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Concepts and misconceptions in the design and fabrication of optical assemblies

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Abstract

With any kind of precision manufactured assembly, the transformation of a concept into a useful product depends on how well the design has been tailored to suit the available methods of fabrication and inspection. Optics is no exception. The tolerances on the drawing must correlate to a method of fabrication and a method of measurement. Among the topics discussed in this paper will be:

1. Some practical aspects of radius tolerancing.
2. The tolerancing and measurements of lens centration.
3. Thickness tolerances in the optical shop.
4. Why method is often more important than tolerances.

Introduction

The skilled designer, using one of the modern computer programs can make a fairly realistic assessment of what the tolerances on an optical system should be. If the designer knows nothing about optical manufacturing methods, and little about mechanical manufacturing methods the excellent programs may provide nothing but meaningless numbers. Worse yet, when a computer tolerance analysis is not available, the draftsman may refer to some previous drawing from which he copies the mistakes of the past. By applying some knowledge of how optical components are made and measured, these mistakes can be avoided, to a large degree, even in the absence of a computer tolerance analysis.

Radius tolerancing

Within the last year, a national magazine published an article purporting to describe what kind of components were easy to make, and which were difficult, based on the tolerance level. In this article, the tolerance level on radii was referred to in percentage of the nominal radius. Thus, any 0.1% tolerance is supposedly more difficult to make than any 1.0% tolerance. This is certainly true for a single designated radius, but is totally false as a general statement. Let us look at some specific examples. Suppose we have a system in which all of the elements are 2.0 inches in diameter. Suppose also that the longest radius is 500 inches and the shortest is 3.0 inches. If we change the 500 inch radius by 0.1% to 500.5, the sagitta of the curve over the 2.0 inch diameter will change by 0.000001 inch or approximately λ/20! On the other hand with the same 0.1% tolerance, the sagitta of the 3.0 inch radius will change by .00018 inch or approximately 9λ. In terms of saggita tolerance there is a factor of 180 between the two tolerances. Now let us examine what happens when we loosen the 500 inch radius tolerance to 1.0%. In this case, the sagitta tolerance is still only 0.00001 inch or λ/2 which is 18 times more difficult than the 0.1% tolerance on the 3 inch radius.

A more reasonable method of general tolerancing is to set a fixed tolerance on the sagitta. After all, our ability to measure sagitta is our limiting factor in our ability to measure radii. This is true whether we use a spherometer or a lens bench or an interferometer. The case of the spherometer is obvious. Not as obvious is the dependence of the lens bench or interferometer measurement on sagitta differences. However, if we eliminate the scale on the bench or interferometer as a source of error, the accuracy of measurement is dependent on our ability to set the instrument focus, first on the surface and then on the center of curvature. Focusing of a microscope can be accomplished to an accuracy of approximately ± λ/4 over the extent of its converging wavefront. This microscope projects out a spherical wavefront which, ideally, should be focused to a point at the center of curvature of the surface being measured. If the focus is shifted from this ideal point, the emergent wave will strike the surface either at the center first and then the edge or vice-versa depending on the direction of focus shift. This is illustrated in figure 1. The deformation of the reflected wave will be equal to the sagitta difference between the incident wave and the surface. Thus a focusing accuracy of ± λ/4 corresponds to a setting accuracy of ± λ/4 in the sagitta of the surface. There will be a similar accuracy tolerance in focusing on the surface. The total sagitta accuracy will combine the two setting uncertainties and will be somewhere between ± λ/2 and ± λ/4 depending on the microscope NA. If the NA is just sufficient to fill the surface being measured from the center of curvature, then the accuracy is ± λ/2. With a higher NA objective the surface setting will be improved. At any rate, we see that wavefront focusing sensitivity is almost directly translatable into sagitta error.

