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Controlling x-ray deformable mirror during inspection

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Synopsis A practical scheme is proposed to control and inspect x-ray deformable mirrors using a feedback mechanism with residual curvature estimated from shape metrology data.

Abstract After years of development from a concept to the early experimental stage, X-ray Deformable Mirrors (XDMs) are used in many synchrotron/free-electron laser facilities as a standard x-ray optics tool. XDM are becoming an integral part of the present and future large x-ray and EUV projects and are getting essential to exploit the full potential of the new x-ray sources currently under construction. The main objective of using XDMs is to correct wavefront errors, or to modify the x-ray beam sizes at the sample location. Due to the coupling among the N actuators of a XDM, usually it is necessary to perform a learning process to control the XDM into its target shape. In order to optimize the actuators settings to reach its target minimizing slope or height errors, an initial measurement need to be collected, commonly with all actuators set to 0, and then either N or $2N$ measurements are necessary to learn the behaviour of each actuator sequentially. Consequently, $N+1$ or $2N+1$ scans are required in total. When the actuators number N is important and the actuator response or the necessary metrology is slow, then this learning process can be time consuming. In this work, we present a fast and accurate method to drive an x-ray active bimorph mirror to a target shape usually with only 3 or 4 measurements. Instead of sequentially measuring and calculating the influence function for each actuator and then predicting the voltages needed for any desired target shape, the current metrology data are directly used to “guide” the mirror from its current status towards the particular target via iterative compensations. The feedback in the iterative calculation is the curvature discrepancy from the target estimated from the measured slope or height data. Three different methods are introduced to estimate the curvature from measured data. The feasibility of this simple and effective approach is demonstrated with series of experiments.

Keywords: x-ray deformable mirror; active optics; mirror inspection; windowed Fourier transform; B-spline curve fitting.

1. Introduction

The use of adaptive optics or say Deformable Mirror (DM) has been extensively studied for the compensation of wavefront distortion in various applications in the visible light domain including human vision, space applications, optical communications, lasers, and microscopy (Tyson, 2000). After years of improvement from a theoretical concept, to the early experimental stage, and finally turning into a sort of standard x-ray optics tool, nowadays the XDM has been widely utilized at many synchrotron/free-electron laser light sources (Idir & Mercere, 2013). The XDM is now becoming an integral part not only in the present but also in the future large x-ray and EUV projects and will be essential in utilizing the full potential of new light sources currently under construction. The primary objective of using an XDM in a synchrotron radiation or a free-electron laser facility is to correct wavefront errors or enable variable focus beam sizes for different experimental setups, which are important aspects for the performance and flexibility of a beamline.

The XDMs are usually long silicon (or glass) mirrors used at grazing incidence and equipped with N actuators allowing local shape deformations. In order to exploit the full potential of an XDM, it is usually necessary to perform a calibration or say learning process to drive the mirror to the desired target shape. Usually, in order to optimize the voltages on actuators for the minimized slope or height errors, the characterization of the XDM is carried out by using the following process: an initial measurement needs to be collected, for example with all voltages of actuators set as 0V, and N or $2N$ measurements are then taken to extract the influence function. The influence function is the characteristic of an XDM corresponding shape response to the action of a single actuator. In the classical learning process of an XDM, $(N+1)$ or $(2N+1)$ measures are required in total to obtain all actuators' influence function. However, when the number of the actuators N is relatively large, *e.g.* $N = 16$, and the actuator response or the necessary metrology is slow, *e.g.* one hour, then the learning process can be time consuming, which is neither expected nor preferred for the day-to-day mirror inspection in a metrology laboratory.

In this work, we present a fast and accurate method to drive an x-ray active bimorph mirror to the desired target shape usually with only 3 or 4 measurements during mirror inspection. Instead of sequentially measuring and calculating the influence function of each actuator and then predicting the voltages, the metrology data are directly used to “guide” the XDM from its current status towards the particular target via iterative compensations. The feedback in the iteration process is the curvature error at each actuator location from the desired target. The curvature is estimated from the measured slope or height data through derivative calculation. Three methods are introduced to estimate the derivative from the measured data. The paper is organized as follows. Section 2 introduces the principle of the proposed method. The experimental results are described in section 3, and section 4 discusses some potential improvements.

