated until the rotational angle of the grating was less than the resolution of the stage.

Through this angle alignment process, the measured pitch line was aligned with the x-axis of the MAFM. The average pitch values were measured at nine different locations distributed in a uniform 3 × 3 grid pattern near the center of the specimens. A line scan profile in the 95 μm range was obtained at each measurement point and the peak positions were determined using the peak-finding algorithm. These peak positions were used in Eq. (2) to calculate the average pitch values in each direction.[10]

4.2 Uncertainty Evaluation

Table 1 shows the contribution of each source of uncertainty to the overall uncertainty in the measurement of x-axis average pitch. The contribution is obtained by multiplying the sensitivity coefficient by the standard uncertainty, and this represents the relative importance of each uncertainty source. The evaluation method of each standard uncertainty is similar to the case of 1-D gratings.[10]

The sensitivity coefficients shown in Eq. (4) can be separated into two groups. One is divided by the individual pitch number N, and the other is multiplied by the nominal pitch value p. Since the same scan range ($\approx N \times p$) was applied to the measurement of each specimen, N and p were inversely proportional to each other. Therefore, if a similar condition is applied to the pitch measurement, the individual pitch number N increases and the averaging effect reduces the measurement uncertainty according to the decrease in the nominal pitch value p. However, the repeatability of the pitch measurement and the nonuniformity of specimens are more closely related to the quality of the specimen than to the magnitude of the nominal pitch.

As shown in Fig. 4, the major sources of uncertainty are the uncertainty in the length measurement, the repeatability, the nonuniformity of the specimen, and the uncertainty in the peak-finding process. The contributions from the uncertainty terms in the length measurement of the MAFM, a and b, are proportional to the nominal pitch value.[10] However, the uncertainty contributions due to the quality of the specimen have similar values in both cases. This is due to the lower quality of the 2D300 although we expected to obtain a higher averaging effect for the larger individual pitch number N.

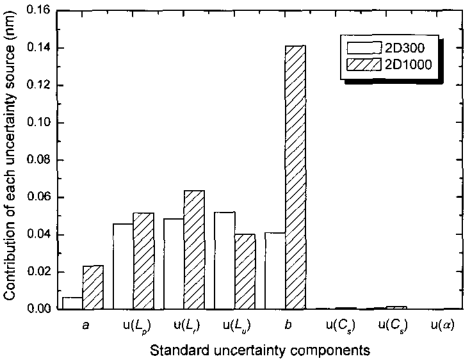

Fig. 4 Comparison of the contribution of each source of uncertainty to the overall uncertainty in the measurement of p_x

The uncertainty contribution due to the peak-finding process is greater for 2-D gratings than for 1-D gratings.[10] The line scan profiles of gratings usually have periodic patterns, such as sinusoidal or rectangular waves. Thus, in the ideal case, two peak-finding algorithms such as the center of gravity method and the zero-crossing method would give identical results. However, since the measured profiles actually deviate from the ideal pattern, the peak positions calculated using the two peak-finding methods are not identical and this is a source of measurement uncertainty. In the measurement of 2-D gratings using the proposed method, if some error exists in the alignment of the rotational angle or the start position of the line scan, the scan line will not track the peak of the pitch patterns exactly, and the obtained profile deviates more seriously from the ideal profile. Therefore, the uncertainty in the peak-finding process is greater for the measurement of 2-D gratings than for 1-D gratings.

The measurement of 2-D gratings with a smaller pitch requires more accuracy in the alignment of the rotational angle and the start position of the line scan. In that case, we can use a 2-D area scan with a limited scan range in the y-axis rather than a 1-D line scan to calculate the peak position more accurately. The scan range in the x-axis (fast scan axis) is sufficiently increased to obtain the averaging effect and that of the y-axis (slow scan axis) is limited to include one complete pitch line. The uncertainty caused by the inaccuracy of peak-finding and the drift of the MAFM can be minimized by using a long narrow 2-D area scan.

Table 2 shows the uncertainty in the orthogonality measurement. The uncertainty in the measurement of the average distance between pitch structures was smaller for the 2D300 than for the 2D1000. However, the sensitivity coefficients c_i include a reciprocal of the average distance and thus the contribution of each source of uncertainty is affected by the relative uncertainty in the measurement of average distance. Thus, the orthogonality measurement of the 2D1000 has a smaller uncertainty than that of the 2D300.

Table 2 Uncertainty in α measurements of the 2D300 and 2D1000 using the MAFM

	Contribution of each uncertainty source $u_i(p_x) \equiv \lvert c_i \rvert\, u(x_i)$ (rad)		
Specimen	$u(d_x)$	$u(d_y)$	$u(d_{xy})$
2D300	3.24×10^{-4}	3.52×10^{-4}	6.13×10^{-4}
2D1000	1.69×10^{-4}	1.59×10^{-4}	3.18×10^{-4}

The measurement results of 2-D gratings using the MAFM and OD are shown in Figs. 5–7. We compared the measured results and the expanded uncertainty (k = 2) obtained using each instrument. The uncertainties in the case of OD are usually one-tenth that of the MAFM,[6] and the accuracy of the MAFM can be demonstrated through these comparisons. The measured values coincided with each other within the expanded uncertainties of the results measured by the MAFM.

