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TOLERANCING TECHNIQUES

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5.1 GLOSSARY

a	relative tolerance error
BK7, SF2	types of optical glass
C to F	spectral region 0.486 to 0.656 μm
f-number	relative aperture as in $F/2.8$
n	refractive index
$r1, r2, r3, r4$	radii of curvature of surfaces
$t2$	airspace thickness in sample lens
V	Abbe number or reciprocal dispersion
W	wavefront or pupil function
x	change factor
Δ	finite change in a parameter
δ	small change in a parameter
λ	wavelength

5.2 INTRODUCTION

Determination of the tolerances on an optical system is one of the most important parts of carrying out an optical design. No component can be made perfectly; thus, stating a reasonable acceptable range for the dimensions or characteristics is important to ensure that an economical, functioning instrument results. The tolerances attached to the dimensions describing the parts of the lens system are an important communication by the designer to the fabrication shop of the precision required in making the components and assembling them into a final lens.

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The tolerances are related to but are not the same as the specifications. Setting specifications is discussed in Chap. 4. The tolerances are responsive to the requested system specifications and are intended to ensure that the final, assembled instrument meets the requested performance. The specifications placed on the individual lens elements or components are derived from the tolerances. Thus there is an interactive relation between the tolerancing activity and the setting of specifications. The system specifications drive the tolerances that need to be determined, and the tolerances are used in setting the specifications for the components of the system. The reality is that neither of these processes can be done fully independently.

At this point it is important to note that most optical design programs include a tolerancing utility that can be used to generate and distribute tolerances automatically once a few questions about goals have been answered by the designer. This appears to be a seductively simple process that is usually quite useful, but can be very disastrous if used uncritically by anyone who does not understand the basics of the process being carried out.

There are three principal issues in optical tolerancing. The first is the setting of an appropriate goal for the image quality or transmitted wavefront to be expected from the system. The second is the translation of this goal into allowable changes introduced by errors occurring on each component of the system. The third is the distribution of these allowable errors against all of the components of the system, in which some components of the optical system may partially or completely compensate for errors introduced by other components.

In this chapter, some basic approaches to distributing tolerances within an optical assembly are discussed. The examples will deal with tolerancing to meet a specified wave-front error and level of image quality. Similar principles apply to nonimaging optical systems, once the procedures necessary for relating errors in components or alignment to the specified operating requirements are established. The user will obviously have to adapt these approaches to the specific system being toleranced.

Optical versus Mechanical Tolerances

The tolerances on mechanical parts, in which a dimension may be stated as a specific value, plus or minus some allowable error, are familiar to any engineer. For example, the diameter of a rotating shaft may be expressed as 20.00 mm + 0.01/−0.02 mm. This dimension ensures that the shaft will fit into another component, such as the inner part of a bearing, and that fabricating the shaft to within the specified range will ensure that proper operational fit occurs. These tolerances may include the effect of environmental effects, such as operating temperature or lubrication needs, on the mechanical assembly.

Optical tolerances are more complicated, as they are generally stated as a mechanical error in a dimension, but the allowable error is determined by the effect upon an entire set of wavefronts passing through the lens. For example, the radius of curvature of a surface may be specified as 27.00 mm ± 0.05 mm. The interpretation of this is that the shape of the optical surface should conform to a specific spherical form, but remain within a range of allowable curvatures. Meeting this criterion indicates that the surface will perform properly in producing a focused wavefront, along with other surfaces in the optical system. Verification that the specific component tolerance is met is usually carried out by an optical test, such as examining the fit to a test plate. Verification that the entire system operates properly is accomplished by an assembled system test in which a specified image quality criterion is measured.

Basis for Tolerances

The process involved in setting tolerances begins with setting of the minimum level of acceptable image quality. This is usually expressed as the desired level of contrast at a specific spatial frequency as expressed by the modulation transfer function. Each parameter of the system, such as a radius of curvature of a surface, is individually varied to determine how large an error in each component is allowed before the contrast is reduced to the specified level. This differential change is then used to set the allowable range of error in each component.

In most cases, direct computation of the change in the contrast is a lengthy procedure, so that a more direct function, such as the rms wavefront error, is used as the quality-defining criterion. In other cases, the quantity of importance will be the focal length, image position, or distortion.