2. Principle

In the adaptive optics community, the measurement of the influence function plays a vital role in assessing the performance of a DM. As one of the most important parameters of a DM, the influence function determines its achievable correction capability. Measuring the influence function (learning process) can be very fast for classical adaptive optics used in visible light (astronomy, laser, *etc.*). However, in the x-ray domain, mirror metrology is often done using slope or height profiler and the measuring time can be as long as one hour for a 500-mm-long mirror.

Unlike the classical learning process generally used for adaptive optics (Tyson, 2000; Vannoni *et al.*, 2016; Vannoni *et al.*, 2015), the proposed approach does not sequentially measure the influence functions, but utilize the metrology data to guide the XDM towards the target shape with a closed-loop feedback mechanism. The essential principle is to generate voltage feedbacks via the curvature estimation from the metrology data. In order to achieve the minimal shape difference from the target, voltages applied to the actuators are adjusted until the minimization goal is achieved. Figure 1 illustrates a flow chart of the whole procedure with a feedback loop.

Figure 1. A feedback loop minimizes the shape error from the target.

The starting voltages could be any applicable values. Usually all actuators set at zero volts or voltages for a certain target suggested by the XDM fabricator or voltages from simulations are applied as the initial voltages. The XDM under the present voltages is then measured with a slope- or height-measurement instrument, *e.g.* NOM/LTP (Qian *et al.*, 1995; Takacs *et al.*, 1987; Siewert *et al.*, 2004) or an interferometer (Yamauchi *et al.*, 2003). The curvature difference ΔC from the target at each actuator location is estimated, after comparing the difference between the current and the target shape. Applying a hypothesis that there is a linear dependence voltage-curvature relationship of the XDM, see Eq. (1), a voltage feedback ΔU can be calculated.

$$\Delta U = K \cdot \Delta C, \quad (1)$$

where the coefficient K links the necessary voltages to have a curvature change on the mirror. The value of K can be experimentally determined by calculating the changes of curvature from two measurements with different input voltages. If the Root Mean Square (RMS) of the shape error is under the specified value ζ_1 or the shape update is within the measurement uncertainty ζ_2 of the metrology instrument then the iteration stop. Otherwise, the loop continues with new updates.

The measurement data from metrology instruments are commonly slope or height, not directly the curvature, so it is necessary to estimate the curvature from the measured slope or height. The curvature can be expressed as Eq.(2).

$$C = \frac{\frac{d^2 z}{dx^2}}{\left[1 + \left(\frac{dz}{dx}\right)^2\right]^{3/2}}. \quad (2)$$

Since the slope of x-ray mirror dz/dx is usually rather small compared to unity, the curvature can be express as the first derivative of the slope, the second derivative of the height, as described in Eq.(3).

$$C \approx \frac{d^2 z}{dx^2}. \quad (3)$$

Once the first derivative can be accurately estimated, it is straightforward to push it to the second derivative, therefore in this work we focus on curvature estimation from the measured slope. Since the limited number of actuators can only correct low frequency shape errors, the curvature estimator should have a capability of extracting local curvature from measurement data with high frequency components (*e.g.* the surface roughness and the measurement noise). Three methods are introduced here to complete the curvature estimation.

2.1. Windowed Fourier Ridges (WFR)

The first method is called as windowed Fourier ridges, which is originally proposed for fringe analysis (Kemao, 2004; Huang *et al.*, 2010). The WFR method has a capability of calculating the local angular frequency, which is the first derivative of the fringe phase. If we consider the slope data as the fringe phase, the one-dimensional (1-D) WFR method can provide the curvature (the first derivative of slope). In implementation, we construct a 1-D plural fringe $f(x)$ which can be described as

$$f(x) = \exp[j \cdot s(x)], \quad (4)$$

where $\exp[\cdot]$ is the exponential function, $s(x)$ stands for the measured slope, and j is the imaginary unit with $j^2 = -1$. The 1-D WFR can be presented as

$$Sf(u, v) = \int_{-\infty}^{\infty} f(x) g(x-u) \exp(-j\xi x) dx. \quad (5)$$

where x and u are spatial coordinates, ξ is the angular frequency, and the window function $g(x)$ is usually chosen to be a normalized Gaussian function as

$$g(x) = \frac{1}{\sqrt{\pi}\sigma} \exp\left(-\frac{x^2}{2\sigma}\right), \quad (6)$$

where σ is the standard deviation. The local angular frequencies ω at position u , can be expressed as

$$\omega(u) = \arg \max_{\xi} |Sf(u, \xi)|. \quad (7)$$

As a result, the first derivative of slope, or say the curvature C , can be determined as

$$C = \frac{\omega}{\Delta x}, \quad (8)$$

where Δx stands for the spatial sampling step in x -direction. Figure 2 demonstrates the first derivative of a given 1-D data can be calculated out by using 1-D WFR method. The values of the first derivative are achieved at the “ridges” in each lateral coordinates.

