New Developments in Optical Design Software

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In this paper we describe three new tools that were developed in response to the needs of optical designers: expert systems for the selection of glass types and for the placement of aspheric surfaces, and a method of examining the effect of surface errors of mid-spatial frequencies.

1 Expert system for the selection of glass types

In practice, optical engineer often find that the glass types that are optimum for the correction of secondary chromatic aberration cannot be used because of non-optical properties such as cost, thermal expansion, or transmission. In such cases, the glass selection process becomes a trade-off of optical performance versus other, non-optical properties. As a result, the designer must spend considerable time determining which glass choices are optically beneficial, then checking non-optical properties of the glasses to determine whether the glass is, in the broader "systems" view, beneficial to the system. It is no exaggeration to state that engineers can spend days or even weeks refining the choice of glasses for a complex system.

To speed this process, Optical Research Associates (ORA$^{®1}$) has developed in CODE V$^{®}$, an expert system that mimics and automates the decision-making process that an optical designer carries out in selecting glass types. The designer enters the maximum allowable thermal expansion mismatch between elements that are cemented to one another, the maximum allowable cost of raw glass for the optical system and for any individual element, and the minimum allowable transmission (at the "bluest" wavelength) of the system. GlassExpert™ then identifies candidate glasses for improving the merit function defined by the user, under the constraint that the limits on thermal expansion, cost, and transmission must be upheld. Many glass types are examined, each with an automated acceptance/rejection decision applied. The program runs autonomously and can be run overnight.

As an example, we created a starting point for a 400 mm focal length, F/2.8 telephoto objective. The starting design met the desired thermal, cost, and transmission requirements, but was employed no "special" glasses and was limited in performance by secondary color. As is widely known, the performance can be greatly improved through the use of glasses with anomalous dispersion, such as NFK51A and NKzFSN8. Unfortunately, these glasses are expensive, and their unrestricted use in the lens would cause the raw glass costs to increase by a factor of 5. Also, cementing these glasses together would cause, for the large elements of this objective, such large thermal expansion mismatches that the cement surfaces would likely fail (delaminate) when subjected to a typical storage temperature requirement.

Running GlassExpert on the initial system produced, in just over 5 hours, a design comprising almost entirely "normal" glasses, which improved the MTF by nearly a factor of 6 while maintaining a tolerable difference of expansion coefficients at the cemented interfaces. Only one special glass (KzFSN8) was selected, and because it was applied only at one of the smallest elements of the system, overall glass cost was held within the desired limits.

2 Expert system for the placement of aspheric surfaces

The surest method for determining which surface of an optical system would have the greatest beneficial effect on the merit function is simply to try aspherizing each surface in succession, with a full system optimization carried out in each case. If that is done, then it is simple to select the system with the best merit function. While the above method may be practical for simple optical systems, it rapidly becomes impractical when the number of surfaces is large, as in a lithography lens. Not only is there a large number of candidate surfaces for aspherization, the time required to optimize each candidate is also large, because of the large number of surfaces and the dense ray sampling required.

In such cases, some method of determining the optimum surface (or surfaces) is desired. Furthermore, the selection method should take into account any restrictions on the depth or steepness of the asphericity that might be imposed by the fabrication and testing methods to be used.

To address this need, ORA developed AsphereExpert™ to analyze the extent to which aspherics located at each of the candidate surfaces can "address" the aberrations of the system. This analysis is carried out with respect to the merit function defined by the user, including, for example, weighted constraints on distortion, length, and diameter. The tool can be used to select a single surface for aspherization and then optimize the system with that aspheric surface in place. Alternatively, the user can ask that several surfaces be simultaneously converted to aspherics. In this case, the program will take into account the anticipated effect of the first asphere when selecting the second asphere. (That is, it will not select two surfaces that have nearly identical effects on the performance.)

As a first example, we entered a Schmidt camera (with a field flattening element), with the corrector plate in place but not yet aspheric. We requested that AsphereExpert suggest two surfaces for aspherization. The program suggested (as expected) the first surface of the corrector plate. It recognized that the second surface of the corrector plate had a large, but nearly identical effect to the first surface, so it suggested the first surface of the field flattening element as the second surface to aspherize.

As a second test of this tool, we entered a 29-element lens designed for use in lithography at 248 nm (Japanese Patent 11006957). The original lens had 4 aspheric surfaces, two near the central waist and two near the low NA end of the system. The field-averaged rms wavefront error was 0.0029 λ. To obtain a starting point for AsphereExpert, we removed the aspherics and reoptimized the lens so that it was no longer evident where the aspherics had been; the rms wavefront error with all spherical surfaces was 0.012 λ. We then asked AsphereExpert to suggest 4 surfaces for aspherization. As shown in Fig. 1, the suggested surfaces included one near the central waist and 3 near the low NA end of the system.

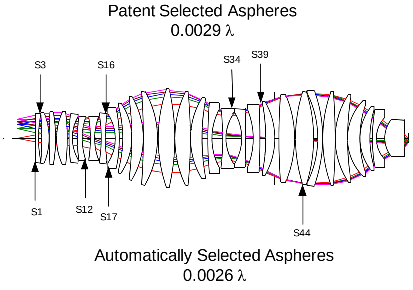
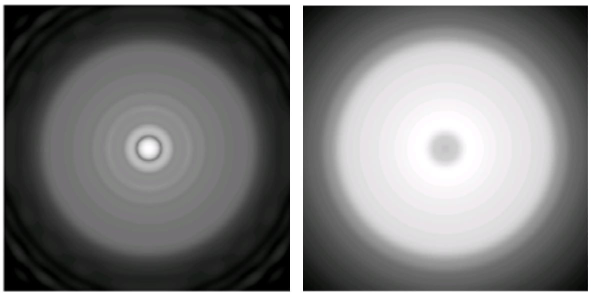


Fig. 1 *Lithographic lens with aspheric surface selection*

After re-optimization, the field-averaged rms wavefront error was 0.0026 λ, a 12% improvement over the choice made by the inventor of the patent.

3 Evaluation of mid spatial frequency errors

The increasing use of modern machining methods for the fabrication of optical surfaces (both aspheric and spherical) has increased the need for tools to assess the performance of systems whose surfaces suffer mid spatial frequency errors. ORA recently implemented a means of examining such errors using a diffraction propagation method based on decomposing the incoming wavefront into a number of small beamlets, then reconstituting the resulting pattern at the image plane as a coherent sum of the beamlets. We describe the surface errors by means of a Power Spectral Density (PSD) function. The user enters the rms of the surface, the exponent with which the amplitude of the surface error diminishes with increasing frequency, and the range of frequencies over which the error is expected to occur. (It is useful to note that the phases of the various frequencies are unknown. Therefore, the PSD can be regarded as a description of the statistics of an ensemble of surfaces, but not a complete description of any one surface.) The program then calculates the ensemble average of the effects of the surface errors on the point spread function (PSF). In fact, we can calculate the stray light separately from the actual PSF. As an example, we set up a Cassegrain telescope with rms surface waviness of 20 nm on both the primary and secondary mirrors. We assumed an exponent of -1, with spatial frequencies ranging from one to 5.4 periods per aperture radius. Figure 2 shows a logarithmic depiction of the stray light, both with and without the PSF plotted. (The stray light appears brighter in the latter case because the figure has been renormalized after removal of the PSF.)



(a) (b)

Fig. 2 *The PSF for the ensemble average of systems (a) PSF with stray light halo, (b) Stray light halo plotted without the PSF.*

References

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