In nonimaging systems, the beam divergence or the uniformity of illumination after passage through the system may be the criterion of interest.

Relating the computed individual errors in the system to the tolerances to be specified is not always a simple matter. If there are several components, some errors may compensate other errors. Thus, it would be easy to assign too tight a tolerance for each surface unless these compensating effects, as well as the probability of a specific distribution of errors, are used in assigning the final tolerances.

Tolerance Budgeting

The method of incorporating compensation of one error by another, as well as the likelihood of obtaining a certain level of error in a defined fabrication process, is called *tolerance budgeting.* As an example, in a lens system it may be found that maintaining the thickness of a component may be easier than keeping the surfaces of the component at the right spherical form. The designer may choose to allow a looser tolerance for the thickness and use some of the distributed error to tighten the tolerance on the radius of curvature. In other cases, the shop carrying out the fabrication may be known to be able to measure surfaces well, but has difficulty with the centering of the lenses. The designer may choose to trade a tight tolerance on the irregularity of the surfaces for a looser tolerance on the wedge in the lens components.

Finally, the effect of a plus error on one surface may be partially compensated by a minus error on another surface. If the probability of errors is considered, the designer may choose to budget a looser tolerance to both surfaces.

This budgeting of tolerances is one of the most difficult parts of a tolerancing process, since judgment, rather than hard numbers, is very much a part of the budget decisions. It is advisable for the engineer carrying out the tolerance budgeting to do some modeling of the system performance using trial sets of parameter variations based on the tolerances that have been obtained. This verification serves as a method if ensuring that the tolerances are indeed reasonable and justified.

Tolerance Verification

Simply stating a set of allowable errors does not complete the integrated process of design and fabrication. The errors must be measurable. Measurement of length can be gauged, but has to be within the capabilities of the shop fabricating the optics. Measurement of error in radius of curvature requires the use of an interferometer or test plates to determine the shape of the surface. Measurement of the nonspherical component of the surface, or the irregularity, requires either an estimate from the test plate, or a computation of the lack of fit to a spherical surface based on measured fringes.

Finally, the quality of a completed lens must be measurable. Use of a criterion that cannot be measured or controlled by the shop or by the user is not acceptable. The contrast mentioned is not always measurable by the optical shop. The surface errors as measured by an interferometer or by test plates are common.

As shown in the Chap. 4 on specifications, the average or rms wavefront error can be related to the level of contrast, or modulation transfer function (MTF), that can be expected in the image. In addition, measurement of the final wavefront from an assembled optical system is most frequently obtained by an optical shop in a summary method by using an interferometer. For this reason, wavefront tolerancing methods have become the most commonly used methods of defining and verifying tolerances.

5.3 WAVEFRONT TOLERANCES

The rms wavefront error tolerancing method will now be used as an example of the approach to evaluating the tolerances required to fabricate a lens. An example which discusses the axial image tolerances for a doublet will be used to provide insight into the tolerancing of a relatively simple system. Most optical tolerancing problems are far more complex, but this example provides an insight into the methods applied. The specific example selected for this chapter is an airspaced achromatic

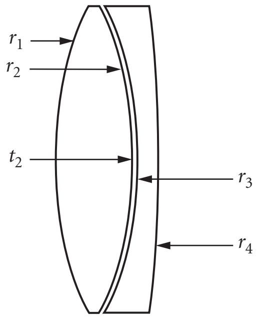

FIGURE 1 Drawing of the doublet lens used for tolerancing.

doublet using BK7 and SF2 glasses, *F*/2.8, 100-mm focal length. The lens design is nominally of moderately good quality, and is optimized over the usual *C* to *F* spectral range, with balanced spherical aberration, and is corrected for coma.

Figure 1 is a drawing of the sample doublet used in this chapter. The locations of the four radii of curvature and the airspace to be toleranced are indicated. The number of possible errors that actually can occur in such a simple lens is surprisingly large. There are four curvatures, two thicknesses, one airspace, and two materials that may have refractive index or dispersion errors. In addition to these seven quantities, there are two element wedge angles, four possible tilts, and four decenter possibilities, plus the irregularity on four surfaces and the homogeneity of two materials. So far, there are 21 possible tolerances that are required in order to completely define the lens. For interfacing to the lens mount, the element diameters, roundness after edging, and cone angle on the edges must be considered as well. More complex systems have far more possible sources of error. For the example here, only the four radii and the airspace separation will be considered.