Figure 2. The WFR method can estimate the first derivative of a given slope data.

It may need an interpolation procedure to get the curvature values at the actuator locations. In practice, the locations where the actuators are installed can be known from the mechanical design of the XDM.

2.2. Weighted Polynomial Fitting (WPF)

Another method is named as Weighted Polynomial Fitting (WPF). Similar to the WFR method, a window centred at the actuator location is used to select the data for analysis as shown in Figure 3.

Figure 3. The measured slope can be fitted with polynomials section by section, and the curvature is then represented through the determined polynomial coefficients.

Only the slope data inside the window region is analysed. The windowed data is then fitted with polynomials (usually no more than 7 orders to avoid overfitting) see Eq.(9).

$$\frac{dz}{dx} \approx s(x) = \sum_{n=0}^N p_n x^n, \quad (9)$$

Once the polynomial coefficients p_n are determined with the least squares method, the first derivative can be expressed in a form of polynomials see Eq.(10).

$$C \approx \frac{d^2 z}{dx^2} \approx \frac{ds(x)}{dx} = \sum_{n=1}^N p_n n x^{n-1}. \quad (10)$$

Finally, a weight function is applied when averaging the curvature results within a section to enhance the noise resistance of the method.

2.3. B-spline based method

Instead of using window based methods, we can use B-splines (Unser *et al.*, 1993) to estimate curvature values from the measured slopes in order to achieve automatic data analysis. In particular, we can represent the slope data with a uniform cubic B-spline (UCBS) as

$$\frac{dz}{dx} \approx s(x) = \sum_{j=1}^J c_j N_j(x), \quad (11)$$

where $N_j(x)$ is the UCBS basis function and it is fully determined with a known sampling position x , and the coefficients c_j is estimated in a least squares sense with the measured slope data. It is straightforward to calculate the derivative with B-splines as demonstrated in Figure 4, because the

derivative of a B-spline of degree d can be expressed as a linear combination of B-splines of degree $d-1$.

$$\frac{dN_{j,d+1}(x)}{dx} = d \left(\frac{N_{j,d}(x)}{k_{j+d} - k_j} - \frac{N_{j+1,d}(x)}{k_{j+d+1} - k_{j+1}} \right), \quad (12)$$

where $k_j \leq k_{j+1} \leq \dots \leq k_{j+d} \leq k_{j+d+1}$ are the selected knots. Therefore, the curvature can be expressed as

$$C \approx \frac{d^2 z}{dx^2} \square \frac{ds(x)}{dx} = \sum_{j=1}^J c_j \frac{dN_{j,d+1}(x)}{dx}. \quad (13)$$

Figure 4. The B-splines can fit the measured slope and estimate its derivative as well.

Once the curvature C is estimated, the voltages can be accordingly updated for the next iteration, if necessary. In the next section, we will demonstrate several experiments to show the feasibility of the iterative approach. The three proposed methods for curvature estimation are used in those mirror inspection experiments.

3. Experiments

In this section, we show series of experiments where a Stitching Shack-Hartmann (SSH) metrology system (Idir *et al.*, 2014) is used to control and inspect the XDMs towards target shapes (see Figure 5).

Figure 5. XDMs are inspected with our stitching Shack-Hartmann system in the NSLS-II metrology laboratory.

In the first series of experiment, the curvatures are then estimated with the WFR method from the slope data taken with the SSH. In the second experiment the WPF method is employed, and the B-spline method is applied in the third experiment.

3.1. Experiment with the WFR method

In the first experiment, the XDM under test is a 700-mm-long bimorph mirror with 12 actuators. There are two target ellipses for this piece of XDM. The first ellipse parameters are $p = 37.35$ m, $q = 13.65$ m, $\theta = 3.5$ mrad, and the parameters for the second one are $p = 37.35$ m, $q = 22.65$ m, $\theta = 3.5$ mrad. The starting voltages for the first ellipse ($p = 37.35$ m, $q = 13.65$ m, $\theta = 3.5$ mrad) are suggested by the XDM fabricator. However, maybe due to mirror transportation and the difference of measurement conditions, the suggest voltages do not drive the mirror to the target shape with the expected specified value of $0.5 \mu\text{rad rms}$, whereas it is still a good initial point to start the iteration.

