Synopsis of Technical Report:

"Designing and Specifying Aspheres for Manufacturability"

By Jay Kumler

3 November 2006

Kyle R. Bryant

Interest / Background

The author of this paper recently produced an asphere for me for use in a Night Vision application. This asphere pushed the limits of fabrication, and was in a position in a lens assembly which caused it to have a high sensitivity to surface figure error. Ultimately, the asphere could not be built accurately enough to perform as designed by even the best methods and machines. At the end of the synopsis, an analysis of this asphere is briefly presented as an example of a manufacturing limit.

Relevance

Aspheric surfaces are being employed in exponentially increasing amounts in optical applications today. They allow weight and size reduction while correcting many aberrations. In order to meet the optical demand of high-performance cameras in lightweight applications, this field is extremely important. Anyone in commercial camera optics, "cell-phone cameras", military, or even laboratory applications is interested in saving weight and size at the same time as increasing optical performance.

Kumler appears to write this paper to an audience of optical designers. This paper tries to educate the optical designer in manufacturing and metrology of glass aspheres, and what he/she can do in the design and tolerancing phase of a project to aid manufacturing.

Key Point Summary

Conics Vs. High Order Aspheres

The paper focuses on grinding of glass aspheres by computer-numerically-controlled (CNC) fabrication machines, and polishing using magnetorheological finishing (MRF). These are the current methods by which most fabricators create aspheres in glass. However, the principles are so general that they also apply to diamond-turned plastics and crystals.

Aspheric surfaces are described by the following sag equation:

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

Conic aspheres, or "conics", have only a curvature c, radial aperture component r, and conic constant k. $\alpha 1$ also helps to define the r^2 term which the conic defines. But in general, it is safest to use only k to design and fabricate a conic surface. Higher order aspheres have coefficients for the r^4 and higher terms.

The paper compares simple conics to higher order aspheres, and shows an F/1, 2-element lens design example. The performance of the simple spherical-surface base design is improved upon dramatically when a simple conic surface is placed on the stop lens. Then, a higher-order asphere is placed on the lens, and the performance improves dramatically again. In this example, the author shows that the sag profile departure from a best-fit spherical surface is also less when the higher-order asphere is used as opposed to the simple conic. More departure from a best-fit sphere means that there must be more glass material removed in fabrication. Therefore, in this case, the high-order asphere proved to be both higher performance and lower fabrication cost.

Metrology

Aspheric surface figures are only as accurate as the metrology that is used to measure them. The optical designer needs to design aspheres that also lend themselves to easy measurement. The main benefit of simple conic surfaces is that they do not require elaborate test setups to gauge the quality of fabricated lenses. This is where conics afford cost savings over high order aspheres. Most conics can simply be tested at their natural conic foci either without additional null optics (concave surfaces in reflection), or simply without custom null optics.

Custom null optics are required to fully test the surface accuracy of higher-order aspheres. Simply, a “null optic” forms a reference to which the actual lens surface is optically compared (via interferometry) to gauge accuracy of the lens surface. For high-order aspheres, this requires that a unique null optic be used to test each unique surface profile. The author indicates that the most common and cost effective method for testing high-order aspheres is by using computer generated holograms (CGH). CGH’s are essentially diffractive optical elements that must be used carefully with additional focusing test optics. These additional lenses help select the correct diffracted order of the CGH to form the null and perform the test. This process is rather expensive.

The author says that if an optical designer only needs the surface profile of a high-order asphere to be accurate to >1 micron surface accuracy, then CGH’s and null lenses are not required. A simple profilometer trace of the surface should be able to provide inexpensive results. However, it is my personal experience that profilometers take only one slice across the diameter of a part. It is not easy to accurately make that slice directly through the optical axis, and it may neglect errors that are not in the scan line. This adds an additional inaccuracy that should be considered.

Surfaces with very low aspheric departure slope are easy to test with most interferometers. But interferometers with a very high dynamic range are required to test aspheres with very steep slopes.

