Laser ray-tracing method for optical testing

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We have developed a novel laser ray-tracing method to measure aberrations in optical systems. It consists of delivering narrow laser pencils (by a laser scanner), recording the spots that are formed on the image plane (with a CCD camera), and computing the position of each centroid. This approach could be considered an experimental (approximate) implementation of standard numerical ray tracing. Several tests and experiments, including a direct comparison with a Hartmann–Shack wave-front sensor, provided highly satisfactory results that confirmed the validity of the method and revealed potential advantages. © 1999 Optical Society of America

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Optical design software is usually based on numerical ray tracing through a virtual optical system. Moreover, optical testing is a necessary tool to verify that an actual manufactured system is close enough to the design specifications. There is a series of techniques,¹ such as interferometric, knife-edge, and Hartmann or Hartmann–Shack (H-S) tests, for measuring wave or geometric aberrations. In particular, H-S wave-front sensors² are becoming popular in adaptive-optics³ devices for compensation for aberrations caused by atmospheric turbulence or other time-varying media.

In this Letter we propose a laser ray-tracing (LRT) technique as an alternative method that might provide a more direct link between the optical testing (LRT) and design (numerical ray-tracing) stages. The method consists of delivering narrow pencils of light (rays) sequentially through the optical system and measuring the position (centroid) of the image spot on the detector (image) plane. It is possible to scan the pupil plane by sequentially delivering rays through different pupil positions. The pupil (or wave front) is sampled as in a H-S sensor.² The main difference is that the H-S sensor uses a monolithic array of small circular apertures (microlenses) to sample the wave front in a reference sphere at the exit pupil, whereas LRT uses a single Gaussian beam as a ray whose coordinates (for both the point object and the entrance-pupil position) can be specified as in standard ray-tracing software. By use of computer-driven laser scanning devices one can apply any desired sampling pattern, which is important if one is to have complete flexibility in pupil exploration. There are antecedents for this kind of technique. In the field of physiological optics, Sivak and Kreuzer⁴ recorded the trajectories of several laser beams that passed through crystalline lenses *in vitro* to study spherical aberration in different species. More recently, Navarro and Losada⁵ measured the aberrations and the relative luminous efficiency of laser pencils in the living human eye.

We have developed a LRT system that consists of a high-quality beam from a TEM₀₀ red He–Ne laser (beam diameter, ~0.6 mm), a two-dimensional XY scanner, and a digital CCD camera (see the top diagram in Fig. 1). Both the scanner and the camera

are controlled and synchronized by computer. In the current software version the scanner can produce different sampling patterns (square, hexagonal, polar) in real time. Different scale factors can be used for the x and y axes for off-axis measurements. In the current setup the system speed is limited to a few rays per second, mainly because of the image acquisition and storage stages. (Nevertheless, the speed could easily be increased by 1 or 2 orders of magnitude simply by use of faster electronics.)

The camera lens produces a small spot (a few pixels wide) on the CCD sensor. The position of the spot for each pupil position (ray) is computed as the centroid of the pixels with intensities that are above a given threshold (equal to the mean plus three times the

Fig. 1. Dual LRT and H-S setup: The optical system is a high-quality low-aperture collimator (reference) with a removable aberrating plate. In (1) the unexpanded laser beam, deflected by an XY laser scanner, is imaged onto a digital CCD camera after the beam passes through a cube beam splitter, the lens, and the aberrating plate. In (2) the pinhole of a spatial filter is the point object and lenses L1 and L2 form an image of the lens's pupil plane on a microlens array; the spots formed by the lenslets are imaged onto the CCD by the auxiliary lens, L3, and the CCD objective.

standard deviation of the image histogram). The resulting experimental spot diagram, which displays the measured geometric ray aberrations, allows a direct comparison with numerical spot diagrams computed during the design stage. From the spot diagram, the wave-front aberration is estimated by a standard least-squares fit of the partial derivatives of Zernike polynomials (up to the fifth order in the current version) to the raw experimental data, following Malacara's notation and ordering.¹

We conducted a series of experiments to test the validity of the LRT method. We used the small central zone (low numerical aperture) of a high-quality collimator lens as our diffraction-limited reference system. Then, different aberrated systems could be obtained simply by placement of either aberrated plates or simple lenses (spherical, cylindrical, or both) right after the collimator. In addition, we built a dual experimental setup, as shown in Fig. 1, that combined the LRT method with a H-S wave-front sensor. In this way we could measure the aberrations of the optical system with both methods under the same conditions. In the H-S sensor (bottom diagram in Fig. 1), two lenses projected the image of the optical system onto a pupil stop in front of a hexagonal microlens array. The lenslets had a 0.5-mm diameter and a 50-mm focal length, with a center-to-center distance of 0.6 mm. The exit-pupil diameter was 6.6 mm for all measurements. This diameter means that the wave front was sampled by a hexagonal grid of 91 microlenses, and hence we had 91 spots on the CCD. To permit direct comparison of the LRT with the H-S sensor we programmed the laser scanner to match this sampling pattern exactly. The width of the laser beam, 0.6 mm, was particularly well suited for this purpose.

