PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Approaching direct optimization of as-built lens performance

McGuire, James, Kuper, Thomas

James P. McGuire Jr., Thomas G. Kuper, "Approaching direct optimization of as-built lens performance," Proc. SPIE 8487, Novel Optical Systems Design and Optimization XV, 84870D (19 October 2012); doi: 10.1117/12.930568

Approaching direct optimization of as-built lens performance

James P. McGuire, Jr. and Thomas G. Kuper

Synopsys Inc., 3280 E. Foothill Blvd., Pasadena, CA, USA 91017

ABSTRACT

We describe a method approaching direct optimization of the rms wavefront error of a lens including tolerances. By including the effect of tolerances in the error function, the designer can choose to improve the as-built performance with a fixed set of tolerances and/or reduce the cost of production lenses with looser tolerances. The method relies on the speed of differential tolerance analysis and has recently become practical due to the combination of continuing increases in computer hardware speed and multiple core processing We illustrate the method's use on a Cooke triplet, a double Gauss, and two plastic mobile phone camera lenses.

Keywords: Optimization, tolerance analysis, objectives

1. INTRODUCTION

Typically, a lens designer will generate a number of potential optical design forms (possibly using global search methods such as those introduced in the late 80's and the early 90's[1-11]) and then select the "best" lens form based on the error function value and whether the lens looks to be easily manufactured. The designer will then proceed to assign tolerances for manufacturing. This process relies on the skill of the designer to achieve the best results.

To assist the designer in desensitizing a lens to manufacturing errors, a number of additions to the error function have been proposed. Tiziani and Gray proposed desensitizing the system to axial coma by including a differential variance in the wavefront produced by an angular tilt or decenter of the surface [12-13]. This method has been implemented in a commercial lens design package for many years[14]. Several authors have discussed cost-effective manufacturing in terms of a local optimum[15-17]. More recently, Jeffs has described a desensitization method based on reducing the angles of incidence at the lens surfaces and minimizing the optical powers of the individual optical elements[18]. Jeff's method is very fast and we have found that a particularly useful variant is to minimize the difference between the angle of the incidence and the sine of the angle of incidence. Aberrations arise from real elements not being paraxial (angles not being the same as the sines of the angle) and this metric is often better at capturing the aberration contribution. All of these methods can be effective tools, but they do not correlate directly to the as-built wavefront error.

Catalan used an analytic, not numeric, approach[19]. He derived the sensitivity of a Ritchey Chretien telescope to errors in the tilt, decenter, and despace of the secondary mirror based on the construction parameters and then *analytically* optimized the design. This technique provides great insight, but also requires a lengthy derivation for every new system that needs to be desensitized.

More recently, a few suggestions have been made to desensitize the model by creating a zoom model with various values of tolerances. Fuse used two configurations for every tolerance: one for a perturbation in the positive direction, and one for a perturbation in the negative direction[20]. Fuse's method requires a very large number of configurations (upwards of 6 per surface). Rogers used a smaller number of zoom positions and randomly perturbed the parameters for each of these surfaces[21]. The number of configurations is independent of the number of surfaces and tolerances. Each zoom position is essentially a Monte Carlo realization of an as-built system. With a sufficient number of Monte Carlo positions, the optimizer can work to find tolerance insensitive forms. The disadvantage of the methods of Fuse and Rogers is slower optimization due to the increase in the number of configurations and often to the increase in the number of fields. A

Novel Optical Systems Design and Optimization XV, edited by G. Groot Gregory, Arthur J. Davis,
Proc. of SPIE Vol. 8487, 84870D · © 2012 SPIE CCC code: 0277-786X/12/$18 · doi: 10.1117/12.930568

rotationally symmetric system analyzed with three fields must be analyzed over 5 y-fields, if only tolerances that affected y-fields are used and must be analyzed over a grid of 5x5 fields, if tolerances that affected both x- and y-fields are used.

In an earlier method, the author used global optimization to generate many local minimum and then sorted based on their predicted as-built performance using CODE V's fast differential tolerance analysis (the TOR option) [22]. This technique allows the designer to sort through hundreds of local minima that can be easily generated in a modern lens design program based on the as-built rms wavefront or MTF performance. However, it does not allow one to directly optimize on the as-built performance.

In 2010, two authors independently proposed computing the changes in the wavefront for selected tolerances types using Rimmer's differential ray trace techniques. Bates used the Tziani and Gray method to include contributions for off-axis aberrations due to surface displacements by using selected rays (5 rays for the mobile phone camera that he optimized)[23]. The minimal ray set to compute only one type of manufacturing error made the evaluation very fast, but the implementation works for only one type of manufacturing error and the user must carefully select the right ray set. Yabe's technique was more general, adding the square root of the increase of the variance of the wavefront aberration for both decenter and curvature errors[24].

