An imaging grating diffractometer for traceable calibration of grating pitch in the range 20 µm to 350 nm

D A Brasil¹, J A P Alves¹, J R Pekelsky²

¹Dimensional Metrology Laboratory (Lamed), Mechanical Metrology Division (Dimec), Directory of Scientific and Industrial Metrology (Dimci), National Institute of Metrology, Quality and Technology (Inmetro), Av. Nossa Senhora das Graças, 50, Xerém, Duque de Caxias, RJ, Brazil, ZIP 25250-020
²Canadian Dimensional Metrology, Ottawa, Canada

E-mail: dabrasil@inmetro.gov.br

Abstract. This work describes the development of a grating diffratometer to provide traceable calibration of grating pitch in range 20 µm to 350 nm. The approach is based on the Littrow configuration in which a laser beam is directed onto the grating which is mounted on a rotary table and can be turned so that each selected diffraction order is retro-reflected in the laser incidence direction. A beamsplitter and a lens direct the reflected diffraction order to form a small image spot on a CCD camera and the spot centering is used to adjust the rotation angle, thereby giving the diffraction angle. Knowing the diffraction angle for several orders and the wavelength of the laser, the average grating pitch can be determined to an uncertainty the order of 14 pm.

1. Introduction

EURAMET is an important Regional Metrology Organization (RMO), which forecasts technology market demands and makes roadmaps of quantities. Its length metrology committee is always looking for ways of develop methodologies capable to deal with measurements of dimensions that get smaller and smaller each day [1]. This is because industrial processes need tighter tolerances to improve quality and performance. As a consequence, eventually, National Metrology Institutes (NMIs) face paradigm breaks whenever new technologies emerge, so they need to implement different methodologies to measure with higher precision.

Optical instruments have experienced a huge development in the last decades with the parallel improvements in microelectronics and automation as well as the incorporation of digital image processing [2-3]. No matter how technological is the instrument, it needs to be calibrated to keep up with the international standardization. Regarding optical instruments, in general they need special gages on which there are engraved lines in one or two dimensions, regularly spaced in dimensions in the micrometric order. They are called diffraction gratings and are shown in figure 1 and are characterized by its average pitch which is calculated over the full area of the surface of the grating. For the calibration of pitch of this order of magnitude, it can be done with a relatively simple and inexpensive system that operates with the optical phenomenon of diffraction. This system allows calibration of gratings with distances between lines in the order of the magnitude of the wavelength of light used to produce the phenomenon, which is, in case of common He-Ne, about 0.6 µm.
Figure 1. Scanning electron microscope (SEM) image of (a) square profile and (b) a ramped grating structure. Both are suitable for pitch calibration by diffractometry [4]

Besides used as standards for optical microscopy, the gratings may be used as reference to calibrate atomic force microscopes (AFM) concerning its horizontal scale. An AFM is an instrument capable of capturing the profile of a surface by scanning a very small tip built in the end of a cantilever whose movement is detected by laser. When the system moves in a direction parallel to the surface, the tip is submitted to deflections due to forces in atomic magnitude so that profiles are obtained with a very high resolution. Those equipment can be found in the market (figure 2.a) and to calibrate them is mandatory before putting them into operation. There are basically two fundamental measurands that must be calibrated: the horizontal distance and the vertical displacement of the tip. Some gages can be used for this purpose, among them, gratings, but calibrating the grating remains a challenge.

NMIs have designed and mounted AFMs to enable its traceability in both vertical and horizontal movement and these are called metrological AFMs (figure 2.b). The task of building an AFM that is intrinsically traceable involves a huge amount of time and resources. Other alternative is to adapt a conventional AFM in order to make it metrological. But even in this case, the complexity is considerable. Both types can be used to calibrate the gratings and disseminate the traceability to other lower quality instruments.

Figure 2. Types of AFM: (a) commercial [5] and (b) metrological [6]
There is, however, a quite big difference between the calibration by using an AFM and the principle of diffractometry: in the first, the pitch P is evaluated at a very localized spot and the path covered by the tip of sensor is in the order of micrometers. In the second, a much larger surface is covered by the spot of laser light so that an average value for the pitch is obtained using a very large number of grating lines.

