Measurements of metric nonlinearities of MCP based Lobster-Eye X-ray Telescope optics by Moiré interferometry

A. S. Tremsin, O. H. W. Siegmund

Experimental Astrophysics Group
Space Sciences Laboratory
University of California, Berkeley
Berkeley, CA 94720.

ABSTRACT

An X-ray all-sky monitor based on a lobster-eye focusing optics concept is a very promising satellite for the future astronomical missions. The angular resolution of the optics based on Angel's geometry, implemented as an array of square pore channel plates is, in theory, limited by the physical size of individual channels. In practice, the metric uniformity, in particular channel misalignment, and surface roughness of the channel plates are the prime factors limiting the efficiency and resolution of the focusing optics. Most of the methods to test the metric uniformity suggested earlier allowed to study the quality of the plates only in local areas. We suggest another method of estimation of the global uniformity, and in particular the multifiber misalignments, over the entire plate area based on moiré interferometry. It is shown that for conventional MCP with 60-pore multifiber diameter this technique in principle can detect the multifiber angular misalignments and twists with an accuracy of about 1.2 mrad. The channel long axis misalignments may also be measured with accuracy of 35/L/p mrad, where L/p is the channel length to interchannel distance ratio. We believe this technique is a powerful tool for the preliminary selection of channel plates to be used in focusing optics.

Key words: X-ray focusing optics, Lobster-eye telescope, Microchannel plates

1 Introduction

A wide-field X-ray telescope based on a lobster-eye configuration offers an order of magnitude increase in sensitivity over previous, non-focusing, designs. It uses slumped microchannel plates (MCPs) to focus parallel X-rays (Fig.1) and is the basis for a small satellite mission proposed by the collaboration of Los Alamos National Laboratory, the University of Melbourne, the University of Leicester and NASA Goddard Space Flight Center. The major advantage of this instrument would be the possibility to monitor the whole sky on a daily basis provided by the gradual rotation of the satellite about the axis pointed towards the sun. The recent progress in the development of microchannel plate x-ray optics provides the basis for the realisation of the lobster-eye telescope's focusing component.

An ideal MCP would consist of a matrix of square channels perfectly aligned in all directions, with channels themselves being perfect both geometrically and in terms of surface roughness. The focused image produced by such an MCP would consist of a central focus containing 34.3% of incoming photons, two line foci, usually
referred as cross arms, with 24.3% in each of them and 17.2% in the diffused unfocused background.\textsuperscript{2} The geometrical distortions in the microchannel plate structure, however, cause deviations from the ideal focusing operation. The performance of such optics is mainly limited by these distortions determined by the manufacturing process.\textsuperscript{3,5,10} The quantitative evaluation of these imperfections becomes important both for selection of MCPs meeting specified requirements and for the improvement of the manufacturing process. Measurements of the geometrical imperfections, including rotations and twists of the channels and multifibers, can be difficult and time consuming at the accuracy levels required. According to Peele \textit{et al.},\textsuperscript{2} the optical efficiency of the Schott Fiber Optics square pore channel plates (200 \textmu m pore size on 240 \textmu m centers, 30:1 L/D ratio) was limited mainly by the channel rotations, twists and surface roughness. The Monte Carlo model of Brunton \textit{et al.},\textsuperscript{3} with the parameters taken from the experimental data on x-ray focusing with a planar, square pore Galileo MCP (85 \textmu m pore size on 122 \textmu m centers, 56:1 L/D ratio), and optical, scanning electron, and atomic force microscopy showed that the main contributions to the focal spot broadening were pincushion and long-axis misalignment.

Several measurement techniques can be used to qualify the structural imperfections in the channel plates. The interchannel and intermultifiber rotation angles can be obtained from optical and scanning electron microscope images of an MCP and were reported to be 15-20 mrad and 23-35 mrad rms, respectively\textsuperscript{2,7} for Galileo Electro-Optics and Schott Fiber Optics MCPs. The main disadvantage of this method is its localized nature leading to a large number of images which have to be analysed in order to qualify the channel plate with the required accuracy.

We have examined a simple high accuracy method of measuring some of the geometrical deformations over a large area with the help of optical moiré interferometry. The moiré interference pattern produced by overlapping two MCP surfaces is distorted by the imperfections in the MCP structure, in particular by the multifiber twists and rotations, and long axis channel misalignments. Hence, here we limit ourselves to these geometrical distortions only and will not address the problem of the surface roughness, channel pincushion and radiusing.
2 Optical moiré interference with MCPs

The term moiré effect generally refers to a geometrical optical interference formed when two periodic two dimensional meshes of similar pattern overlap. Moiré interference has found its applications in metrology, topography, and strain analysis, and has been well described in the literature. An MCP consists of a large array of small (usually 5\(\mu\)m to 50\(\mu\)m diameter) glass capillaries, which are generally arranged into multifiber bundles. The multifiber bundles are fused together and then sliced into wafers to make an MCP. The effective open area is normally 60-70 percent and the channel length to diameter ratio (L/d) is usually in the range 40:1 to 120:1. When two plates are stacked together an interference pattern is formed by the overlapping of the pores of one plate with interstitial areas of the other MCP. For geometrically ideal MCPs the period of the pattern would be constant over the entire area. Very small variations in the MCP period lead to considerable changes in the beat pattern. In other words, the moiré interference is very sensitive to the distortions in the period of the overlapping patterns, in our case multifiber rotations and twists and pore’s long axis misalignments.