Parameter Error Quality Definitions

The starting point for a tolerance calculation is the definition of a set of levels that may be used to define the initial allowable range of variation of the parameters in the lens. The magnitude of these classes of errors is determined by experience, and usually depends upon the type of fabrication facility being used. Table 1 presents some realistic values for different levels of shop capability.

These values are based on the type of work that can be expected from different shops, and serves as a guide for initiating the tolerancing process. It is obvious that the degree of difficulty in meeting the quality goals becomes more expensive as the required image quality increases.

Computation of Individual Tolerances

The individual tolerances to be applied to the parameters are obtained by computing the effect of some arbitrary but reasonable parameter changes upon the image-quality function. For the example doublet, if made perfectly with no errors in the individual components or assembly, the nominal amount of rms wavefront error at the central wavelength is 0.116 waves, rms. It is determined by the user from consideration of the needs for the application that the maximum amount of error that is acceptable is 0.15 waves, rms. Thus a distribution in allowable errors that results in no greater than about a 0.15 wavelength rms wavefront error would produce an acceptable system. The tolerancing task is to specify the tolerances on the radii of curvature and the separation between the component surfaces such that the goal is met.

TABLE 1 Reasonable Starting Points for Tolerancing a Lens System

Parameter	Commercial	Precision	High Precision
Wavefront residual	0.25 wave rms	0.1 wave rms	<0.07 wave rms
	2-wave peak	0.5 wave peak	<0.25 wave peak
Thickness	0.1 mm	0.01 mm	0.001 mm
Radius	1.0%	0.1%	0.01%
Index	0.001	0.0001	0.00001
V-number	1.0%	0.1%	0.01%
Homogeneity	0.0001	0.00001	0.000002
Decenter	0.1 mm	0.01 mm	0.001 mm
Tilt	1 arc min	10 arc sec	1 arc sec
Sphericity	2 rings	1 ring	0.25 ring
Irregularity	1 ring	0.25 ring	<0.1 ring

The reason for the choice of 0.15 wave rms is indicated by Fig. 2. The designer experimented with several choices of focus position to obtain a set of plots of the MTF for different amounts of error. This is not a completely general conclusion since the source of error produces an rms error which may not be the same for every source of error. But the samples permit the intelligent selection of an upper bound to the required error. In a lens with more sources of error, and with larger amounts of aberration in the basic design, setting up an example such as this is extremely important to avoid an error in the goal for the final image quality.

The first computation of the effect of nominal changes in the parameters on the rms wavefront error leads to the results in Table 2. (Only the radii and thickness are considered for this example.) The two columns for rms wavefront effect are first, for the aberration if no adjustment for best focus is made, and second, permitting the establishment of best focus after assembly of the lens.

Table 2 shows that the effect of a change in the parameter will have an effect proportional to the change, but that the factor relating the change to the resulting wavefront error is different for the various parameters. The amount of change permitted if the parameter is not compensated by allowing an adjustment for best focus is quite small. Any one of the parameters would have to be maintained within a range far less than the delta used in computation. The allowance of a compensating focal shift does greatly loosen the tolerance.

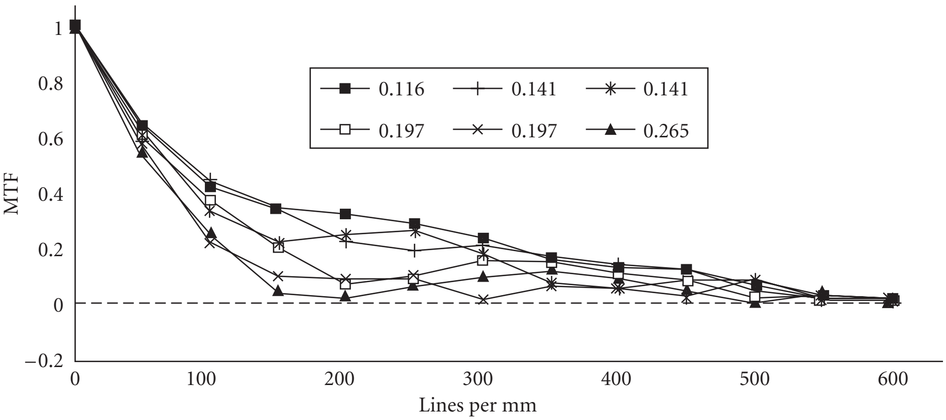

FIGURE 2 Some examples of the effect of various rms errors on the MTF of the sample doublet. (The rms error is stated in wavelengths.)