This paper describes the direct inclusion of the differential tolerance analysis into the error function and thus the direct optimization of the as-built wavefront (mean + 2sigma) for all the tolerances types supported by CODE V (decenter, curvature, index, thickness, aspheric errors, wedge, tilt, etc.) including the effects of compensators in the alignment procedure. Section 2 briefly outlines the inclusion of the differential tolerance sensitivities into the error function. Section 3 discusses the optimization of the as-built performance of example photographic objectives: a simple Cooke triplet, a double Gauss lens, and two mobile phone camera lenses.

2. DIFFERENTIAL TOLERANCE ANALYSIS

Damped Least Square (DLS) optimizers typically used in lens design software work best when the error function comprises many contributions that are affected approximately linearly by the variables. For example, in the case of spot size error functions, the transverse errors for every ray are entered into the error function, not the single number describing the RMS of the errors (which carries less information than the set of individual ray errors). Thus, we will build an error function that is composed of the contributions from each individual tolerance on the wavefront error evaluated using differential tolerance analysis to minimize the computational burden.

The differential tolerance analysis is based on real ray tracing and predicts the effect of the various tolerances on RMS wavefront error. It is based on a wavefront differential ray trace[12,25] that provides the derivative of the OPD with respect to the tolerances. This provides an extremely efficient way to calculate the changes in RMS wavefront error[26-27] used in the statistical calculations[28].

In differential tolerance analysis, grids of rays are traced through the lens as needed. For each ray, the wave aberration derivatives are calculated for each perturbation and appropriately summed. The final result is a set of coefficients defining a function that describes the expansion of the variance of the wavefront with respect to each of the parameters of interest (perturbations).

$$\Delta\text{variance} = \sum_{i=1}^{N} \left(\mathrm{A_i\,T_i^2} + \mathrm{B_i\,T_i} + \sum_{j=1}^{\mathrm{N}} \mathrm{C_{ij}\,T_i\,T_j} \right). \tag{1}$$

where A_i ,B_i and C_{ij} are expansion coefficients, and T_i, and T_j are the tolerance values, and N is the number of tolerances. C_{ij} is a strictly upper triangular matrix. This is a simple second order Taylor series expansion. CODE V provides the A_i , B_i , and C_{ij} coefficients through the AS_BUILT_ABC macro function (the A_i and B_i coefficients are also listed in the TOR option output).

Once the differential expansion of the wavefront variance is computed, we need a way to include this sensitivity information in the error function. As a starting point, consider the square of the wavefront squared plus the mean plus 2σ value of the wavefront variance as an as-built error function

$$AB = (W_0^2 + \mu_W + 2\sigma_W)^2 \tag{2}$$

where W_0 is the nominal wavefront error, μ_W is the mean of the change in the wavefront variance and σ_W is the standard deviation of the change in the wavefront variance. If the system probability distribution is Gaussian (often a good approximation due to the central limit theorem), 97.7% of the as-built lenses will have an RMS value that is better than the mean plus 2σ.

Equation (2) can be evaluated using the expression derived by Koch for the mean and standard deviation for symmetrical, zero mean probability densities

$$\mu_W = \sum_{i=1}^{N} \mathrm{A_i}\,\sigma_\mathrm{i}^2 \tag{3}$$

$$\sigma_W^2 = \sum_{i=1}^{N} \left(A_i^2\,(\upsilon_{4\mathrm{i}} - \sigma_\mathrm{i}^4) + B_i^2 \sigma_\mathrm{i}^2 + \sigma_\mathrm{i}^2 \sum_{j=1}^{\mathrm{N}} C_{ij}^2\ \sigma_\mathrm{j}^2 \right) \tag{4}$$

where $\upsilon_{4\mathrm{i}}$ is the fourth moment of the tolerance probability distribution and σ_i^2 is the variance of the tolerance probability distribution[28] ($\mathrm{A_i}$, $\mathrm{B_i}$, and $\mathrm{C_{ij}}$ are the differential expansion coefficients in (1)). The resulting expression is not easily incorporated into a DLS optimizer, because the resulting expression is not a simple sum of squares of aberrations. Therefore, we built a Simplified As-Built (SAB) error function composed of a sum of components that depend on only one tolerance

$$SAB = \sum_{i=1}^{N} \mathrm{Aberration_i^2} \tag{5}$$

where the square of the aberration for each tolerance is

$$\begin{aligned}\mathrm{Aberration_i^2} = {} & \frac{W_0^4 + 4\sigma_W W_0^2}{\mathrm{N}} + 2W_0^2 \mathrm{A_i}\,\sigma_\mathrm{i}^2 + 4\sigma_W \mathrm{A_i}\,\sigma_\mathrm{i}^2 + 4\mathrm{A_i^2}(\upsilon_{4\mathrm{i}} - \sigma_\mathrm{i}^4) \\ & + 4\mathrm{B_i^2}\sigma_\mathrm{i}^2 + 4\sigma_\mathrm{i}^2 \sum_{j=1}^{N} \mathrm{C_{ij}^2}\sigma_\mathrm{j}^2 + \mathrm{A_i}\,\sigma_\mathrm{i}^2 \sum_{j=1}^{N} \mathrm{A_j}\,\sigma_\mathrm{j}^2\end{aligned} \tag{6}$$