The moiré pattern from two identical square-pore MCPs rotated by angles \(\alpha_2\) and \(-\alpha_2\), correspondingly, has the centers of the beat pattern maxima at \(R_{LM}\) given by

\[
R_{LM} = \frac{p}{2\sin(\frac{\alpha}{2})} [L; M] \tag{1}
\]

where p is the distance between pore centers. The moiré period \(T_{moiré}\) - the distance between two maxima, is apparently given by

\[
T_{moiré} = \frac{p}{2\sin(\frac{\alpha}{2})} \tag{2}
\]

Translational shift \((\delta_x, \delta_y)\) of the channel plate rotated by \(-\alpha_2\) does not change the moiré period and leads only to translational shift of the beat pattern, which would have maxima at coordinates \(R'_{LM}\) given by

\[
R'_{LM} = \frac{p}{2\sin(\frac{\alpha}{2})} [L + \delta_L; M + \delta_M] \tag{3}
\]

\[
\delta_L = \frac{1}{p} \left( \delta_x \sin\left(\frac{\alpha}{2}\right) + \delta_y \cos\left(\frac{\alpha}{2}\right) \right) \tag{4}
\]

\[
\delta_M = \frac{1}{p} \left( \delta_y \sin\left(\frac{\alpha}{2}\right) - \delta_x \cos\left(\frac{\alpha}{2}\right) \right) \tag{5}
\]

In case of MCP hex packing with pore centers \(r_{im} = p(\frac{\sqrt{3}}{2}l; m + \frac{1}{2})\) equation (3) becomes

\[
R'_{LM} = \frac{p}{2\sin(\frac{\alpha}{2})} \left[ L + \frac{M}{2} + \frac{\sqrt{3}}{2}M + \delta_M \right] \tag{6}
\]

3 Measurements of MCP metric nonlinearities

3.1 Multifiber rotations

The multifiber rotations may be calculated from measured variations of the beat pattern period \(T_{moiré}\), equation (2). The interference pattern formed by overlapping two microchannel plates with the same period, p,
is distorted by the multifiber rotations in both MCPs, thus providing the modulation of $T_{\text{moiré}}$. To measure the contribution of only one microchannel plate we need to image it digitally with relatively high resolution (at about 20 pixels per pore) and then superimpose the same image rotated by a certain angle or with a correspondingly made digital mask image. The accuracy of this measurement is limited by the maximum value of $T_{\text{moiré}}$, which in turn, is determined by the multifiber diameter. Indeed, at least two moiré maxima should be present inside each multifiber, so that the value of $T_{\text{moiré}}$ can be measured inside each of them. In the opposite case, the contribution from the variation of intermultifiber web thickness may dominate the contribution of the multifiber rotations, equation (3).

Fig. 2 shows the moiré beat pattern obtained with two Philips MCPs (80:1 channel length to diameter ratio, 25 µm square pores, 13° bias, 40 pore multifiber) back illuminated with a white light. Digital imaging was performed by a PULNIX TM-7CN CCD camera. Resolution of the CCD camera was only 640x480, therefore many translationally shifted images were obtained and then mosaiced together. The strong localized nature of multifiber angular deviations is clearly seen in the image as orthogonal cross hatch pattern. Illustrating the capabilities of this technique, the entire MCP area is examined in one simple measurement. There are multifibers with two maxima in them, and some have 4 maxima, which correspond to the angular rotation of $\sim 44$ mrad between these areas. The multifiber diameters of these MCPs was only 40 channels, therefore the resolution of this measurement could not be done with accuracy better than $\sim 2.5$ mrad as it follows from equation (2) and Fig.2 showing the variation of $(T_{\text{moiré}}/p)$ with the rotation angle $\alpha$. For a standard production line microchannel plate with 60 pores multifiber diameter, the ratio $T_{\text{moiré}}/p$ can be $\sim 30$ (half the multifiber size) and the value $\alpha$ can thus be measured with an accuracy of $\sim 1.19$ mrad. This is about an order of magnitude better than the rms angular displacements of MCPs available at the moment and should be better for a larger number of channels per multifiber. Fig. 4 shows the moiré beat pattern obtained with two round-pore Philips MCPs (80:1 channel length to diameter ratio, 12.5 µm pores on 15 µm centers, 0° bias, 60 pores multifiber size). Analysis of these data reveals that the angular distortions between multifibers of these two plates is as large as 60 mrad in some areas. According to Brunton et al. the interchannel rotation angle and the intermultifiber rotation angle of the plates they measured were in the ratio of 0.67:1.0. Thus, although our method does not allow to measure the single channel rotations explicitly, they still can be estimated from the rotations of the multifibers.