TABLE 2 Finite Differentials for Computing Tolerances

Parameter	Delta	Rms Uncompensated	Rms Compensated
*r*1	0.1%	0.740	0.117
*r*2	0.1%	1.187	0.171
*r*3	0.1%	1.456	0.157
*r*4	0.1%	0.346	0.110
*t*2	0.025 mm	1.155	0.152

Since the acceptable goal is 0.15 waves, rms, the amount of change of an individual parameter to attain the acceptable level is about 50 times that of *r*1 and *r*4, but the change of 0.1 percent would be excessive for *r*2 and *r*3. The allowable change for *t*2 alone would be just about the delta of 0.025 mm.

Combination of Tolerances

No parameter in a lens lives alone. The effect upon the image will be the result of combining the effect of all of the errors. If the errors are uncorrelated, then the usual statistical summing of errors can be used. This states that the total amount of aberration produced by the errors can be found by using

$$W_{\mathrm{rms}} = \sqrt{\sum_i W_i^2} = \sqrt{\sum_i \left(a_i x_i \frac{\partial W_{\mathrm{rms}}}{\partial x_i} \right)^2}$$

where the sum is taken over the *i* parameters of interest. The *x* factors are the amount of change used in computing the change of wavefront error and the *a* factors are the relative amount of tolerance error allotted to each parameter in units of the delta used in the computation.

There are implicit assumptions in the application of this method to distributing tolerances. The principal assumption is that the fabrication errors will follow normal gaussian statistics. For many fabrication processes, this is not true, and modification of the approach is required.

For the example of the doublet, Table 3 can be generated to evaluate the different possibilities in assigning tolerances. The allowable change in rms wavefront error is 0.033 waves; thus the root sum square of all of the contributors must not exceed that amount.

In Table 3 the first column identifies the parameter, the second states the delta used in the computation, the third states the amount of wavefront error caused by a delta amount. The final two columns show different budgeting of the allowable error. Distribution 1 loosens the outer radii and the thickness at the cost of maintaining the inner radii very tightly. Distribution 2 tightens the outer radii and spacing tolerances, but loosens the inner radii tolerances. Depending upon the capabilities of the shop selected to make the optics, one of these may be preferable.

The interpretation of these statistical summations is that they are the sum of a number of different random processes. Thus, if the interpretation of each of the values given is the width of a normal distribution, which implies that 67 percent of the samples lie within that value, then 67 percent of the resulting combinations will lie within that range. If the interpretation is a two- or three-sigma value, the interpretation of the result follows similarly.

TABLE 3 Two Possible Tolerance Distributions for the Doublet

Parameter	Delta	Coefficient	Distbn. 1	Distbn. 2
*r*1	0.1%	0.00071	10.0	0.1
*r*2	0.1%	0.05440	0.25	0.4
*r*3	0.1%	0.04069	0.25	0.4
*r*4	0.1%	0.00069	10.0	0.1
*t*2	0.025 mm	0.03589	0.75	0.5
		rms change	0.033	0.033