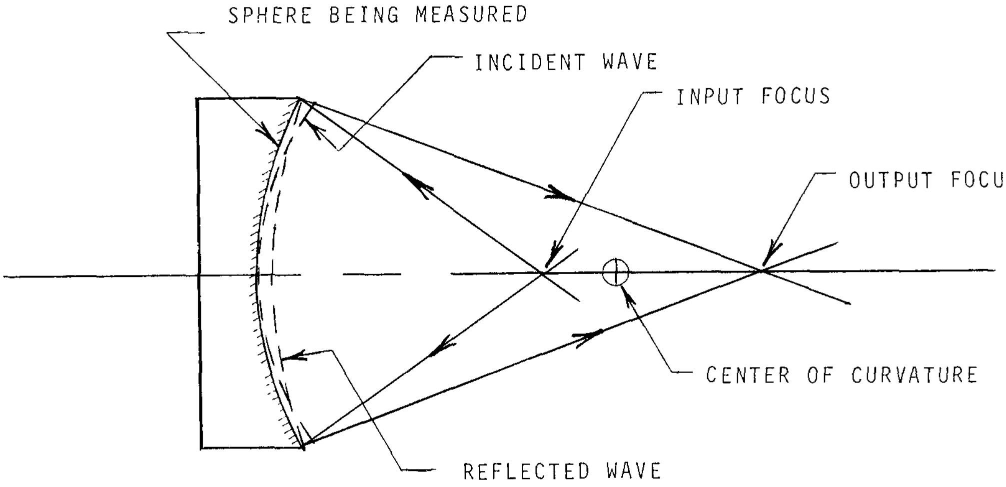


Figure 1

The same argument applies when the foci on the surface and at the center of curvature are sensed interferometrically. The accuracy of each setting can be as small as $\lambda/20$ using purely visual interpretation of fringe straightness. Under the rare circumstances where a more sensitive setting is required, a computer analysis of the fringe pattern at each setting can be used. It should be noted that the scale on the bench or the interferometer may not be capable of measuring to the accuracy obtainable in setting focus. This, however, is a problem in instrumentation and not in method.

The least accurate, but most widely used device for measuring radii is the spherometer. The usual sagitta sensitivity is of the order of 0.0001 inch (5λ), although some spherometers may be more sensitive than this.

Sagitta tolerances can be converted into radii tolerances with the following equation,

$$\Delta R = \frac{\Delta x}{1 - \frac{R}{\sqrt{R^2 - d^2/4}}}$$

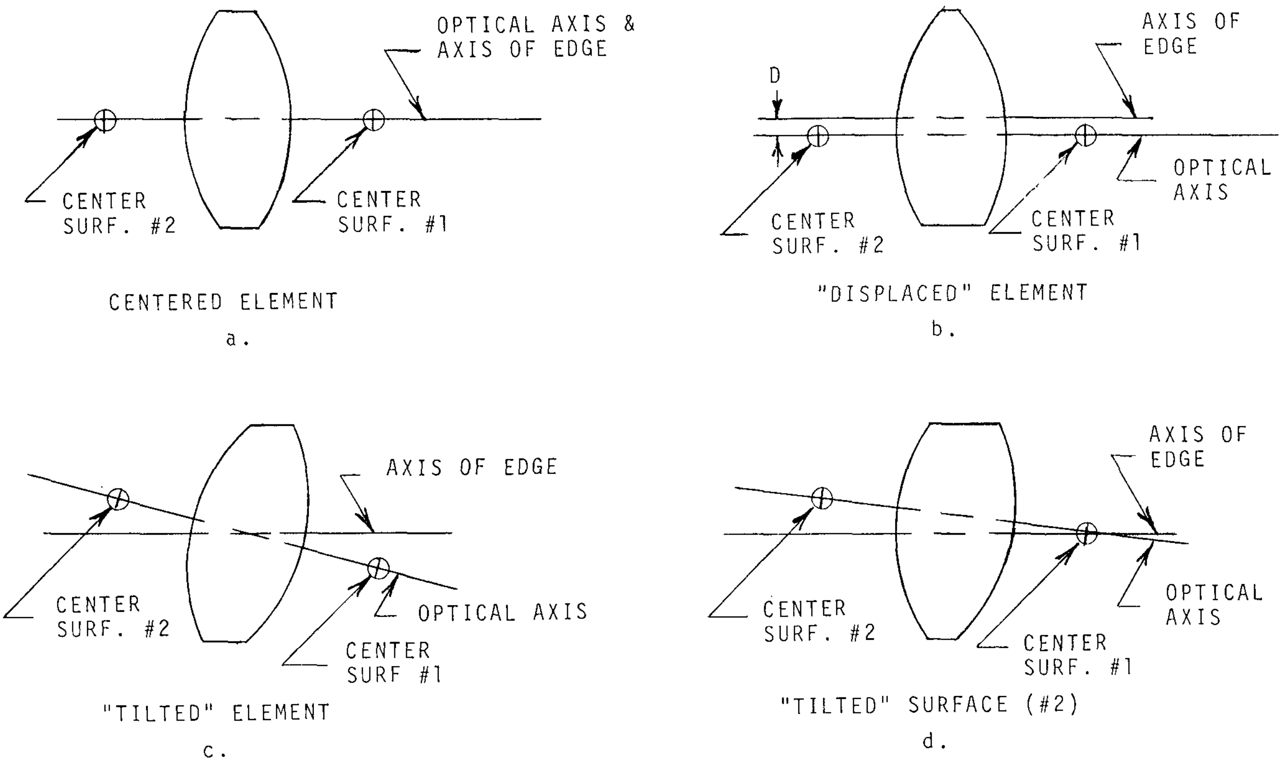
where:

