Automated in-situ optimisation of bimorph mirrors at Diamond Light Source

John P. Sutter, Simon Alcock, Kawal Sawhney
Diamond Light Source
Bimorph mirror:
Mirror composed of two piezoelectric layers:
- Series of electrodes deposited on layer surfaces
- Precisely ground and highly polished silica layer on top surface
- Heavy metal coatings (Pt, Rh, Pd) on silica layer to increase reflectivity.

Routinely used to focus synchrotron beams at
- APS
- SOLEIL
- PETRA III
- Diamond Light Source:
  - I02, I03, I04 (macromolecular crystallography)
  - I07 (surfaces and interfaces)
  - I19 (small-molecule single-crystal diffraction)
  - I22 (non-crystalline diffraction)
  - I24 (microfocus macromolecular crystallography)
I02 VFM – 8 piezos
Bimorph mirrors have many electrodes (up to 32) → non-cylindrical (e.g. elliptical) figures well approximated → low spatial frequency roughness/slope error (period $\geq 20$ mm) can also be corrected.

But optimisation is also challenging:

Measurement of slope errors must be
- portable
- reproducible
- accurate (error $\ll 1$ $\mu$rad)
- automated
- quick ($< 2$-3 hours).

Performed by pencil-beam method.

Calculation of electrode voltage corrections is done by the well-known interaction matrix method.
Ex-situ vs. in-situ: both done at Diamond Light Source

Ex-situ: examination of mirror in metrology cleanroom lab (Diamond-NOM, Fizeau interferometer, micro-interferometer)
- Initial characterisation and optimisation
- Not dependent on synchrotron beam → saves scarce beamtime

But beamline operating environment can differ greatly from controlled cleanroom:
- mounting strains
- ultra-high vacuum
- heat load imposed by incident beam.
→ in-situ examination is also necessary.

In-situ: examination of mirror in its beamline, at its operating wavelength
Pencil-beam method: application to synchrotron beamlines

Upstream slit reduced to 10-20 µm
→ only small area (several mm) of mirror are illuminated at a time

Camera measures reflected beam position $y_{ij}$ from $i$th section in $j$th scan.

No less than 2-3 points scanned per electrode.
Piezo response functions: change in mirror figure per 1 V change of voltage to given electrode

Example: I04 vertical focusing mirror (VFM): 8 electrodes

Ex-situ on Diamond-NOM

In-situ on beamline I04

Noisier in-situ height measurement due to coarser slope error scan → finer scans would better smooth out measurement noise.
Interaction matrix $H$: Shows each actuator’s effect on figure.

Begin collection of scans

Run pencil-beam scan

Increment scan counter $k$ by 1

Is scan counter $k \leq$ number of electrodes?

YES

Increment $k$th electrode voltage by $v$

NO

Scan collection completed

$H_{ij} = (y_{i,j+1} - y_{ij})/v$

Vector $Y$: $Y_i =$ correction to reflected beam position from $i$th point

Vector $V$: $V_j =$ voltage correction for $j$th electrode

Shortest length least squares solution: $V = H^\dagger Y$

$H^\dagger =$ Moore-Penrose pseudoinverse of $H$
Types of X-ray cameras used at Diamond Light Source: **X-ray eye**

Small, portable camera with 4.65 μm/pixel, 90% integrated line spread function = 4.65/6.35 μm
Inline viewing system: permanently installed in MX beamlines. Intensity ~ 3 orders of magnitude less than that of X-ray eye, but S/N ratio still enough.
Beamline controls: done in-house by our own Controls and Data Acquisition groups

Beamline motors and X-ray camera control: **EPICS**

X-ray camera image collection: **EPICS & Firewire**

Pencil-beam scan setup and execution: **Generic Data Acquisition (GDA)**

Image processing to extract reflected beam positions: **Jython script peak2d**

Inversion of interaction matrix to derive voltage corrections: **Jython script using inbuilt linear algebra routines**
Ability to focus/defocus beam in-situ: **I19**

**Initial**

**Focused**

**Defocused**

---

**H**

**V**

- **Initial**:
  - FWHM = 32.6 pixels
  - $= 151.6 \, \mu \text{m}$

- **Focused**:
  - FWHM = 17.7 pixels
  - $= 82.3 \, \mu \text{m}$

- **Defocused**:
  - FWHM = 42.4 pixels
  - $= 197.2 \, \mu \text{m}$

---

- **Initial**:
  - FWHM = 13.4 pixels
  - $= 62.3 \, \mu \text{m}$

- **Focused**:
  - FWHM = 12.3 pixels
  - $= 57.2 \, \mu \text{m}$

- **Defocused**:
  - FWHM = 18.8 pixels
  - $= 87.4 \, \mu \text{m}$

---

**Smoothed intensity vs. Pixel**

---

[Logos and text from the image are not relevant to the natural text representation and have been omitted.]
Repeatability: *I19*: 4 consecutive slit scans in same direction

VFM: taken at 7 m →
1 pixel = 0.33 µrad slope error

HFM: taken at 6 m →
1 pixel = 0.39 µrad slope error

Successive plots shifted by intervals of 2.
P-V = peak-to-valley difference
σ = standard deviation of difference
Agreement of in-situ with ex-situ measurements

I02 VFM

I03 VFM

I04 VFM

Ex-situ: from Diamond-NOM

Sharp jumps in slope error due to surface damage — cause being investigated.

Good agreement in slope error for 3 independent mirrors!
Agreement of X-ray eye and inline viewing system

Pencil beam technique is independent of the camera.
Diffraction from incident beam slit sets the ultimate spatial resolution of the pencil-beam scan.

1-D Fresnel diffraction patterns of a rectangular slit

Best spatial resolution obtained at ~10 µm slit width.

Narrower slits actually increase the footprint!
Conclusions

An automated procedure has been used at Diamond Light Source to optimise bimorph mirrors quickly and easily.

This procedure is repeatable to within \(~0.1\) camera pixels, or \(~0.1\) \(\mu\)rad with camera at 6 m from mirror.

It yields measurements that agree well with those taken ex-situ with the Diamond-NOM.

It permits both focusing and deliberate defocusing of X-ray beam.

Diffraction limits the ultimate spatial resolution that can be achieved by reducing the incident beam slit width.
This automated method is not confined to hard X-ray bimorph mirrors!

Ex. Diamond I20 collimating mirror
- Curved using mechanical benders
- Gravitational sag compensated by 2 prop loads
- Pencil beam scans used to adjust both curvature and sag.

Pencil-beam scans of slope error are similar to calculations of elastic bending of beams.
Acknowledgments

Diamond Light Source Controls:
Ronaldo Mercado
James O’Hea
Nick Rees

Diamond Light Source Data Acquisition:
Chris Coles
Paul Gibbons
Rob Walton