Figure 6. The voltages are suggested by calculating the curvature residuals with the WFR method.

The slope of the mirror is measured by the SSH after voltages are applied. Comparing the current slope with the target one, the slope residual is $1.026 \mu\text{rad rms}$ as plotted in Figure 6. Using the WFR method, the curvature residual can be estimated. The suggested voltages in Figure 6 are then updated to the XDM for the next measurement. Figure 7 shows that the slope residuals are reduced to $0.456 \mu\text{rad rms}$ after applying the suggested voltages, which indicates that the feedback is effective.

Figure 7. The 2nd mirror iteration gives smaller slope residuals.

It is possible to continue driving the mirror from the present shape to the second target ellipse ($p = 37.35$ m, $q = 22.65$ m, $\theta = 3.5$ mrad). As shown in Figure 8, it is obvious that the slope residual will be rather large ($10.49 \mu\text{rad}$ rms) once we change the target shape from the first ellipse to the second one.

Figure 8. Curvature needs to be changed accordingly, once the target changes.

The curvature residual estimated with the WFR method in Figure 8 indicates big curvature variation along the full mirror size due to the modification of the target. The voltage change calculated from Eq.(1) is used as a feedback in the loop. The suggested voltages shown in Figure 8 are updated to deform the mirror and the iteration continues.

Figure 9. The slope residuals reduce along iterations. Slope residual drops from $10.49 \mu\text{rad}$ rms to less than $0.5 \mu\text{rad}$ rms with three iterations.

Figure 9 shows the iterations can effectively reduce the Root Mean Square Error (RMSE) of the updated slope data. With two more iterations, the RMS of slope residuals was successfully reduced from $10.49 \mu\text{rad}$ down to $0.43 \mu\text{rad}$ as shown in Figure 9, which is already similar to the performance for the first ellipse target shown in Figure 7. The results in Figure 7 and Figure 9 indicate that the WFR method can successfully calculate the curvature from the measured slope data and provide the correct feedback to guide the mirror towards the targets.

3.2. Experiment with the WPF method

In this section, we demonstrate another experiment of controlling an XDM to show the effectiveness of the proposed approach with the WPF curvature estimator. The bimorph mirror under test is about 740mm long with 16 actuators and two 4 mm wide stripes (Pd-coating and Si). The Shack-Hartmann optical head used as a metrology tool has about $12 \text{ mm} \times 18 \text{ mm}$ field of view in a single shot, so both stripes can be measured during one scan. The target shape for both stripes is the same ellipse with $p = 40.69 \text{ m}$, $q = 11 \text{ m}$, $\theta = 2.5 \text{ mrad}$ with $0.2 \mu\text{rad}$ rms residual slope error.

Starting with the fabricator-suggested voltages, the Pd-coating stripe is analysed first and the RMSE of the slope is about $0.330 \mu\text{rad}$. With a polynomial fitting section by section, the coefficients of polynomials are determined to represent the slope data as shown in Figure 10.

Figure 10. The voltages are updated with WPF-estimated curvatures.

In addition, the curvature values at the 16 actuator locations can be estimated through the determined polynomial coefficients according to Eq.(10). The voltage updates are then determined and applied to the XDM for the next round of metrology.

Figure 11. The curvature estimation with the WPF method guides the slope error on the Pd-coating stripe down to a lower level.

Figure 11 shows that the slope is reduced to 0.211 μrad rms in two iterations. It is not difficult to notice that the slope residuals seem quite similar to each other during the optimization, excepting the changes of the local curvature (local tilts in slope).

If we move our analysis to the Si stripe, due to the difference in location of the stripes in the mirror, the optimized voltages used for the Pd-coating stripe will not work perfectly (see Figure 12, The Si strip is at $0.426 \mu\text{rad}$ rms with the same target ellipse). In order to find the optimal voltages for the Si stripe, additional iteration needs to be performed.

Figure 12. The optimal voltages found for the Pd-coating stripe do not provide the same level of slope error on Si stripe. Additional iterations are needed to get the optimal voltages for the Si stripe.

One of the advantages of the proposed method is that the initial voltages for a new loop can be any applicable voltages (satisfying the voltage constrains), which means the iteration for the Si stripe can start from the optimized voltages for the Pd-coating stripe.

Figure 13. The Si stripe is investigated from the optimal voltages for Pd-coating stripe, and it converges to 0.23 μrad rms.

