Synopsis of Technical Report:

"Designing and Specifying Aspheres for Manufacturability"

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Abstract

Since aspheres have become more common in optical designs, papers such as this one have helped us to gain an understanding of how aspheres are manufactured and tested. I will highlight the most important points adding comments where appropriate.

The author focuses on glass aspheres produced by sub-aperture lap by CNC processes, in particular MRF (magnetorheological finishing) machines by QED Technologies[1]. It should also be noted that these guidelines might apply to diamond turned surfaces as the author notes

The key points from this paper are as follows:

- Conic sections versus higher order aspheres
- Testing aspheric surfaces
- Tolerancing
- Design guidelines, including slope steepness, size limitations and glass selection

Conic Sections or Higher Order Aspheres

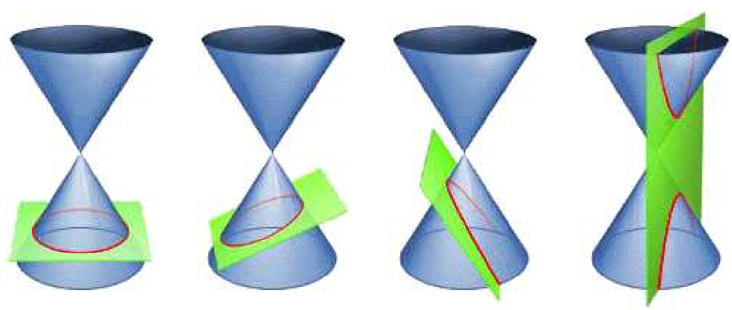
The general even order aspheric equation can be found in optical design references and softwares (symbol designation of variables may be different from one reference to another):

$$Surface\ \ sag = Z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \alpha_1 r^2 + \alpha_2 r^4 + \alpha_3 r^6 + \alpha_4 r^8 + \alpha_5 r^{10} + \alpha_6 r^{12} + \alpha_7 r^{14} + \alpha_8 r^{16}$$

Where c is the radius of curvature ($c = 1/R_0$), r is the radial aperture component and k is the conic constant.

Conic sections, parabolic, elliptical, hyperbolic or circular sections created when a plane intersects a cone, can be defined in the equation by varying the radius of curvature c and the conic constant k. The diameter is defined by the radial component r.

$$\begin{aligned} k < -1 &\Rightarrow Hyperboloid \\ k = -1 &\Rightarrow Paraboloid \\ -1 < k < 0 &\Rightarrow Prolate\ \ Ellipsoid(major) \\ k > 0 &\Rightarrow Oblate\ \ Ellipsoid(minor) \\ k = 0 &\Rightarrow Sphere(circle) \end{aligned}$$



Higher order aspheres can have all the same variables as the conic sections but can also include the higher order deformation terms α's from the equation. A very important point designers should remember is that although some optical design softwares allows optimization using the α_1 term, not all machines support its use in the expansion. The author gives the rule of thumb: "It is safer to use the conic constant and keep the α_1 coefficient equal to 0." I fact, in my experience, allowing the conic constant and α_2 (sometimes referred to the A_4 term) can cause conflicts during optimization.

In this section the author gives a detailed performance summary of a two-lens, f/1, all spherical system versus the same system with an aspheric surface added to it, comparing the effects of using only the conic constant and several higher order terms. He goes even further by adding a third spherical element and comparing all the performances. The amount of aspheric departure (from a spherical surface) is used as a metric to identify a 'more manufacturable' surface, see Table 1 in the appendix for an example. It should be noted that this depends on the aspheric figuring method; the MRF method, which starts with a polished spherical surface and 'aspherizes' it, therefore more departure does mean longer polishing times.

The conclusion from these comparisons is that a higher order asphere is more effective at reducing transmitted wavefront error than adding an additional spherical element. What I noticed in the examples used is that the aspheric surface was located at the pupil, which is the most effective position to control most aberrations.