The idea behind the diffractometer method is that the incident light in a grating will be diffracted back by retroreflection just in some specific angular position of the grating. First, the grating is positioned so that the reflection signal for the zero order is obtained. Then, the grating is rotated relatively to the axis of the laser beam by a sufficiently precise angular position, using for instance a precise rotary table, until a new point of maximum reflection intensity appears. The bright points can be imaged into a CCD camera which works as a null detector. So, from a bright spot correspondent to the zero order to another one correspondent to the m\(^{th}\) diffraction order, an angle is realized and can be associated to the pitch of the grating. To each position, is associated a mode of diffraction and in those positions the incident and reflected light are coaxial (the Littrow configuration).

NMIs in various countries have been developing and assembling diffractometers, such as NRC in Canada, PTB in Germany, METAS in Switzerland and CENAM in Mexico, to name a few. They basically differ in the detection of the beam: METAS uses a quadrant detector, CENAM and NRC a CCD camera, and PTB a mix of both.

At METAS measurements are possible to step from 20 µm down to 320 nm for red light He-Ne laser (633 nm) and below 275 nm for green light laser He-Ne (543 nm). At PTB they use three sources of lasers with a wavelength range of 633 nm, 543 nm and 266 nm (UV), allowing reticle calibration in the range 150 nm to 10 µm. Depending on the pattern quality, PTB can achieve an uncertainty smaller than 10 pm, and smaller than 6 pm can be obtained at METAS [7-9]. NRC developed a methodology which resembles that developed by METAS, as mentioned above. According to study reported NRC, three different grating pitches of 700 nm, 4 µm and 10 µm were measured using a laser source wavelength of 633 nm, to uncertainties of about 7 pm [10].

The use of diffraction phenomenon to calibrate the distances between grating lines is the path taken by many NMIs because of its simple methodology and low cost of implementation and operation compared with a metrological AFM. It fits InmetroO’s goals since it opens room for the development of methods for fine-pitch grating calibration by using light phenomena associated with high accuracy at low cost.

2. Methodology
The schematic drawing of the proposed diffractometer is presented in figure 3 and the CAD drawing in figure 4 and was modeled after NRC imaging diffractometer design. The main concept is to use the Littrow configuration in grating mounting and observe each angle \( \theta \) relative to the zero order angle of the rotary table, figure 5, that reach a reproducible common position of the diffracted spot in a CCD camera (null detector mode) [10]. With these results and the wavelength of the monochromatic laser \( \lambda \), the average pitch \( P \) can be determined for the m\(^{th}\) order by the equation:

\[
P = \frac{m^\text{th} \lambda}{2 \sin \theta}
\]  

(1)

The pitch found is an average result because the laser beam covers an area spanning many pitches of the grating. The retro-diffracted beam creates a pattern image for diffraction order composed by each retro-diffracted pitch of the same order.

The Littrow configuration is a special grating mounting in which the grating is positioned with incident beam coincident with the retro-diffracted spot. The zero order, figure 5(a), is the base position whose return beam has higher intensity. To reach Littrow configuration of other orders, the diffraction grating is mounted on a precision rotary table and properly aligned. In the figure 5(b) the first order was obtained turning the rotary table to reflect the diffracted beam back along the direction of the incident beam.
Figure 3. Inmetro diffractometer schematic drawing

Figure 4. Inmetro diffractometer CAD drawing

Figure 5. Littrow configurations. (a) Zero order. (b) Negative first order.
2.1. Zeiss rotary table
Looking at the equation 1, it can be seen that the rotary table is a critical element in the design. It must be good enough to avoid a high influence in pitch uncertainty and tends to be quite an expensive item. As Inmetro/Lamed already had a high quality rotary table with its CMM, Zeiss RT-05, some tests were carried out in order to determine if it had suitable accuracy, zero repeatability with and without hysteresis consideration. The RT-05 was analyzed by mounting an autocollimator Taylor-Hobson DA-80 with a 12 faces Leitz polygon to measure the rotary angle deviations.

The first experiment was made searching 30 degrees relative positions completing a turn. To find the accuracy of the table, each RT-05 deviation of the relative angle was subtracted by the DA-80 value and corrected by the polygon calibration. The accuracy found was 1 second.

A second experiment was made to analyze the zero repeatability of RT-05, disregarding hysteresis. The RT-05 was triggered to reach a position closer to zero always from +10 minutes to zero, repeating the movement 10 times, taking the difference between the RT-05 deviations from zero to that of the DA-80. The result was a repeatability of 0.1 second for the zero position.

Finally, the last experiment was made to analyze the zero repeat of RT-05 with hysteresis. This experiment was similar to the previously described but the RT-05 was trigger from +10 minutes to zero and sequentially from -10 minutes to zero. The result was a repeatability of 0.3 second in zero position. The results for these experiments revealed an excellent rotary table whose characteristics fit the diffractometry purposes, as will be analyzed next.