ΔR = Radius tolerance
Δx = Sagitta tolerance
R = Radius of curvature
d = Diameter over which the tolerance applies

As a general rule, sagitta tolerances are set for the clear aperture diameter. A tight tolerance is 0.000005 inch, a moderately close tolerance is 0.00005 inch and a loose tolerance is 0.0001 inch. A tolerance analysis may establish either tighter or looser tolerances.

Centration tolerancing

Centration is one of the least understood subjects in lens design and fabrication, so let us start with some fundamentals. The optical axis for a single element is easy to define. It is the straight line joining the centers of curvature of the two surfaces. (A single spherical surface has no unique axis). Using the definition of the axis above, it is easy to illustrate what a centered lens is, and what some forms of decentration are. In figure 2a. we have a centered lens. Its outside diameter has been made concentric with the optical axis by proper edging. In figure 2b. the axis of the cylindrical edge has been displaced by an amount, D, from the optical axis. In figure 2c., the axis of the cylindrical edge crosses the optical axis in the center of the lens element. This type of decentration can be defined as "tilt." In Figure 2d., the center of curvature of one surface lies on the axis of the cylindrical diameter, but the other center of curvature does not. The offending surface can be designated as either being tilted or displaced. There is no difference between tilt and displacement of a single surface.



CENTERED ELEMENT
a.

"DISPLACED" ELEMENT
b.

"TILTED" ELEMENT
c.

"TILTED" SURFACE (#2)
d.

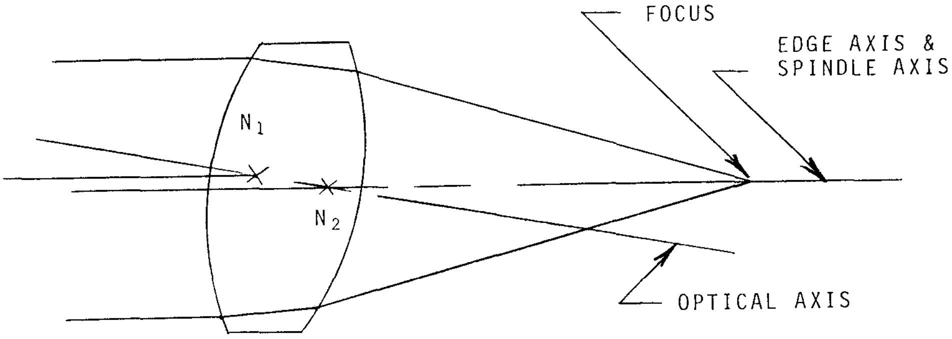
Figure 2.

In general, an actual decentered element will not exactly fit any one of these simple cases. Instead, the two centers of curvature will lie at arbitrary distances from the axis of the edge. When a stack up of group of lenses is made, even when these lenses fit the internal bore of the mount with essentially "zero clearance", the centers of curvature will not fall on a single line, but will make a three dimensional array of points. We always hope that all of these points will fall very close to the axis of the mount; the closer the better.

In 41 years of observation, I have found that most mechanical engineers, when first introduced to the problem of optical centration within a mount will try to solve the problem by making each element adjustable with six degrees of freedom. What they fail to realize is that this also must imply a method of measurement to determine when each adjustment has been made correctly. It is not enough to get one center of curvature onto some predefined axis, but we must get both centers on to that same axis. We must then repeat this process until all surfaces of all elements are similarly aligned. All of the practical methods of in-assembly centration used today require that one surface be centered by means of a precision machined seat, while the opposite surface is "run in" to a prescribed tolerance and then is "potted" in place using an elastomeric compound. No lenses are made totally independently centerable. Except for the most expensive lenses where the surface tilts are measured in microradians, in-assembly centration procedures are too expensive and too time consuming. Instead, we usually depend on tight tolerancing of element centration and a close fit between the O.D. of each element and the I.D. of each bore. For a more complete discussion of the mounting problem, the reader should consult reference 1.

