TOLERANCING OPTICAL SYSTEMS

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Abstract

Determination of the tolerances upon an optical system is one of the most important subjects in optical design. Since no component cannot be perfectly manufactured, stating a reasonable acceptable range for the dimensions or characteristics is important to ensure that an economical, functioning instrument results. The tolerances are responsive to the requested system specifications, and are intended to ensure that the final, assembled instrument meets the requested performance. In this report, the process of optical system tolerancing is discussed and examples are given to show how to apply those processes to achieve system performance while minimizing cost.

Introduction

Economics has always been playing an increasing role in the optical design and production process, especially in the commercial ventures in the product arena. To target the system performance while keep as low as possible in cost, a proper design approach should begin with a thorough examination and refinement of the requirements form the top down since the ultimate cost and value of an optical product is very dependent on the preliminary and detail design processes.

The detail design phase must include an adequate tolerance analysis and distribution, because the assignment of tolerances to the various dimensions and parameters of an optical system is a critical element in determining the resulting performance and final cost of the product.

Tolerancing is difficult because it involves complex relationships across disciplines of several aspects, System engineering, Optical design and analysis, Fabrication, etc. In order to get the best result, a system of merit should be selected and all performance specs propagated through assembly.

Process of optical system tolerancing

There are three principal issues in optical tolerancing. The first is the setting of an appropriate goal for the image quality 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. As a mature experience, the process of optical system tolerancing shown below should be done step by step through the designing.

1. **Define quantitative figures of merit for requirements**

   A plethora of performance metrics exist for optical systems are shown in Table 1. In some cases the tolerances of an optical system may be physical parameters such as effective focal length or back focal length, and in other cases image quality metrics are the performance metrics used. For instance, systems used with detectors may look at spot size with respect to pixel size. The Modulation Transfer Function (MTF), Geometric RMS image size, and RMSWE are commonly used metrics.

   Table 1 Typical requirements

   –RMSWE (root mean square wave front error)
   –MTF at particular spatial frequencies
   –Distortion
   –Fractional encircled energy
   –Beam divergence
   –Geometric RMS image size
   –Dimensional limits
   –Bore sight

   Usually, the application of the system will determine which metric to employ.

2. **Estimate component tolerances**

   After setting the goal of the system (like the image quality of a lens assembly), the next step is to identify the variable tolerances within the system. What need to be toleranced often include: General parts (usually machined metal), Physical dimensions of optical elements, Optical surfaces, Material imperfections for optics, and Optical assembly.

   Usually, starting with rational, the designer gives estimate tolerances for components. The rules of thumb for tolerances is an easy way to apply. The rules of thumb for machined parts, optical elements (include optical surfaces), material imperfections for optics, and optical assembly are shown in table 2-5, respectively.

   Table 2 Rules of thumb for machined parts

Tolerance Guide for Machined Parts		
Machining Level	**Metric**	**English**
Coarse dimensions (not important)	±1 mm	± 0.040”
Typical machining (low difficulty)	±0.25 mm	±0.010”
Precision Machining (readily available)	±0.025 mm	±0.001”
High Precision (requires special tooling)	< ±0.002 mm	< ±0.0001”

Table 3 Rules of thumb for optical element tolerances (lenses)

Parameter	Base	Precision	High precision
Lens diameter	100 µm	25 µm	6 µm
Lens thickness	200 µm	50 µm	10 µm
Radius of curvature Surface sag Value of R	 20 µm 1%	 1.3 µm 0.1%	 0.5 µm 0.02%
Wedge (light deviation)	6 arc min	1 arc min	15 arc sec
Surface irregularity	1 wave	$\lambda/4$	$\lambda/20$
Surface finish	50 Å rms	20 Å rms	5 Å rms
Scratch/dig	80/50	60/40	20/10
Dimension tolerances for complex elements	200 µm	50 µm	10 µm
Angular tolerances for complex elements	6 arc min	1 arc min	15 arc sec
Bevels (0.2 to 0.5 mm typical)	0.2 mm	0.1 mm	0.02 mm

Base: Typical, no cost impact for reducing tolerances beyond this.
Precision: Requires special attention, but easily achievable in most shops, may cost 25% more
High precision: Requires special equipment or personnel, may cost 100% more

Table 4 Rules of thumb for material imperfections for optics (glass)

Parameter	Base	Precision	High precision
Refractive index departure from nominal	± 0.001 (Standard)	±0.0005 (Grade 3)	±0.0002 (Grade 1)
Refractive index measurement	$\pm 3 \times 10^{-5}$ (Standard)	$\pm 1 \times 10^{-5}$ (Precision)	$\pm 0.5 \times 10^{-5}$ (Extra Precision)
Dispersion departure from nominal	± 0.8% (Standard)	± 0.5% (Grade 3)	±0.2%% (Grade 1)
Refractive index homogeneity	$\pm 1 \times 10^{-4}$ (Standard)	$\pm 5 \times 10^{-6}$ (H2)	$\pm 1 \times 10^{-6}$ (H4)
Stress birefringence (depends strongly on glass)	20 nm/cm	10 nm/cm	4 nm/cm
Bubbles/inclusions (>50 µm) (Area of bubbles per 100 cm^3)	0.5 mm^2 (class B3)	0.1 mm^2 (class B1)	0.029 mm^2 (class B0)
Striae Based on shadow graph test	Normal quality (has fine striae)	Grade A (small striae in one direction)	Precision quality (no detectable striae)