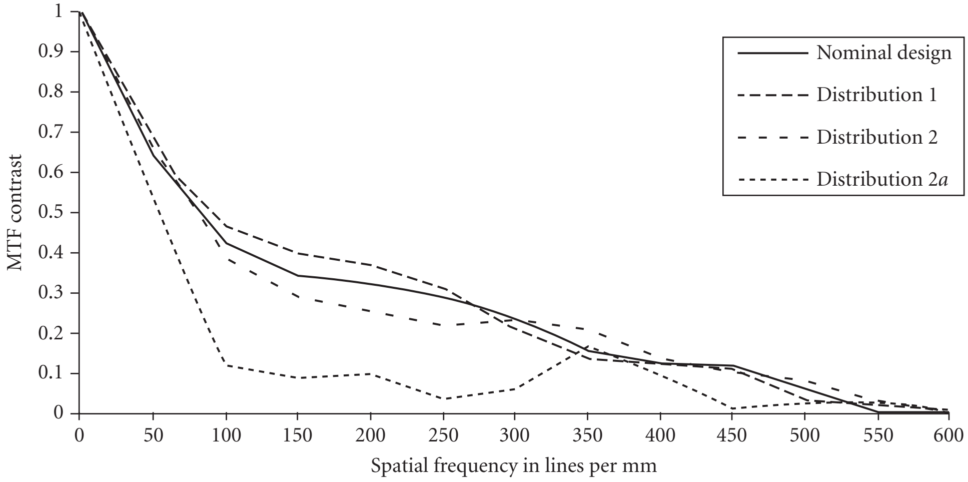

FIGURE 3 The resulting effect of different tolerance budgets for the sample doublet.

Figure 3 shows the effect of the various choices of allowable error distribution on the modulation transfer function of the lens. Either of the distributions stated in Table 3 provides an acceptable lens. For comparison, the allowable tolerances were doubled to provide distribution 2*a*, which is clearly not an acceptable lens. A spot check of some sample distributions is always relevant when doing tolerancing just to ensure that a reasonable relation between the toleranced system and acceptable image quality exists.

In any manufacturing process, the individual statistics will not necessarily follow a random rule. The interpretation is somewhat modified, but the principle still remains. In some cases, parameters may not be independent. For example, in the doublet there is a linking between the values of *r*2 and *r*3 that would loosen the tolerances if both are in error in the same direction. This could be used to advantage if the manufacturing process is carefully defined.

Use of Compensators

The use of compensators to loosen the tolerances was indicated above. An example of compensation for aberrations can be seen from a single lens element. If the first curvature is varied, both the element power and the spherical aberration from the element will change. However, a specific change of the second radius can restore the focal position and reduce the change of spherical aberration. Thus the tolerance allowed to the first curvature needs to take into account the possibility of a correlated or deliberate change in the second curvature. It is evident that the proper use of compensators can greatly loosen the tolerances applied to a surface.

A compensation that is frequently employed is the establishment of the correct focal position after assembly of the lens. If this procedure is followed, the individual tolerances on the surface of the elements can be loosened. It is obvious that the tolerancing and the development of a plan for fabrication and assembly must be coordinated.

5.4 OTHER TOLERANCES

Often, a particular optical parameter for the lens must be specified and maintained. Sometimes, for example, the focal length or back focus must be obtained within some tolerance. The computation of these paraxial constants for the lens can be made in the usual manner, and tolerances obtained by using differentials relating each of the parameters to the quantity, such as the focal length, and then distributing the tolerances in a manner similar to that shown above for the doublet in Table 3.

Boresight

The pointing direction, or boresight, for a lens is sometimes of interest. Errors in boresight are usually due to asymmetric fabrication or mounting errors for the lens. In the simplest manner, one needs simply to trace an axial ray through the lens, and evaluate the direction of this ray as a result of introducing tilts and decenters of the surfaces, or of entire components. Tolerances on the lens parameters can be obtained by the procedure described for the doublet above, substituting the boresight error for the wavefront error.

Distortion

Distortion is the failure of the lens to provide a constant mapping from object space to image space. There are alternate interpretations for this error, which can have radial components due to symmetric errors in the lens, as well as tangential components from tilt and decenter of the lens components. This can be toleranced in the usual manner, but may be related to some general properties of the lens, such as the overall glass thickness of the components. In the simplest case, the tolerances upon distortion may be obtained from direct aberration computation. In complex cases, it may be necessary to compute the actual location of the centroid of the image as a function of image position and in the best image location.

Assembly

Assembly tolerances are related to the tolerances on image quality. The elements must be located and held in position so that the resulting image-quality goals are met. There are additional questions of allowing sufficient clearance between the elements and the lens barrel so that the elements can be inserted into the barrel without breaking or being strained by the mountings. These must be considered in stating the allowable dimensional range in the diameter, wedge, and concentricity of the edge of the lens.

