Specifying, Manufacturing and Measuring Aspheric Lenses – Part II

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This paper will highlights the similarities and differences between tolerancing, manufacturing and measuring spherical and aspheric surfaces. It will outline how Optimax communicates aspheric forms, the manufacturing challenges, what metrology options Optimax has for aspheres, and some example specifications for each specific metrology option. In addition, guidelines provided for the optical designer suggest where to loosen tolerances in order to achieve the best quality aspheric surfaces in the most time and cost effective manner.

SPECIFYING AN ASPHERIC LENS

Specifying an asphere begins with material selection and specification of diameter, thickness, cosmetics and clear aperture in the same way a spherical lens would be specified. The same style of tolerancing applies for these attributes as they would for a spherical lens. There are many complete guides available[1, 2].

Optimax uses the General Aspheric Equation[3] to communicate aspheric forms, and other forms such as the Forbes Form[4] or a Power Series may be used. Specifying form involves specifying Vertex Radius, Conic Constant and applicable Aspheric Coefficients. Adding Aspheric Coefficients adds complexity and therefore cost, and there is a point of diminishing returns in adding terms. Fourth order terms fix fourth order errors, meaning a sixth order term adds nothing to a fourth order correcting asphere except cost.

Tolerancing form error for an asphere is similar to tolerancing a combination of power and irregularity, showing deviation from ideal form. Instead of showing power, a vertex radius tolerance is given. For a precision optic, a vertex radius tolerance corresponding to a change in sag of ±0.001mm for the nominal asphere is a good starting point. Optimax does not tolerance Conic Constant or the Aspheric Coefficients.

Form error is largely determined in a compromise between what measurement accuracy is possible, what modeling shows is needed and what time and money is available. More information on what measurement accuracy is possible and sample form error specifications are shown in the Metrology section.

Centration errors can destroy lens performance, and critical consideration must be given to manufacture and measurement methods. Centering aspheres involves aligning aspheric axis to mechanical axis and the other surface, three things instead of two for spheres. Modeling will guide tolerancing of tilt and decenter.

ASPHERE MANUFACTURING CHALLENGES

While aspheric forms and their promise have been known to optical designers for centuries, for most of that time only the mildest forms have been physically realizable. Spherical lens manufacture historically has worked two surfaces together in full contact. This works for surfaces of constant curvature, but it doesn't work once curvature reaches sufficient variance over a surface. By changing the amount of contact from 100% to a subaperture where change in local curvature approaches zero, some portions of traditional spherical lens manufacturing techniques can be applied. Brittle removal by high speed diamond grinding followed by ductile removal using polishing slurry (ceria, alumina, etc) can be used to prepare aspheric surfaces. It's about here the similarity ends.

In the past, labor intensive, artisan processes produced aspheric surfaces, and the costs were extreme. The growth of CNC and CAD/CAM technology has made aspheric optic manufacturing practical. A peripheral diamond wheel on a CNC platform traces the surface to generate the aspheric profile. The surface is then deterministically polished by working only a small area at a time. Each iteration has potential error inducement associated with it, so making as few correction runs as possible is a primary focus. All of this is done while maintaining location of the aspheric axis around which the solid of revolution was formed.

In grinding, machining accuracy determines profile accuracy. A more accurate ground profile makes a more accurate polished profile more likely, since there's less correction needed. Particular attention must be paid to wheel wear, wheel balance, positional accuracy and overall stiffness of the grinding platform. Since the tool is in contact with the part, errors in these items transmit into the surface being created.

Typically, asphere polishing is a feedforward, deterministic process. Local curvature of aspheres may appear constant, globally it isn't. Asphere polishing requires an adaptive tool and knowledge of what local curvature changes and errors are ahead. This requires knowledge of how the tool will evolve and how much removal is needed both locally and overall. Deterministic processes provided by Zeeko/Loh and QED machinery are examples of such tools. These processes characterize the removal rate as a function of curvature for a given tool and combine that with and error map of the surface to be worked. The resulting removal schedule accommodates for volumes to be removed and tool performance at that local curvature.

Unlike spherical lenses, centration errors in aspheres may not be removed. Centering errors in a spherical lens could be removed through realignment with sufficient diameter overage[5]. Realignment is not possible for an aspheric surface because the aspheric surface is centered about an axis and not a point. To avoid errors like coma, centration must be conserved throughout processing.

Conventional spherical interferometric techniques don't translate to asphere metrology either. Since local curvature is nonconstant, interferometric techniques for aspheres are custom. The setup and equipment is unique for a given aspheric form, so time and money demands are large. Profilometry is comparatively fast, and as a 2-D compromise the current industry standard.

METROLOGY ACCURACIES AND SAMPLE FORM ERROR SPECIFICATIONS

The three main metrology options are listed below, each possessing its own benefits and restrictions. Each of these metrology tools must be evaluated in light of the specific aspheric form to be targeted and the measurement certainty needed. They are arranged in order of increasing complexity and subsequently cost, and some detail of each is given.