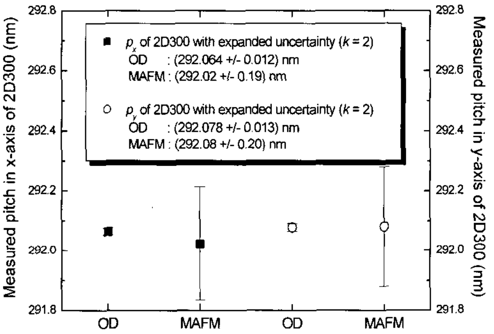

Fig. 5 Measured average pitch values (p_x, p_y) of the 2D300 using the MAFM and OD

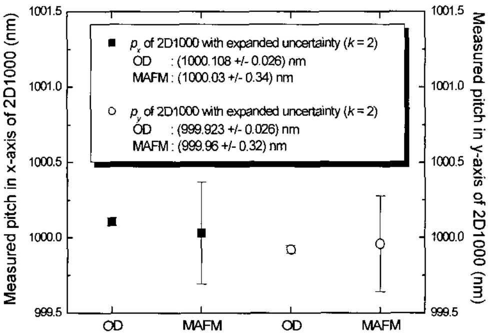

Fig. 6 Measured average pitch values (p_x, p_y) of the 2D1000 using the MAFM and OD

Table 1 Uncertainty in p_x measurements of the 2D300 and 2D1000 using MAFM

	Contribution of each uncertainty source, $u_i(p_x) \equiv \lvert c_i \rvert\, u(x_i)$ (nm)							
Specimen	a	$u(L_p)$	$u(L_r)$	$u(L_u)$	b	$u(C_s)$	$u(C_t)$	$u(\alpha)$
2D300	6.49×10^{-3}	4.56×10^{-2}	4.82×10^{-2}	5.19×10^{-2}	4.10×10^{-2}	2.13×10^{-4}	4.36×10^{-4}	1.36×10^{-4}
2D1000	2.33×10^{-2}	6.36×10^{-2}	4.00×10^{-2}	5.16×10^{-2}	1.41×10^{-1}	8.26×10^{-4}	1.28×10^{-3}	5.81×10^{-6}

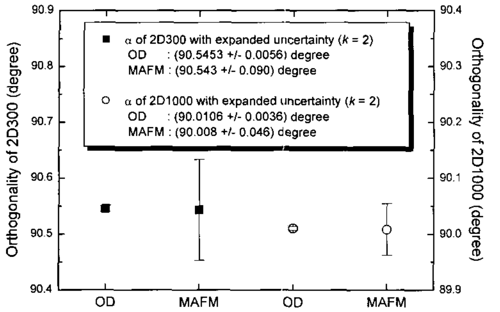

Fig. 7 Measured orthogonality (α) of the 2D300 and 2D1000 using the MAFM and OD

5. Conclusions

We measured the average pitch and orthogonality of 2-D gratings using the MAFM and evaluated the measurement uncertainty. We devised a new measurement method for 2-D gratings that takes into account the limitation of the measurement system and the angular alignment of the specimen. This method required finding the peak position. We measured 2-D gratings with nominal pitches of 300 nm and 1000 nm and estimated the contribution of each source of uncertainty. The expanded uncertainties (k = 2) of measured pitch values were 0.2 nm and 0.4 nm and those of measured orthogonality values were less than 0.09° and 0.05° for the 2D300 and 2D1000, respectively. The values measured with our method agreed closely within the expanded MAFM uncertainties with the measurements made using the OD. This shows that the MAFM can be used as an effective tool for the calibration of 2-D gratings.

REFERENCES

1. Teague, E. C., "Nanometrology," Proc. AIP Conference on Scanned Probe Microscopy, Vol. 241, pp. 371-407, 1991.
2. Carneiro, K., "The need for metrology in nanotechnology," Danish Institute of Fundamental Metrology, pp. 1-5, 2001.
3. Postek, M. T., Vladar, A. E., Jones, S. N. and Keery, W. J., "Interlaboratory study on the lithographically produced scanning electron microscope magnification standard prototype," Journal of Research of the National Institute of Standards and Technology, Vol. 98, No. 4, pp. 447-467, 1993.
4. Nakayama, Y., Okazaki, S. and Sugimoto, A., "Proposal for a new submicron dimension reference for an e-beam metrology system," Journal of Vacuum Science and Technology B, Vol. 6, No. 6, pp. 1930-1933, 1988.
5. Meli, F., Thalman, R. and Blattner, P., "High precision pitch calibration of gratings using laser diffractometry," First International Conference and General Meeting of the Euspen Society for Precision Engineering and Nanometrology, pp. 252-255, 1999.
6. Kim, J. A., Kim, J. W., Park, B. C., Kang, C. S. and Eom, T. B., "Measurement of grating pitch standards using optical diffractometry and uncertainty analysis," Journal of the Korean Society for Precision Engineering, Vol. 23, No. 8, pp. 72-79, 2004.
7. Meli, F. and Thalmann, R., "Long-range AFM profiler used for accurate pitch measurements," Measurement Science and Technology, Vol. 9, No. 7, pp. 1087-1092, 1998.
8. Misumi, I., Gonda, S., Kurosawa, T. and Takamasu, K., "Uncertainty in pitch measurements of one-dimensional grating standards using a nanometrological atomic force microscope," Measurement Science and Technology, Vol. 14, No. 4, pp. 463-471, 2003.
9. Kim, J. A., Kim, J. W., Park, B. C., Eom, T. B. and Hong, J. W., "Development of a metrological atomic force microscope for the length measurements of nanometer range," Journal of the Korean Society for Precision Engineering, Vol. 21, No. 11, pp. 75-82, 2004.
10. Kim, J. A., Kim, J. W., Park, B. C., Eom, T. B. and Kang, C. S., "Pitch measurement of one-dimensional gratings using a metrological atomic force microscope and uncertainty evaluation," Journal of the Korean Society for Precision Engineering, Vol. 22, No. 4, pp. 84-91, 2005.
11. BIPM, IEC, IFCC, ISO, IUPAC, IUPAP and OIML, "Guide to the Expression of Uncertainty in Measurement," ISO, 1993.