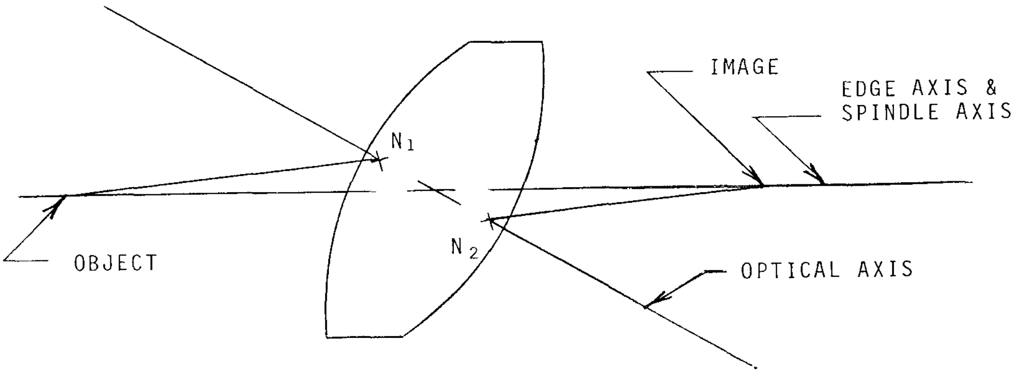
How is centration measured? As we saw in the previous paragraph, we can try to measure the surface tilt or the displacement of the center of curvature from the axis of the O.D. of the element. Tilt can be measured, either by an optical reflection measurement or by mechanical indicator runout while on the centering and edging spindle. Once the lens is off of the spindle, it becomes infinitely more difficult. The usual measurement requires us to mount the lens on a testing spindle by means of a collet or some other chucking device. In mounting the lens we must get the edge to run true to the spindle axis while simultaneously one surface is in contact with a true running shoulder on the same chuck. The spindle is hollow and a transmitted image is observed for runout as spindle is turned. If we follow the procedure outlined in MIL-O-13830, the projected image will be collimated and the image will be located at the focal point of the lens. Thus, for a centration call-out of 3.0 minutes (0.00087 radian) the radius of the image runout will be 0.00087f, where f is the focal length of the element being tested.

There are some problems with this method which are worth mentioning. First, for an element requiring centrations in the region of a few microradians, rather than milliradians, it will be virtually impossible to build as much precision into the measuring device as we have built into our edging equipment. All chucks have runout, whereas the centering bell is cut in place on the edging spindle and is limited in runout only by the precision of the spindle bearings. Second, for short focal length lenses, the image runout is very small and will be difficult to measure. Still another important factor in transmission centration measurements is the inherent potential for error in thick elements (finite separation of nodal points). If, as illustrated in figure 3a., the second nodal point is on the spindle axis, but the first is not, the collimated transmission method will show "perfect" centration in an obviously decentered element. There is a similar case when finite conjugates are used.



LENS TILTED ABOUT THE SECOND NODAL POINT
(NO IMAGE RUNOUT FOR A COLLIMATED INPUT)

a.



RAY FROM OBJECT TO N_1 PARALLEL TO RAY FROM N_2 TO IMAGE
(NO IMAGE RUNOUT FOR A FINITE OBJECT DISTANCE)

b.

Figure 3.

This is illustrated in figure 3b. In this case, the first nodal point is displaced by the same angle at the object point as the second nodal point is at the image point. This also shows no image runout on rotation. Although the chances of either of these cases occurring precisely as illustrated is rare, the possibility of approaching these conditions and thus getting an erroneous measurement is dictated by Murphy's Law.

Thickness tolerances

During the fabrication process, thicknesses are both difficult to measure and even more difficult to maintain to a close tolerance. This is due to the peculiarities of the optical fabrication process, and most particularly to the methods which must be used to hold the glass while it is being processed. Lens elements cannot be held in a mechanical chuck while being processed. The surface distortion resulting from the lightest kind of clamping pressure is too great to be tolerated when manufacturing even the lowest quality optical surface (except perhaps for opthalmic lenses). Instead, components are held on a blocking tool during grinding and polishing by means of blocking waxes or pitches. After mounting in this fashion, the second surface is no longer accessible, and no direct measurement of thickness can be made. Instead the component thickness is gaged by measuring the total build-up of tool, wax and glass. If some precision is lost in this process, it is not surprising.