Figure 2: Variation of interference pattern period $(T_{\text{moiré}}/p)$ with angular displacement $\alpha$ between two identical MCPs ($p$ is the interchannel distance).
3.2 Multifiber Twists

To measure multifiber twists both front and rear surfaces of the same microchannel plate should be imaged with a relatively high resolution (~20 image pixels per pore) and then superimposed, forming the moiré beat pattern. Some imperfections visible on both sides (e.g., plugged pores) allow to align these two images so that front and back surface will translationally match each other. In that case the angular rotations of multifibers will not contribute to the moiré pattern distortions and only the multifiber twists within this single MCP will determine the variation of the period $T_{\text{moire}}$. Fig.5 shows the beat pattern formed by overlapping the front and back surfaces (rotated by 3 degrees) of one of the round-pore MCPs described above. Fig.5a corresponds to the aligned case, when only multifiber twists determine the variation of $T_{\text{moire}}$. Fig.5b represents the case when the front and back images were deliberately misaligned, so both twists and rotations contribute to the formation of the moiré pattern. Analysis of these images concludes that for this particular MCP angular displacements between multifibers is $<45$ mrad, while the twists are less than 5 mrad.

3.3 Multifiber Long Axis Rotations

The angular deviations of channel’s long axis $\Delta\gamma$, or in other words their parallelility, are not measurable in a straightforward way. Brunton et al. showed that they can be measured explicitly through the combination of MCP x-ray focusing experiments and computer simulation. We found that moiré modulation between the images of the front and back surfaces of an MCP can, in some cases, also be used for measuring the value $\Delta\gamma$ between multifibers, though not as accurately as with the previous method.

Apparently, the long axis misalignments $\Delta\gamma$ lead to variation of multifiber coordinate centers if compared on front and rear surfaces. This, in turn, corresponds to variation of $\delta_x$ and $\delta_y$ in equations (4), (5) and consequently the positions of the moiré maximums in the neighbouring multifibers are shifted by $\Delta S$. Only plates with small angular distortions can be evaluated here as the contribution of the angular displacements between these MCP areas to the value of $\Delta S$ should be relatively small in order to obtain long axis misalignments $\Delta\gamma$. The value of displacement between two multifibers $i$ and $i+1$, $\Delta\gamma^i$ can be found from

$$\Delta\gamma^i_x = \arctan\left(\frac{p}{LT_{\text{moire}}} \Delta S_y^i\right)$$

$$\Delta\gamma^i_y = \arctan\left(\frac{p}{LT_{\text{moire}}} \Delta S_x^i\right)$$

where $L$ is the MCP thickness. The accuracy of these measurements, again, depends on the number of channels in one multifiber, which limits the maximum value $T_{\text{moire}}$. Fig.6 shows the variation of the value $T_{\text{moire}}/p$ with $\gamma$ for a $L/p = 300 : 1$ channel plate. For a standard 60-pore multifiber diameter MCP the lowest measurable value $\Delta\gamma$ is only 0.12 mrad. The sensitivity of this method is not always sufficient for qualitative tests of MCP optical performance, although in some cases it can be used by the manufacturers. Before cutting channel plates from a boule, they can have much bigger values of $L/p$, which will lead to much better accuracy of this method, providing the contribution of multifiber twist distortions is relatively small.

4 REFERENCES


Figure 3: Moiré beat pattern obtained with two Philips square pore MCPs (80:1 L/D, 13° bias, 25 μm pores) back illuminated with white light.
Figure 4: Moiré beat pattern obtained with two Philips circular-pore hexagonally packed MCPs (80:1 L/D, 0° bias, 12.5 μm pores on 15 μm centers).
Figure 5: Moiré interference pattern obtained by overlapping images of two sides of the same MCP. Front and rear sides were imaged separately and then digitally superposed. (a) Images are aligned so front positionally matches the back image. Multifiber rotations do not contribute to the pattern distortions. (b) Images are misaligned. Angular rotations between the multifibers determine the visible variation of pattern period.
Figure 6: Variation of interference pattern period \( T_{\text{moire}} / p \) with long axis inter-multifiber rotation \( \Delta \gamma \), assuming value \( \Delta S^i \) in equations (7,8) can be measured with an accuracy of one interchannel distance \( p \) and \( L/p = 300 \), where \( L \) is the channel length.