Testing Aspheric Surfaces

While designers can come up with wonderful aspheric shapes, the difficulty is ensuring the desired surface is produced. The author gives strong arguments to stay with conic sections as they can be tested interferometrically at their natural conic foci. A concave parabola, concave hyperbola and concave ellipse can be tested without any additional null optics[2]. Even oblate spheroids (concave and convex)[3], convex hyperbolic mirrors in reflection[4] and convex hyperbolic mirrors[5]. Test configurations for these conic sections are also included which I found particularly interesting.

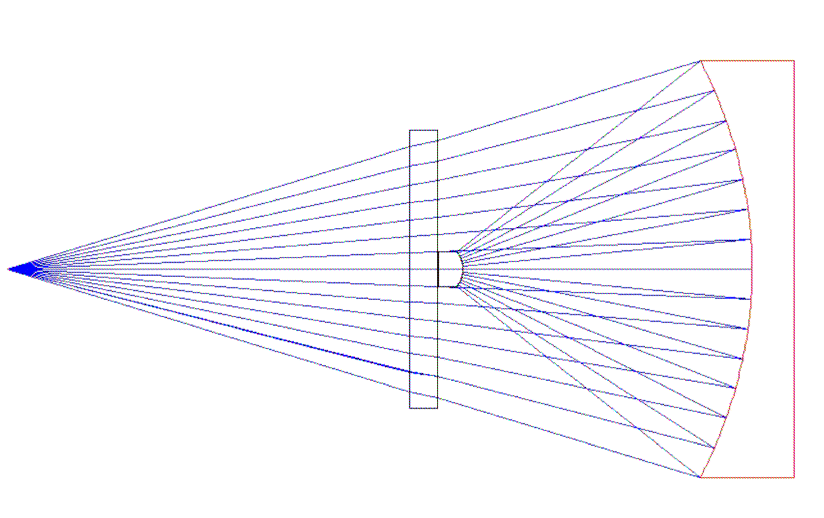


Figure 1: Null testing concave ellipse at conic foci

Figure 1 shows one of the test configurations from the paper. Although this interferometric test does work, I found it to be sensitive to decenter and tilt errors due to the stages moving when testing large mirrors. Alignment of the mirror to foci can be tricky; the spherical reflector (typically a ball) has to be located exactly at the second focus of the ellipse under test.

For testing higher order aspheres, computer generated holograms (CGH's) are often used. But to separate the desired diffractive order, 'enough' aspheric departure is required. Off-axis surfaces can also be tested with CGH's because they can be made to compensate between interferometer and asphere axes, which sometimes (usually) aids in separating the diffraction orders. Drawbacks to the use of CGH's are that they are expensive and unique to each aspheric surface. Hologram manufacturers have also progressed in developing easier to set-up null tests by adding alignment aids on the CGH as well as the diffractive null.

I will include tolerancing in this section as it follows nicely from the previous testing information. In general, the author would like to see aspheres toleranced as loose as possible. As a rule of thumb, he suggests the figure requirements for aspheric surfaces be two of three times that for spherical surfaces. From a lens manufacturing point of view this is very desirable, but from an optical standpoint, may not always be possible.

If surface figure accuracy of the asphere is 1 micron or looser, contact profilometry can be used to qualify the surface in place of a CGH or null lens. This can significantly affect the manufacturing budget for a lens. To this, I would like to add that if contact profilometry is used, more than one trace should be used. Minimum 3 traces spaced 120° apart should be used to ensure that the surface doesn't suffer from astigmatism or some other non-rotationally symmetric defect. Some of the newer profilometers make this task easier to do and can be programmed to do various tests automatically.