An additional problem is imposed by the necessity for producing a surface which is free from pits and scratches. The operator can not always quit when the nominal thickness has been reached but may have to run it undersize to remove a scratch. If such procedures are not followed, then the scrap rate is too high and the components too costly. Even after the element is finished, care must be taken to prevent marring surfaces during subsequent thickness measurements. The need for protecting the surface limits our ability to gage thickness accurately. Because of the many factors contributing to the difficulties of maintaining tight thickness controls, the optical industry has traditionally utilized selective assembly for achieving high performance systems. This selective assembly may consist of something as simple as changing an airspace in order to bring the most critical aberration (usually spherical aberration or off-axis astigmatism) under control. In the most critical high performance lenses, the entire assembly may have to be respaced by computer optimization once the thicknesses of all the elements have been measured.

Method vs. tolerances

The selective assembly procedure discussed above is just one of the cases where method may prove to be far more important than tolerances. Perhaps the most important area where method is more important than tolerances is in machining of lens mounts. The one cardinal rule is to machine all critical bores pilot diameters, lens seats and retaining ring threads in a single chucking. This will insure that they are concentric or perpendicular to one another within the accuracy of the lathe spindle. Traditionally, machinists will use the machining method that will take the least time. This may mean turning the part on one machine and threading on another. The machinist will use up all of the tolerance you give him just to save time. As in the case of measuring the centered lens, it is difficult to provide an accurate means of inspection of concentricity of bores and perpendicularity of seats. The inspection set-up process itself is usually suspect, and is not likely to yield reproducible measurements.

I will illustrate this last point by a simple experiment carried out 20 years ago on some precision aerial reconnaissance lens cells. These had an outside pilot diameter and seat and an outside thread which mated into a shutter. The thread and pilot were machined in a single chucking, with the O.D. of the pilot held to ± 0.0005 inch. The mount was then turned over and threaded into a pot chuck which had an inside pilot which was only 0.0002 to 0.0003 inch larger than the maximum O.D. of the pilot on the cell. The internal thread in the pot chuck was deliberately made loose, in the theory that it would not affect centration. The pot chuck was never removed from the lathe spindle after machining in order to preserve its concentricity to the machine axis. To machine the lens seats and bores, the partially machined cells were threaded into the pot chuck, seated on a true running seat and held "concentric" by the close fitting pilot. Then all bores and seats were machined. We found that after machining, if we removed the cell, rethreaded it into the pot chuck and indicated the bores, we detected a runout which was often very close to the diametral clearance between the inside and outside pilot diameters. In addition, when the experiment was repeated several times, using the same cell, the "high spot" would move around in a random fashion. The conclusion was reached that each time the cell was rethreaded into the pot chuck, different hand pressures would force it to one side in the loose thread where it would make a first hard contact at one point and then pivot about that point until restrained by the line contact between the two pilot diameters. Obviously, the same thing happened when the cells were threaded into the shutter, except that the clearances were somewhat larger and the decentrations more severe. Such a mounting scheme was just barely adequate for the reconnaissance lenses of that era. Today, many of the lenses being built for both industrial and military users have optical designs many times superior to those of 20 years ago. However, unless the problem of centration is understood by the mechanical designer, the optical shop technician, the machinist and the assembler, that superior performance will not be realized in the fabricated lens assembly.

In the most critical assemblies, the "elastomeric" mounting method described by Bayar may be required. In other less critical, but still high performance systems, tight tolerances, coupled with intelligent use of the best machining methods will spell success. In those cases, the cardinal rules are: 1. Eliminate "loose joints;" 2. Make every machining operation you can in one chucking; and 3. Center and edge the lens elements to one degree higher precision than you think you need.

References

1. Bayar, M., Mechanical Design Aspects of Optomechanical Engineering, SPIE Volume 193-11
2. Smith, W. J., Modern Optical Engineering, McGraw-Hill , 1966
3. Malarca, D., Optical Shop Testing, John Wiley and Sons , 1978
4. Scott, R. M. Applied Optics and Optical Design, Vol. III, R. Kingslake, Editor, Academic Press , 1965
5. Twyman, F., Prism and Lens Making, Hilger and Watts, Ltd. , 1957