2.2. Detection path
Separating the incident light from the retro-diffracted beam, a beam splitter is used to redirect the retro-diffracted beam to an orthogonal direction. Using a mirror and a collimation lens, the retro-diffracted beam is redirected again to be aligned and focused into the CCD camera as a spot image to maximize its resolution.

2.3. Optical isolator
Part of the retro-diffracted beam might return to the laser causing distortions on it what can prejudice the pitch result. The stabilized laser can be unlocked and the wavelength may be changed [10]. In order to eliminate the influence of the retro-diffracted beam effect on laser wavelength, an optical isolator can be used. These optical isolators are composed by waveplates, which turn the beam in two orthogonal polarizations, and polarizers, which can eliminate one of these orthogonal components permitting that only the component aligned with the polarizer goes through. When the beam returns, it will restore linear polarizations but blocked by a polarizer with orthogonal polarization [11].

2.4. Intensity controller
The retro-diffracted beams have less intensity at higher orders. The laser power and image spot brightness are designed so that the weakest order can be detected. However, sometimes the first orders are so bright that the diffraction beam saturates the CCD sensor. An intensity control must be added in order to cut the power of the brighter orders.

2.5. Spatial filter
The spatial filter reduces the wavefront distortions of the incident beam and a lens with an iris is used to collimate the beam and control the spot size (sample area) on the grating.

3. Discussion
This part of the paper examines the estimation of pitch uncertainty. This estimation was made consistent with the GUM [12]. Considering the equation 1, the two parameters that have influence on the pitch average are the wavelength of the laser and the angle of grating relative to the zero order...
(m = 0). The uncertainty of pitch will be influenced by laser wavelength and the relative angle position, both based on uncertainty of the instruments used for these purposes.

Analyzing the diffractometer schematic drawing (figure 3), optical components have an influence on pitch as well as wavelength and angle. All optical components have imperfections on construction that can disturb the main signal. Some can be analyzed to have a common mode error. The images captured on CCD camera have the same distortion to every diffracted order because each passes through the same optical elements in the same area and in the same direction. Thus, optical elements influence can be removed in a relative analysis as a main pattern response.

The alignment of the system and ambient interferences are the other important influences in the uncertainty of the measured pitch. Basically, the alignment should influence the relative angular position of the grating and the retro-diffracted beam position on CCD camera image. To make the errors due to alignment negligible, a good verification has to be performed to observe and minimize the deviation of the spot position between each order of retro-diffracted beam on CCD camera. Ambient interferences act on all elements of the system and can be modeled as random errors and must be considered in the uncertainty analysis.

The other influences, such as refractive index of air, sample temperature, thermal expansion, humidity, atmospheric pressure and air temperature, were considered for the calculus of the expanded uncertainty estimation (table 1), using ambient values of laboratory standard conditions. The misalignment of the grating is another influence that can interfere with pitch measurement. It is very difficult to measure, but many of these sources are negligible or are in common mode [10]. They are considered negligible in this work.

The estimated result is of the order of picometers for the diffraction first order of a 700 nm pitch sample, which is an excellent result. This is consistent with an international comparison of one dimen-

| Influence                        | Standard uncertainty | Sensitivity coefficient | Contribution to overall combined standard uncertainty |
|----------------------------------|----------------------|-------------------------|------------------------------------------------------|
| Laser vacuum wavelength          | $8.08 \times 10^{-8}$ µm | $P/\lambda_0$           | Negligible                                           |
| Refractive index of air          | $4.8 \times 10^{-6}$  | $P/n_{air}$             | 3.36 pm                                              |
| Angle traceability               | 0.420 second          | $P \cot \theta$         | 2.82 pm                                              |
| Angle resolution                 | 0.578 second          | $P \cot \theta$         | 3.86 pm                                              |
| Angle repeatability              | 0.382 second          | $P \cot \theta$         | 2.56 pm                                              |
| Sample temperature               | 1.2 °C                | $-aP$                   | 0.80 pm                                              |
| Thermal expansion coefficient     | $4 \times 10^{-6}$ °C$^{-1}$ | $(20 - T)P$         | 2.80 pm                                              |
| Humidity                         | 161.936 Pa            | $\frac{\partial n_{air}}{\partial f} P/n_{air}$ | 0.04 pm                                              |
| Atmosphere pressure              | 615.788 Pa            | $\frac{\partial n_{air}}{\partial p} P/n_{air}$ | 1.16 pm                                              |
| Air temperature                  | 0.578 °C              | $\frac{\partial n_{air}}{\partial T} P/n_{air}$ | 0.76 pm                                              |
| Combined standard uncertainty     | ----                  | ----                    | **7.15 pm**                                          |
| Expanded uncertainty (k=2)       | ----                  | ----                    | **14 pm**                                             |
sional (1D) grating pitch [13]. As this result is an estimative for just one order, optical elements with no imperfection and standard environmental characteristics of laboratory calibration, it can be expected a larger uncertainty value in a real situation. It can be expected a tens of picometers order variation in uncertainty results with a good manufactured grating.

