Smoothing mid-spatial frequency errors on freeform surfaces

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Freeforms

Mid-spatial frequency error

Manufacturing freeforms

Smoothing and results
Freeform optical surfaces have:

- Improved optical performance – less aberration
- Lightweight systems – reduced number of optical components
- Increased ability to go off axis – smaller/tighter packing

J M Howard and S Wolbach, “Improving the performance of three-mirror imaging systems with Freeform Optics,” OSA Freeform Optics Conference, 3-7 November 2013

3-Mirror system shows up to 30 times improvement in system performance with freeforms, Partially for larger field of views.
A freeform can be defined in many ways

- Equation
  - asphere equation with X and Y terms
  - toroid
  - Atoriod
  - anamorphic asphere
  - Acylinder
  - Zernikes
- Cloud of points
- Solid model

- Little to no symmetry
- Every part is different
Who/What is using freeforms?

- 3-mirror telescope systems
- Beam shaping
- Corrector plates
- Conformal windows
- Corrector optics for aerodynamic domes
- Heads-up displays

Simple definition of mid-spatial frequency

‘The wiggles’
Spatial periods of \( \sim 1 \text{ mm} \) - 5 mm
(depending on part size)

Irregularity error

Mid-spatial frequency error
Why is MSF such a factor for freeforms? (aspheres, too)

Generating and machining is done on a 5 - (or more) axis with complicated toolpaths and possible error motions (more/higher than for spherical optics)

Polishing is done with small tools – which (depending on the spatial period of interest) can only create MSF, can’t remove it.
Typical freeform manufacturing steps

Polishing

- Generation
  - Sub-Aperture Polishing
    - Sub-Aperture Polishing for Figure Correction

Diamond Turning

- Generation
  - Diamond Turning, slow-tool servo

Typical methods induce MSF inherently and can’t fix it.
Optimax’s freeform manufacturing steps

Commercial Quality

Generation

Generation Surface Correction

VIBE Full Aperture Polishing

Precision Quality

Generation

Generation Surface Correction

VIBE Full Aperture Polishing

Sub-Aperture Polishing for Figure Correction

Smoothing Process
CNC generation process produces freeform shape with minimal surface form error
Pre-polishing required to remove damage while maintaining freeform shape

VIBE process removes material using proprietary conformal pad technology
Measurement of freeforms is still a gating item

Coordinate Measuring Machine

- Touch-trigger scanning probe
- Measures the deviation between the nominal shape and actual shape
- Good to ~ 1 µm
Measurement of freeforms is still a gating item

Stitching Interferometer

Projects are ongoing with QED to adapt aspheric stitching interferometer to measure ‘mild’ freeforms

CGHs – Computer Generated Hologram

Difficult to separate alignment and surface errors. We have ongoing projects to design CGHs which measure the part fiducials to eliminate alignment problems.
Deterministic figure correction process selection depends on material and part geometry.
Smoothing reduces the mid-spatial frequency errors in the part.

Smoothing reduces the MSF without greatly affecting the figure error with proprietary conformal tooling and active layers.
Smoothing reduces the mid-spatial frequency errors in the part

The smoothing method and tooling varies dependent on part geometry and material.
Importance of smoothing, 1/3

Fine lines caused by step-over in the generation process must be smoothed, fixing this ~1-2 mm sized features is not possible with sub-aperture polishing.

~35 mm diameter
Importance of smoothing, 2/3

CMM measurement of atoriod after generation showing low form error, but unacceptable MSF

90 mm diameter

3 mm spatial period
Importance of smoothing, 3/3

Freeform optical surface 75 mm by 25 mm
Both SN1 and SN2 meet the PV specifications

SN1: Not smoothed

SN2: Smoothed
Smoothing results show dramatic decrease in MSF

- 2.7 µm
- 4.9 µm
- 16.9 µm
- 14.2 µm

Power Spectrum Plot

Spatial Freq (1/mm)

Power (A^2/µm²)
Conclusions

• MSF is typically a natural consequence of manufacturing freeforms
• MSF can’t be fixed the sub-aperture polishing
• VIBE polishing minimizes the creation of MSF
• Smoothing removes existing MSF
Next Steps

- Steeper, more complicated surfaces
- Work toward the <5 nm rms levels of MSF
- Better measurement of the MSF on freeforms using CGHs
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Questions?