Design Guidelines

The author states the following guidelines about using higher order aspheres:

- When optimizing higher order aspheric coefficients, you must design for a larger aperture than required for the clear aperture of the surface in order to control the polynomial inside the clear aperture and safely outside the margin of the clear aperture. Design for an aperture radius at least one polishing lap footprint larger than the clear aperture.
- When optimizing an optical system that uses a higher order aspheric surface, you must optimize for more field points than you would when designing using only spherical surfaces. On-axis, full field and 0.7 field points will sufficiently sample a system with all spherical surfaces, but a system with generalized aspheres should have seven to nine field points in the model.
- Higher order aspheres improve performance in diamond turned optics and molded optics with little or no increase in cost or complexity
- When designed correctly, higher order aspheres can improve the aspheric fit and reduce the departure and difficulty of an aspheric surface.

My comments about these guidelines are that in general they are good rules of thumb but there are occasions where following these would be difficult. For example, optimizing the asphere over an aperture one lap footprint larger than the clear aperture is good practice, but special mechanical constraints may make this difficult to adhere to. Also, the optical designer would need to know the actual size of the polishing footprint.

Allowing this size to be a variable could lead to very small footprints being required which could potentially result in surface slope problems.

This brings us to the steepness of the slope (aspheric slope) section. Designing with higher order terms in the polynomial can lead to surfaces with steep slope and even slope reversals. To allow proper figuring of such surfaces, the size of the polishing footprint must get smaller to address these small features. The author notes that if the departure from best fit sphere is greater than 2 microns aspheric departure per mm of aperture, the aspheric figuring will be slow, it will be difficult to keep the surface smooth and the interferometric testing will likely be sensitive to decenter errors.

Size and geometry of the asphere should be considered carefully to ensure we don’t exceed the mechanical limits of the machine. The author includes some machine capabilities as well as some practical guidelines of aspheric limitations with MRF technology, including max diameters (<240mm), thickness (<90mm), surface figure accuracy (0.008waves rms on aspheres <50mm diameter) to name a few of the more interesting ones. See appendix for the complete table

A concave or convex surface can also affect the manufacturability. In general, a convex surface is desired because it isn’t limited by the polishing wheel diameter as in the case of a concave surface. The polishing tool for a concave surface must be smaller than the radius of curvature of the surface, but a short convex radius can be polished with a large diameter polishing wheel. Additionally, the actual footprint of the polishing tool limits the defect size that can be corrected. The rule of thumb here is for the smallest diameter feature that needs to be corrected, a tool with a footprint of half that diameter should be used to effectively correct the defect. A defect can be a local defect like a ‘bump’ and it can be rotational like spatial periods on the lens

The next guidelines target glass selection. In my experience, these are universal guidelines as most lens manufacturers like to work with stable, non-staining glasses, without steep curvatures whether it is an aspheric surface of not. Unfortunately, the glass types often desired in high performance optical design are the ones that manufacturers don’t like to work with because they are stain sensitive, very soft, heat sensitive, etc., generally poor mechanical properties.

Conclusion

Although some of the information at first glace seems to be obvious to someone who has worked with or designed aspheres before, it does provide a very good base knowledge of the potential problems and pitfalls for a relatively new designer. I believe that author’s intent was to make optical designers, new and experienced, more aware that real mechanical difficulties exist in manufacturing and testing aspheres and staying within a set of soft rules of thumb can help both the optical designer and the lens manufacturer achieve success.

Appendix

Table 1: Transmitted wavefront and aspheric departure for 2 and 3 element designs

	BK7 and Fused Silica			Three element (BK7/BK7/Fused Silica)		
aspheric order	wavefront (waves rms)	aspheric departure at 100 mm diameter (mm)	aspheric departure at 120 mm diameter	wavefront (waves rms)	aspheric departure at 100 mm diameter (mm)	aspheric departure at 120 mm diameter
spherical	43.600000	0.0000	0.0000	1.611	0	0
conic	0.071200	0.7655	1.9960	0.0573	0.1971	0.3783
4th order spherical	0.006867	0.8709	2.3407	0.04866	0.514	1.061
6th order spherical	0.002886	0.7265	1.8722	0.02645	0.5151	0.8062
8th order spherical	0.000811	0.6305	1.5830	0.01098	0.4834	0.7575
10th order spherical	0.001492	0.4564	1.0367	0.005673	0.4636	0.7021
12th order spherical	0.000970	0.4763	1.0798	0.005844	0.4674	0.7247