After one iteration, the slope error for the Si stripe is reduced to 0.223 μrad rms (see Figure 13), which is close to the result of the Pd-coating stripe. Just to be sure whether there is some room to improve the shape, one more round is conducted. The resultant slope residuals become 0.227 μrad rms (see the last iteration in Figure 13). Comparing to the previous round, the RMS of the slope residuals keeps on the same level with no obvious improvement and the slope variation is less than our measurement uncertainty, which indicates it could be treated as the optimized status for this XDM under investigation with the particular metrology, mirror surface, and degree of freedom by these actuators.

3.3. Experiment with the B-spline method

In this section, we demonstrate that the B-spline based method can be used to estimate the curvatures and then feedback voltages to control the XDM towards the right target from all-zero voltages as our starting point. In this experiment, the XDM under test is a 500-mm-long bimorph mirror with $N = 16$ actuators. The target shape is a cylinder with a radius of curvature $R = 5390$ m.

Figure 14. Voltage updates are suggested via the curvature estimation with the B-spline method.

As shown in Figure 14, starting with all actuators at zero volts, the measurement shows that the mirror slope error is $0.941 \mu\text{rad}$ rms from the cylinder target. By using B-spline to estimate the “curvature distance” using as a break number the actuator number $N = 16$, a new voltage combination is suggested.

Figure 15. The mirror with updated voltages gets smaller slope residuals.

The suggested voltages in Figure 14 are then updated to the XDM for the next iteration. Figure 15 shows that the slope residuals drop down to $0.272 \mu\text{rad}$ rms after applying the suggested new voltages, which indicates that the iteration process is effective. A fine adjustment on voltages is suggested from B-spline based curvature analysis.

Figure 16. Curvature needs to be changed accordingly, once the target changes.

By using the newly updated voltages, the residual slope error further reduces down to $0.191 \mu\text{rad rms}$ after one more round as shown in Figure 16. Since the slope residual meets the specification ($< 0.2 \mu\text{rad rms}$), the iteration stops.

Figure 17. The slope residuals reduce along the iterations. Slope residual reduced from $0.941 \mu\text{rad rms}$ down to $0.191 \mu\text{rad rms}$ with two iterations.

Figure 17 shows the iterations can effectively reduce the Root Mean Square Error (RMSE) of the updated slope data. With two iterations, the slope residuals are reduced from $0.941 \mu\text{rad rms}$ down to $0.191 \mu\text{rad rms}$. The results indicate that the B-spline based method successfully estimates the curvature from the measured slope data and offers the correct feedback to control the mirror towards the target shape.

4. Discussion

It is meaningful to discuss the limitations and merits of the proposed approach with the three derivative estimators to identify some potential improvements. Generally speaking, the proposed approach has the following limitations and merits.

Limitations:

- This approach can inspect the XDM for quality check, but it is not able to predict voltages for an arbitrary target shape, since the influence function is not measured.
- The proposed method assumes that all actuators are similar with the same K coefficient. A reliable way to determine the localized K parameter (each actuator may have a different K value) may be needed for further improvement.
- The window size in WFR and WPF methods may need to be adjusted, according to different actuator numbers, and mirror length, as well as scanning steps. The WFR method is not good to calculate derivative at the two boundary regions of the mirror, because zero padding at the data boundaries will yield error in estimation.

Merits:

- There is no need to measure all the influence function for each actuator, which saves metrology time.
- During the iteration, the slope or height is monitored by the metrology tool. The resultant performance under the optimal voltages is always double checked with measurement.
- The data processing with the B-spline based method is highly automatic with no human-computer interaction, so the issue of window size selection in the WFR and WPF methods are avoided in principle.

5. Conclusion

In this work, a practical scheme is presented to control and inspect the XDM with a feedback mechanism. The mirror shape is measured under a closed loop control with adjusting the applied voltages. By estimating the curvature residual according to the slope or height metrology data, the voltages are updated based on the relation between the changes of voltage and curvature. Three methods (WFR, WPF, and B-spline) are introduced to estimate the derivative in order to get the curvature from measured slope or height data. Series of experiments demonstrate that the proposed approach is able to control the XDMs towards the desired target shapes. The iteration commonly converges with 3 or 4 measurements. This technique is effective and efficient in day-to-day XDM inspection in optical metrology laboratory. It should be noted that this approach can also be used in situ with an x-ray wavefront sensor (pencil beam, Hartmann, grating shearing, or curvature sensor).

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