5.5 STARTING POINTS

Shop Practice

Table 3, given as part of the sample tolerancing of the doublet, provides some estimates of the accuracies to which an optical shop may operate. These generic levels of error convey what is likely to be possible. The designer carrying out a tolerance evaluation should consult with probable fabrication shops for modification to this table. The tolerances that are ultimately assigned relate errors in the system to acceptable errors in the image. However, an understanding of shop practice is of great assistance in intelligent budgeting of tolerances.

Measurement Practice

Contemporary practice in optical fabrication and testing is to use interferometry to define wavefronts and surfaces. A convention that has become common in recent years is the use of polynomials fitted to the wavefront as a method of describing the wavefront. There are several representations used, the most frequent of which is a limited set of Zernike polynomials. These ideally serve as an orthonormal set describing the wavefront or surface up to a specific order or symmetry. In tolerancing, the principal use for the coefficients of the Zernike set has been the easy computation of the rms wavefront error fitted to a given order. Thus the residual error in the system can be described after removal of low-order error such as focus or coma, which can sometimes be attributed to properties of the test setup.

5.6 MATERIAL PROPERTIES

The most important material is optical glass. Specification of the material usually includes some expected level of error in index of refraction or dispersion. In addition, glass is offered having several different levels of homogeneity of index of refraction. The usual range allows for grades of glass having index of refraction inhomogeneity ranging from ±0.00001 to less than ±0.0000001 within a single glass blank. It is usually assumed that this variation will be random, but the process of glass manufacturing does not guarantee this.

To place a tolerance upon the required glass homogeneity variation, the concept of wavefront tolerancing can be used. In general, the amount of wavefront error that can be expected along a glass path of length t through the glass is

$$\delta W = \frac{\delta N \times t}{\lambda}$$

For example, if a lens has a glass path of 5 cm but an error of 0.01 wavelengths is assigned to glass homogeneity, then the allowable glass homogeneity is about 0.00000013 within the glass. Thus precision-quality glass is needed for this application. For less glass path or looser tolerance assignment to glass homogeneity error, the required glass precision can be loosened. For a prism, the light path may be folded within the glass, so that an effective longer glass path occurs.

5.7 TOLERANCING PROCEDURES

The example of the doublet serves to illustrate the basic principles involved in determining the tolerances on a lens system. Most lens design programs contain routines that carry out tolerancing to various degrees of sophistication. Some programs are capable of presenting a set of tolerances automatically with only limited input from the designer. The output is a neat table of parameters and allowable ranges in the parameters that can be handed to the shop. This appears to be a quite painless method of carrying out a complex procedure, but it must be remembered that the process is based on application of a set of principles defined by the program writer, and the result is limited by the algorithms and specific logic used. In most cases, some trials of samples of the suggested tolerance distribution will suggest changes that can be made to simplify production of the lens system.

Direct Calculation

The preceding discussion describes methods used in calculating the tolerance distribution for a lens system. Frequently, tolerance determinations for special optical systems are required that either do not require the formal calculation described above, or may be sufficiently unusual that the use of a lens-design program is not possible. In that case, application of the principles is best accomplished directly.

The procedure is first to decide on a meaningful measure of the image quality required. In fact, the term "image quality" may require some broader interpretation. For example, the problem may be to optimize the amount of energy that is collected by a sensor in an optical communication system;

or the goal may be to scan a specific pattern with specific goals on the straightness of the projected spot or line during the scan.

The next step is to express the desired image quality in a numeric form. Usually, the rms wavefront error is the useful quantity. In some cases, other values such as the focus location of a beam waist or the size of the beam waist may be pertinent. In radiometric cases, the amount of flux within a specified area on the image surface (or within a specified angular diameter when projected to the object space) may be the pertinent value.

Once this is accomplished, the third step is to determine the relation between small changes in the parameters of the optical system and changes in the desired image quality function. This is usually accomplished by making small changes in each of the parameters, and computing the value of each differential as

$$\frac{dW}{dx_j} = \frac{\Delta W}{\Delta x_j}$$

where the right side is a finite differential. On occasion, the magnitude of this relation is nonlinear, and may require verification by using different magnitudes of change in the parameter.