Table 2: Practical limitations of aspheric figuring by polishing with MRF Technology (at Coastal)

Aspheric amplitude (MRF Polishing only from a polished spherical surface)	50 microns (demonstrated on 90 mm diameter surface)
Aspheric amplitude (aspheric generated and MRF polished)	950 microns departure over 45 mm diameter (see figure 8)
Aspheric slope (MRF only)	2 microns per mm as along as part is < 120 mm diameter
Surface figure accuracy	0.008 wave rms demonstrated on powered aspheres up to 50 mm in diameter
Accuracy of Surface slope	12 microradians peak to peak, demonstrated on space qualified parabolic mirrors 110 mm in diameter over off-axis subaperture

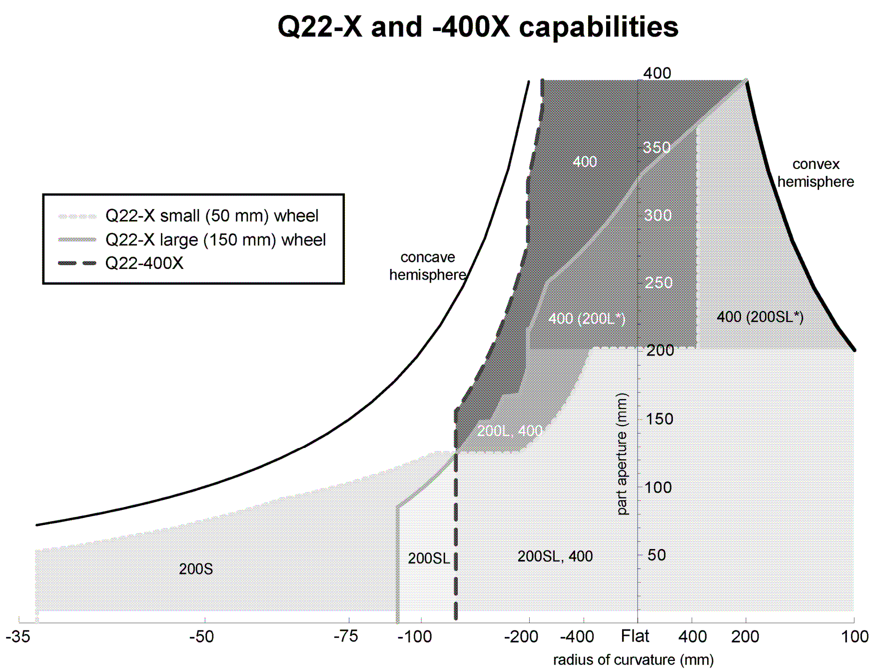


Figure 2: Size capabilities of QED MRF machines (courtesy of QED)

References

J. Kumler, "Designing and Specifying Aspheres for Manufacturability", in *Current Developments in Lens Design and Optical Engineering VI*, Proc. of SPIE 5874 (2005)

Endnotes

[1] QED Technologies, 1040 University Avenue, Rochester NY 13607

[2] Daniel Malacara, *Optical System Testing*, Wiley-Interscience; 2nd edition (January 1992)

[3] "Null tests of Oblate spheroids", by John M. Rogers and Robert E. Parks, Applied Optics, Vol 23, No. 8 (15 April 1984)

[4] "Null test for hyperbolic convex mirrors", Donald Bruns, Applied Optics, Vol. 22, No. 1 (1 January 1983)

[5] "Self-null corrector test for telescope hyperbolic secondaries", Aden B. Meinel and Marjorie P. Meinel, Applied Optics, Vol. 22, No. 4 (15 February 1983)