4. Conclusion
The design of a diffractometer involves lot of research and analysis before obtaining an acceptable system. The rotary table, an important part of diffractometer, was tested and revealed a good instrument for this application. The estimation of uncertainty of the pitch measurement was 14 pm for the first order of a 700 nm pitch sample. This value is consistent with the results of an international comparison of one-dimensional (1D) grating pitch [13]. The next steps of the project are the acquisition of all the necessary elements, the diffractometer assembly and then the preliminary tests.

References
[1] EURAMET 2012 Roadmap Dimensional Metrology Science and Technology Roadmaps for Metrology - Foresight Reference Document of the Technical Committees of EURAMET e.V. Draft Update, Retrieved Mar 14, 2014 from http://www.euramet.org/fileadmin/docs/Publications/roadmaps/EURAMET_Science_and_Technology_Roadmaps_for_Metrology.pdf
[2] Lega X C 2012 Model-Based Optical Metrology Optical Imaging and Metrology: Advanced Technologies ed W Osten and N Reingand (Weinheim: Wiley-VCH) chapter 13 pp 283–302
[3] Bodermann B, Buhr E, Li Z and Bosse H 2012 Quantitative Optical Microscopy at the Nanoscale: New Developments and Comparisons Optical Imaging and Metrology: Advanced Technologies ed W Osten and N Reingand (Weinheim: Wiley-VCH) chapter 12 pp 255–282
[4] University of Eastern Finland n.d. Wave-optical engineering, Department of Computer Science and Statistics, Department of Physics and Mathematics, Retrieved Mar 17, 2014 from http://www.ifc.joensuu.fi/index.php?page=wo
[5] ARDIC INSTRUMENTS n.d. P100 – AFM with CCD portfolio, Retrieved Mar 17, 2014 from http://portfolios.scad.edu/gallery/ARDIC-P100/12316571
[6] Leach R K, Claverley J, Giusca C, Jones C W, Nimishakavi L, Sun W, Tedaldi M and Yacoot A 2012 Advances in engineering nanometrology at the National Physical Laboratory Meas. Sci. Technol. 23 074002
[7] METAS 2015 Measurement Services: Laboratory for Length, Nano- and Microtechnology, Retrieved Feb 6, 2015 from http://www.metas.ch/dam/data/metas/Fachbereiche/Laenge_Nano-_und_Mikrotechnik/Preisliste_5111_E.pdf
[8] Buhr E, Michaelis W, Diener A and Mirandé W 2007 Multi-wavelength VIS/UV optical diffractometer for high-accuracy calibration of nano-scale pitch standards Meas. Sci. Technol. 18 pp 667-674
[9] Meli F, Thalmann R and Blattner P 1999 High precision pitch calibration of gratings using laser diffractometry Proc. of the 1st Int. Conf. on Precision Engineering and Nanotechnology (Bremen) vol 2, ed P PeKown et al pp 252-255
[10] Pekelsky J R, Eves B J, Nistico P R and Decker J E 2007 Imaging laser diffractometer for traceable grating pitch calibration Meas. Sci. Technol. 28 pp 375-383
[11] Williamson R 2005 Polarization Optics Tutorial: Polarizers, Waveplates, Rotators and Lyot Filters, Retrieved Mar 13, 2014 from http://www.ray-optics.com/Polarization_Tutorial.pdf
[12] JOINT COMMITTEE FOR GUIDES IN METROLOGY (JCGM) 2008 Evaluation of measurement data – Guide to the expression of uncertainty in measurement JCGM 100
[13] Decker J E, Buhr E, Diener A, Eves B, Kueng A, Meli F, Pekelsky J R, Pan S-P and Yao B-C 2009 Report on an international comparison of one-dimensional (1D) grating pitch Metrologia 48 04001