Table 5 Rules of thumb for Optical assembly tolerances

Parameter	Base	Precision	High precision
Spacing (manual machined bores or spacers)	200 µm	25 µm	6 µm
Spacing (NC machined bores or spacers)	50 µm	12 µm	2.5 µm
Concentricity (if part must be removed from chuck between cuts)	200 µm	100 µm	25 µm
Concentricity (cuts made without de-chucking part)	200 µm	25 µm	5 µ

3. **Define assembly/alignment procedure and estimate tolerances**

Following the estimation of tolerances for components, the assembly/alignment procedure should be given. The rules of thumb for the assembly in table 5 could be used for this term. Then, to estimate system performance, use a merit function that uses RSS to combine independent contributions:

$$\Phi = \sqrt{\Phi_0^2 + (\Delta\Phi_1)^2 + (\Delta\Phi_2)^2 + \ldots}$$

Φ_0 is from design residual – simulation of system with no manufacturing errors

$\Delta\Phi_i$ is effect from a single parameter having an error equal to its tolerance

4. **Calculate sensitivities**

After the merit function defined, the sensitivity of each single parameter could be calculated. A small perturbation Δx_i should be applied (0.001 for index, 0.01 mm for thickness/diameter/etc.) to each parameter x_i in order to find the resulting change in the performance specification (This can be done in optical design codes.) Or, the small perturbation could be replaced by the nominal tolerance (initial assigned by using rules of thumb) of each parameter, since the sensitivities can be approximated to be linear. From here the sensitivity is simply equal to

$$\frac{\partial \Phi}{\partial x_i} \cong \frac{\Delta \Phi}{\Delta x_i} \quad = \text{(change in merit function) / (change in parameter)}$$

which is recognized as the slope with the intercept set equal to zero (representing the part manufactured at the specification). Where:

Δx_i is the tolerance for x_i which could be adjusted

$\Delta\Phi$ is the effect from a single parameter x_i having an error equal to its tolerance Δx_i

It should be evident that certain parameters are more sensitive than others and therefore have a large effect on system performance. From this point, tolerances can be assigned to each parameter (x_i). The resulting change in system performance ($\Delta\Phi_i$) for each tolerance should subsequently be found or calculated using its respective sensitivities. The contribution from a tolerance Δx_i on parameter x_i is

$$\Delta\Phi_i = \frac{\partial\Phi}{\partial x_i}\Delta x_i \qquad = \text{(sensitivity)} * \text{(tolerance)}$$

For most optical systems, a final focus adjustment will be made after the system is assembled. The tolerance analysis must take this into account.

5. **Estimate performance**

To find the net effect of all the tolerances on the system, the RSS is used. This net value (Φ) resulting from all system parameters needs to fall below the performance specification for the system. Calculate system merit function by scaling from the sensitivities, and use RSS:

$$\Phi = \sqrt{\Phi_0^2 + \left(\frac{\partial\Phi}{\partial x_1}\cdot\Delta x_1\right)^2 + \left(\frac{\partial\Phi}{\partial x_2}\cdot\Delta x_2\right)^2 + \ldots}$$

Putting the sensitivities into a spreadsheet allows easy calculation of the system errors with all effects. Table 6 shows an example tolerance table for assembly errors for a simple doublet. Here the performance characteristic is wavefront error. A tolerance is assigned to each parameter and the respective sensitivity and resulting wavefront error is displayed. The RSS of all the assembly parameters is calculated and displayed at the bottom of the table. By adjusting the tolerance, the designer could change the system performance such that the value be less than the performance specification of the system.

Table 6– Example of a tolerance budget

Displaying tolerance, sensitivity, and resulting wavefront error (change in performance).

Parameter	Tolerance	Sensitivity	Change in performance
Lens 1			
Decenter	0.11 mm	0.19056 λrms/mm	0.02096 λ rms
Tilt	0.12°	0.11253 λrms/degree	0.01350 λ rms
Lens 2			
Decenter	0.11 mm	0.19036 λrms/mm	0.02094 λ rms
Tilt	0.11°	0.20016 λrms/degree	0.02202 λ rms
Lens Spacing	0.4 mm	0.01755 λrms/mm	0.00702 λ rms
		*RSS**	**0.03998 λ rms**

6. **Adjust tolerances, balance cost and schedule with performance**

In order to achieve system performance, the initial tolerances need to be refined based on the sensitivity. The principle factor of adjusting tolerances is to recognize which parameters are the most sensitive. These parameters will ultimately control the tolerance budget. Usually, terms with small effects on the system performance could be loosen tolerances while the terms with big effects may need to tighten tolerances.

The designer should always keep the cost in mind when adjust the tolerances. Generally placing a tight tolerance on a component leads to increased cost. Ronald Willey has provided several in depth analyses looking at the relationship between tolerances and production costs. More information refer to the reference. As new techniques and high precision machine development, and based on the quantity of production, the cost would change case by case. The most effective way is to talk to the fabricators. With the "cost sensitivity" of each parameter known, the cost of each tolerance now becomes part of the tolerance budget just as each parameter's effect on system performance. The engineer can now properly evaluate the cost of each tolerance in the optical system and subsequently optimize.

Conclusion

To get a quick image of the cost of an optical system, the designer could use the rules of thumb to initial the tolerance. To get a more precise result, tolerance analysis should be made by following the process of tolerancing.

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