Slope Steepness

One of the most important points the author makes is that the steepness of the surface slope on an asphere has the most impact on manufactuability. The aspheric departure magnitude is also important, but in order to fabricate the surface, a grinding and polishing wheel must be able to trace out the surface profile. The wheel radius of curvature sets a minimum local radius of curvature (or surface slope) that can be made.

The author recommends aspheric departure slopes < 2 microns / mm across the radius of the lens to make accurate surface profiles. Also, if the surface slop is greater than this, it becomes very difficult to center the asphere for testing.

Always design aspheres on oversized apertures, at least one “lap footprint” (the polishing machine minimum surface contact area) larger than the actual clear aperture. This helps to control the aspheric departure at the edge of the part, where it is typically the greatest. The nature of the aspheric sag formula makes it possible for crazy departures to occur at larger radii. Designing to an oversized aperture also means that the optical designer must design an aspheric lens to have more edge thickness than a spherical lens would. Also, the author recommends using 7-9 field points in software optical design of an asphere. This gives more sample points to optimize across the part, and helps to keep the surface profile smooth and low-slope.

The author says that a typical wheel radius is 35mm, and a typical lap footprint is 4-5mm. This really limits the aspheric departures of concave surfaces. It is my experience that there are some other methods ("small-ball", and "MR Jet") that can do better than this, but they obviously cost more, and fewer people can do it.

Max / Min Part Sizes

Maximum part size for standard QED polishers is < 240mm diam and < 90mm thick. Standard profilometers are used to test the aspheres "in-process", and have scan lengths of < 120mm and < 200mm. Minimum diameter is controlled by smallest footprint of polisher. The smallest possible diameter is >2x the smallest lap footprint. The author has only done 3X (12mm with 4mm footprint).

Glass Selection

Aspheric lenses should be designed in non-staining (<2 stain in Schott catalog) glass that is preferably high-index. The high index is so that more optical surface power can be obtained with less surface slope.

Tolerancing Concerns

The paper says that an optical designer should always keep the required surface figure accuracy on an asphere to at least 3-4X the surface figure accuracy required of similar spherical surfaces. There are definite production cost benefits if one balances out the required surface figure error in the design of an asphere-containing lens assembly.

Personal, "Real-Life" Example: A Challenging Asphere

The following sag profile in Figure 1 is of an asphere that I attempted to have fabricated. Take this as an example of what currently can ***not*** be done; or at least done accurately. In this figure, "Asp Sag" is the designed surface profile of the asphere. "Sph Sag" is the surface profile of a best-fit reference sphere from which aspheric departure is measured, and from which the glass material is removed in fabrication of the asphere. "Departure" is the difference between these two curves. The magnitude and slope of this curve is the one that determines manufacturing feasibility.

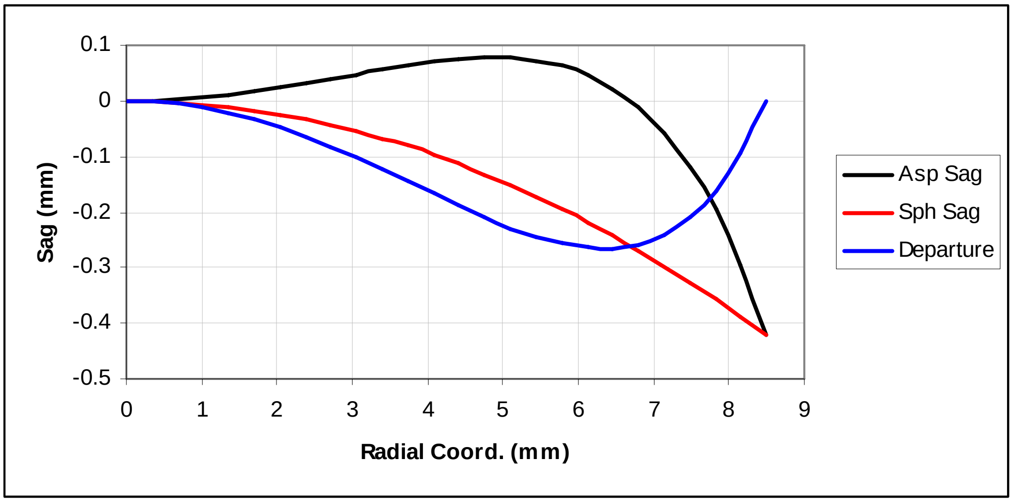

Figure 1: Surface Profile (Sag) of Challenging Asphere

The maximum departure on this asphere was 250µm. Aspheres with up to 400µm have been made successfully, but this particular aspheric departure slope was maximally almost 200 um/mm! That is almost 100 times what Kumler suggests as a maximum slope.