Profilometry

This is the most commonly used metrology option for aspheric forms. The device measures height of the surface as a function of movement along one axis, producing a 2-D table of data. Using information about the ideal form and how the profilometer is set up, the data is analyzed, showing error from theoretical form with setup related tilt removed. Measurement certainty here is ~0.1 µm at best, and it decreases for extremely steep or extremely flat surfaces.

A sample specification here would be "± 1µm of deviation from theoretical form", where deviation in this case would be from the form generated by the aspheric equation. There would also need to be some allowance for variance in the vertex radius, analogous to spherical type power seen in spheres and flats.

Interferometry in Reflection

Reflective interferometry for aspheres works in the same manner as spheres or flats, except the null target is unique to the specific desired ideal aspheric form. Lenses that may be measured interferometrically can be specified in the same manner as any spherical surface, with a linear tolerance on the vertex radius and the irregularity as the deviation from aspheric form. Power may also be used, and Optimax would convert the resulting sag difference into a linear tolerance.

There are three reflective techniques here, on-axis measurement for mildest forms, subaperture stitching for more complex forms and holographic testing for the most complex forms.

- On-axis Measurement

For some cases the asphericity is mild enough where an interferometer can see through the aberrations present. On-axis testing with a Zernike based aberration subtraction is sufficient. This process is typically reserved for aspheres of less than < 10µm of aspheric departure and < 150mm of diameter. Allowable departure is proportional to diameter.

- Subaperture Stitching

More departure can be handled by stitching interferograms together. Using QED's Subaperture Stitching Interferometer (SSI) or Zygo's VeriFire AT mild aspheric forms can be formed using conventional transmission spheres. While moving the part until the local curvature becomes manageable, several (ranging from ~5 to ~100) overlapping measurements are made. A full aperture representation of the deviation of the aspheric surface is formed by stitching the measurements together. Broadly speaking the present limit is < 50µm of aspheric departure and < 200mm of diameter. Allowable departure is proportional to diameter.

For both the on-axis and stitched cases measurement certainty is about λ/20 at the 632.8nm HeNe laser wavelength used here at Optimax. Local rates of change are extremely important here. The departure must be evenly distributed, and test apertures where departure increases rapidly (more than ~1 λ/mm at HeNe) will likely be immeasurable. Again, this is highly case specific.

- Holographic Testing

Interferometric testing is still possible for larger departures using a holographic null. Each asphere requires its own null, each costing about $10 – 15K and taking about 10 – 15 weeks to get. Measurement certainty is about λ/8 at HeNe here, as setup induced errors are difficult to identify and eliminate. While less sensitive, the same issues of rate of change and location of departure still apply.

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Interferometry in Transmission

For aspheric lenses, there are some specific cases where testing in transmission as opposed to reflection offers a simpler solution. It is possible with one simple null assist optic or even none at all an asphere may be tested, saving time and money over reflectance testing. The test measures literal transmission wavefront error (TWE), looking at the sum of all errors. It sums up the contributions from errors in centration, form and material. This sum is targeted and corrected. This is an extreme special case. The short list of criteria is below.

- Field of ±5º or less
- Small spectral range, monochromatic is ideal.
- A fully understood model of spectral performance of the lens. The lens must be well behaved interferometrically. Retrace error and vignetting must be considered and if present addressed.
- An interferometer capable of handling the expected aberrations plus any normal fabrication errors. Lens aberrations must not exceed the capabilities of the interferometer to be used. Aberrations need to be modeled, and interferometric performance must be characterized.
- Consider wavelength of use versus wavelength of test. A lens that has a beautiful test at HeNe for example may not look so good in the near IR. On a related note, the lens material must transmit in the wavelength range of the interferometer.

If any of these criteria cannot be met this option may not be used.

A sample specification here would be "< 0.25 λ of deviation from theoretical form", where deviation in this case would be from the expected wavefront of an aberration free part. There would be no other specification since the sum of all errors is the target.

CONCLUSIONS

- Pick a form to fix aberrations, making it no more complex than needed
- Look for fatal errors of manufacturability
- Model errors to determine tolerancing for form and centration
- Match metrology to form, modeled errors and budget

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[1] W.J. Smith, *Modern Lens Design*, Ch 23, McGraw Hill, New York City, 2005

[2] R.E. Fischer, B. Tadic-Galeb, P. Yoder, *Optical System Design*, Ch 18, McGraw Hill, New York City, 2008

[3] R.E. Fischer, B. Tadic-Galeb, P. Yoder, *Optical System Design*, Pg 116, McGraw Hill, New York City, 2008

[4] G.W. Forbes, "Asphere, O Asphere, how shall we describe thee?", Proc. SPIE 7100, Pg 710002-710002-15 (2008)

[5] B. Braunecker, *Advanced Optics Using Aspherical Elements*, Pg 91 - 92, SPIE , Bellingham, WA, 2008