This computation provides relations for independent, individual changes of the parameters. The possibility of compensation by joint changes in two or more parameters also has to be investigated. The best approach is to compute changes in the image-quality parameter in which specific coupling of parameters is included. For example, the differentials for variation of the curvatures of the two surfaces of a lens independently will be significantly different than the coupled changes of both surfaces simultaneously, either in the same or different directions.

Spreadsheet Calculation

The differentials must be combined in some manner to provide insight into the tolerance distribution. The best way to accomplish this is to develop a spreadsheet which allows simultaneous evaluation of the combination of errors using the equation for rms summation stated earlier. The use of spreadsheets for calculation is so common today that details need not be covered in this chapter.

Lens-Design Programs

The use of lens-design programs for tolerance calculation has become very widespread because of the proliferation of programs for use on the PC-level computer. The status of lens-design programs changes rapidly, so that any specific comments regarding the use of any program is sure to be out of date by the time this book appears in print. Suffice it to say that all of the principal programs have sections devoted to establishing tolerances. Usually the approach follows the procedures illustrated earlier in this chapter, with finite changes, or sometimes true computed analytical derivatives, used to establish a change table relating parameters to changes in the state of correction of the lens. In this case, the tolerances would be a listing of the allowed changes in the parameter to remain within some specified distance from the design values in aberration space. Some programs use a more complex approach where the allowable change in such quantities as the contrast value of the modulation transfer function at specified spatial frequencies is computed.

The distribution of tolerances is usually established according to the statistical addition rules given above. Some programs permit the user to specify the type of distribution of errors to be expected for various types of parameters.

As recommended above, it is strongly suggested that the user or designer not accept blindly the results of any tolerancing run but, rather, do some spot checking to verify the validity of the range of numbers computed. It is frequently found that alterations in the specified tolerances will occur as a result of such an investigation.

5.8 PROBLEMS IN TOLERANCING

Finally, it is useful to recite some of the problems remaining in establishing tolerances for a lens system. Even though the computational approach has reached a high level of sophistication for some lens-design programs, there are aspects of tolerancing that more closely approach an art than a science. The judgment of the designer or user of a tolerance program is of importance in obtaining a successful conclusion to a project.

Use of Computer Techniques

The use of a computer program mandates the application of rules that have been established by the writer of the program. These rules, of necessity, are general and designed to cover as many cases as possible. As such, they are not likely to be optimum for any specific problem. User modifications of the weighting, aberration goals, and tolerance image-quality requirements are almost always necessary.

Overtightening

The safe thing for a designer to do is to require very tight tolerances. This overtightening may ensure that the fabricated system comes close to the designed system, but the cost of production will likely be significantly higher. In some cases, the added cost generated by the overtight tolerances can raise the cost of the lens to the point where the entire project is abandoned.

The designer should consult with the fabricators of the optical system to develop an approach to assembly and testing that will allow the use of more compensating spacings or alignments to permit loosening of some of the tight tolerances.

Overloosening

A similar set of comments can be made about too-generous tolerances. In many schemes for production, these loose tolerances are justified by inclusion of an alignment step that corrects or compensates for cumulative system error. Too casual an approach to developing tolerances that require specific assembly processes, which are not fully communicated to the project, can result in a lens which is initially inexpensive to build, but becomes expensive after significant rework required to correct the errors.

Judgment factors

The preceding two sections really state that judgment is required. There is no completely "cookbook" approach to tolerancing any but the very simplest cases. The principles stated in this chapter need to be applied with a full knowledge of the relation between a change in a system parameter and the effect upon the image quality. In some cases, a completely novel relationship needs to be developed, which may include, for example, the connection between the alignment of a laser cavity and a nonlinear component included within the cavity. Finite difference calculations to obtain the output level can be developed using whatever computation techniques are appropriate. These values can be combined in a spreadsheet to examine the consequence of various distributions of the allowable errors.

5.9 REFERENCES

There are many useful references on optical tolerances that deal with specific topics not directly covered by the general discussion in this chapter. The most useful suggestion is that the users having the task of setting specifications on a specific product or system use the massive capabilities of internet search engines to look for specific data applicable to that task. A general Google search on "Optical Tolerances" provided 1,600,000 hits, of which probably less than 10 will be applicable to any specific problem.