Despite the challenge, this asphere was actually fabricated and tested. The null test in figure 2 was done to measure the wavefront error due to surface figure errors.

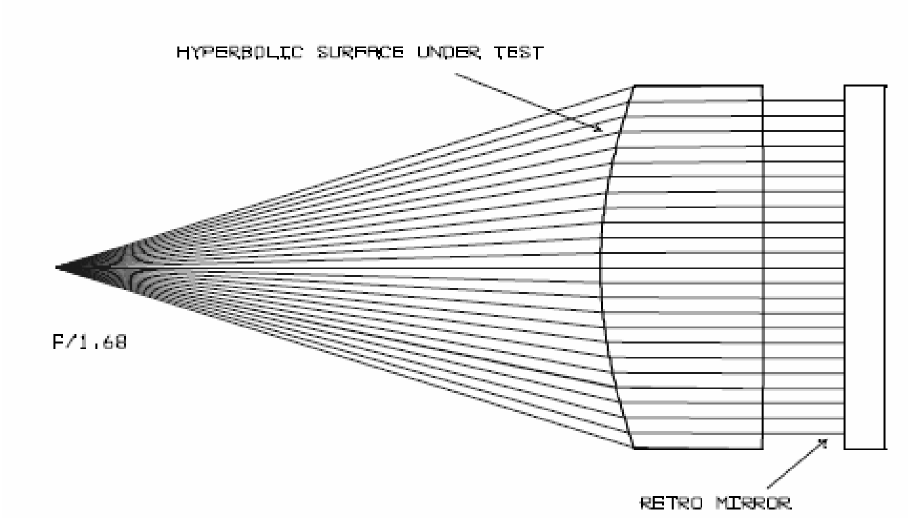

Figure 2: Null Lens Test for Asphere

Even with the best technology applied to building this lens, the asphere simply could not be made accurately to the design. The results of the wavefront test are shown below. They are dominated with high-order spherical and other aberrations that result from the inability to create such a steep surface slope. Therefore, this proves Kumler's point in his paper: aspheric departure slope is the most important characteristic to control when designing aspheres.

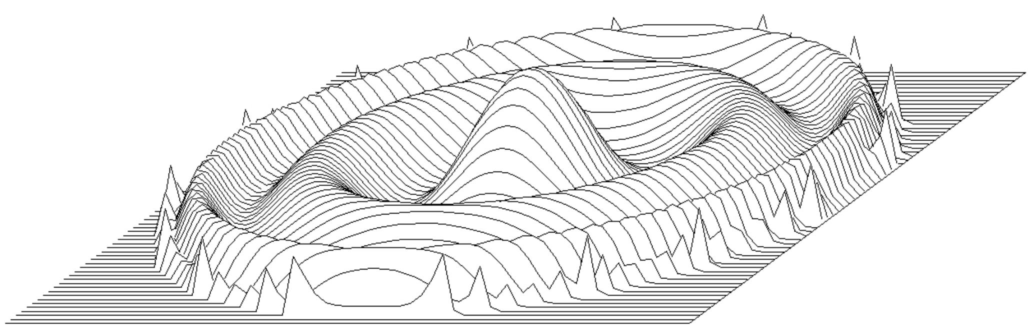

Figure 3: Null Test Wavefront of Challenging Asphere at λ = 632.8nm
PV error: 1.71 waves, RMS error: 0.29 waves

References:

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

J. Kumler, K.Bryant: Data from asphere fabrication