Note that there are three terms without tolerance subscripts in the above equation: the number of terms, N, the nominal wavefront, W_0, and the standard deviation of the wavefront, σ_W (not to be confused with standard deviations of the tolerance probability distributions σ_i^2 and σ_j^2). The number of tolerances and the nominal wavefront error are constants and do not depend on the values of the tolerances. The standard deviation σ_W depends on the individual tolerances, but we choose to simplify the calculation of the merit function by computing (4) and taking the square root. The choice of the error function (5) allows the straightforward incorporation of the $\mathrm{A_i}$, $\mathrm{B_i}$, and $\mathrm{C_{ij}}$ expansion coefficients for each tolerance with the minimal loss of information. The SAB error function is easily added to the existing error functions and has proven to be successful in desensitizing a wide range of systems.

The designs described in the remainder of this paper utilize the *SAB* error function described above, in conjunction with the standard transverse aberration or wavefront error functions. Because SAB is based on a second order Taylor series expansion and has a few simplifications, SAB was not used as a standalone merit function. Best results were most frequently obtained when the relative weighting of the SAB and standard error functions were the same order of magnitude, although the optimum weights varied for each lens (as one might expect). While the SAB error function can reuse the rays traced for the standard error function, computation of the A_i, B_i, and C_{ij} coefficients and the increased matrix size in the DLS optimization does increase the computational burden. The designer can improve the speed by using only the most sensitive tolerances from the lens. Because *SAB* is simplified, and not an exact description of the wavefront, it can "push" the optimizer in a useful direction. SAB has often been found to work better as a complement to a standard error function, rather than as a standalone error function.

It is important to note that the sensitivity coefficients A_i, B_i, and C_{ij} include the effects of any tolerance compensators in the system. That is, SAB estimates the as-built performance under the condition that the specified compensators are used. The compensators could be as simple as setting focus or could include multiple layers of compensation, for instance decentering a lens to correct axial coma, and then readjusting focus. The implementation of this method in CODE V allows the user to enter different compensators for different sets of tolerances (through labeling tolerances and compensators). This may be used, for example, on a relay system, consisting of two sub-assemblies, each of which is built and assembled separately. (Importantly, handling the tolerances in this way prevents the two sub-assemblies from "cross-correcting" each other's aberrations.) It can also be used to model transverse compensators for coma and air space adjustments for spherical aberration, in for example, a microscope.

3. EXAMPLES

In general there are two types of design problems: design-to-performance and design-to-cost. In design to performance, we want to find the global minimum for manufacturing cost to meet a particular set of performance requirements. This involves designing the most manufacturable lens for the requirements and then choosing the most appropriate set of tolerances and compensators to minimize manufacturing cost of that lens. In design-to-cost, we want to find the highest performing lens for a given set of manufacturing parameters. In this section we will describe three simple design-to-cost examples: a Cooke triplet, a double Gauss lens, and a mobile phone camera lens.

3.1 Cooke triplet

The Cooke triplet is a photographic lens designed and patented in 1893 by Dennis Taylor, who was chief engineer of T. Cooke & Sons of York, England[29]. It consists of two positive singlet elements and one negative singlet element. The negative flint element is located in the middle of the positive crown elements, thus maintaining a large amount of symmetry. It has enough effective degrees of freedom (6 radii, 2 air spaces, 3 indices) to affect all the primary aberrations (longitudinal color, lateral color, field curvature, astigmatism, coma, and spherical aberration). At the time, the Cooke triplet was a major advancement in lens design. It was superseded by later designs in high-end cameras, but is still widely used in inexpensive cameras and other applications.

As a first example of the use of this technique, we start with the Cooke1 lens design shipped with CODE V. Table 1 lists the specifications. Figure 1 shows the design locally optimized with a 100 mm focal length constraint and a) transverse error function, b) wavefront error function, c) SAB and transverse error function, and d) SAB and wavefront error function. For the SAB optimization, we used the "commercial quality" tolerances in Table 2 and only a focus compensator. All tolerances in the SAB optimization are assumed to have uniform probability distributions. The optimization with transverse aberration error functions resulted in larger, weaker lenses with larger air spaces between elements. (There was no length constraint.) The glasses for the first two elements changed from moderate index crowns and flints ($n \approx 1.63$) to high index crows and flints ($n \approx 1.73$). The SAB error function led to more "relaxed" designs. Figure 2 shows the nominal wavefront aberrations for the four cases. All designs have large residual chromatic aberrations, which the SAB error function cannot fix. (There are not enough degrees of freedom with "normal" glasses to correct secondary color and the variations of aberrations with wavelength.) Both SAB designs have larger residual

DOCKET ALARM

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.

WHAT WILL YOU BUILD? | sales@docketalarm.com | 1-866-77-FASTCASE

fastcase® Smarter legal research.