We first measured the reference high-quality lens, making sure that the chief ray in the LRT passed through the central lenslet of the H-S sensor. For both methods we obtained negligible amounts of aberration, less than $\lambda/4$ (the average rms wave-front error of the different series was $0.094\text{ }\mu\text{m}$ for the H-S method and $0.02\text{ }\mu\text{m}$ for the LRT method). The significantly lower values obtained for LRT, along with the fact that the H-S method requires more optical components, suggest that these aberration values are attributable to small defocusing, misalignment, and tilt in the setup as well as to imperfections in the lenslet array and aberrations of the optical elements. In addition to these residual aberrations, the two-dimensional laser scanner is composed of two rotating mirrors that are separated by $\sim 11\text{ mm}$. As a consequence the beam that is deflected by the first mirror scans one line segment of the second mirror, or equivalently, the beam that is deflected by the second mirror scans a virtual line on the first mirror. Since both mirrors are orthogonal, so are the lines. Therefore the rays do not come from a single point object, and we have object astigmatism; the corresponding Sturm interval is the distance between the mirrors. For the focal length of the lens that is being tested, 200 mm, this interval amounts to 0.32 D (the corresponding Zernike coefficient is $Z_5 \approx 0.65\text{ }\mu\text{m}$). We verified experimentally (see below) that this astigmatism can be com-

pensated for either optically, by placement of a cylindrical lens in front of the optical system, or numerically, *a posteriori*, by subtraction of the positions of the spots obtained with the reference diffraction-limited collimator from those obtained with the (aberrated) system being tested. This compensation can also be hybrid; it can be partially optical, for instance, with a 0.25-D lens followed by numerical compensation for the residual astigmatism of 0.07 D. This hybrid method is interesting, since depending on the focal length of the system we might not have a cylindrical lens to compensate exactly for the scanner's astigmatism. Nevertheless, the best way to avoid astigmatism is to use a scanner with a single mirror in a gimbal mount, which permits pure rotations without displacements of the beam. We plan to use a single gimbal-mount mirror in future versions of our system. In all measurements we subtracted the reference value of the position of each sample (ray for LRT or lenslet for the H-S method) that was obtained for the reference high-quality lens (spot diagrams) from that of the system being tested to avoid, or at least minimize, the effect of residual aberrations in the setup.

The next step was to calibrate the measuring system with known aberrations. Thus we introduced low-order aberrations into this set of measurements by placing lenses (spherical, cylindrical, or both) with known refractive powers close to the reference system. In this way we produced controlled, known amounts of defocus and (or) astigmatism. The nominal powers of these lenses were ± 0.5 and $\pm 1\text{ D}$ for spherical and cylindrical lenses, and combinations of both types were also tested. Measurements obtained in six cases resulted in an average difference between measured and nominal values of defocus and astigmatism (estimated from the Zernike coefficients) of 4.6%.

The last experiment was a direct comparison between the LRT and the H-S methods in which we measured the aberrations of an optical system composed of a high-quality collimator and a strongly aberrating phase plate, with the setup depicted in Fig. 1. The results are displayed in Figs. 2, 3, and 4

Fig. 2. Zernike coefficients of the aberrating plate, obtained with the two methods.

Fig. 3. Wave-front distortion obtained with the two methods. The increment in wave aberration between adjacent contour lines is $1 \mu\text{m}$.

Fig. 4. Top left, spot diagrams (raw experimental data or geometric aberrations); top right, bottom left, PSF's computed from wave aberration data; and bottom right, PSF recorded directly on the CCD.

in different formats: individual Zernike coefficients, overall wave-front distortion, and spot diagram and estimated point spread function (PSF), respectively. The geometric ray aberrations (raw data) are shown at the top left of Fig. 4. Figure 2 shows how both methods give consistent results for each individual Zernike coefficient. The differences are reasonably small and can be partly explained by potential differences between the two parts of the experimental setup. In fact, H-S coefficients tend to be slightly larger, perhaps because of the more-complex setup for this method, which has more optical components. This difference is reflected in Fig. 3, in which one can see that the

H-S method gives a rms wave-front error that is 12% larger than that obtained with LRT (2.79 compared with $2.46 \mu\text{m}$). From these two estimates of the wave aberration we computed the PSF as the squared modulus of the Fourier transform of the pupil function.⁶ In Fig. 4 the resulting PSF's are compared with the actual PSF that was recorded directly on the CCD camera (after we removed the objective). The computed and recorded PSF's show differences, and one reason for this is that the recorded PSF was obtained with a 6-mm pupil, whereas the computed PSF was obtained with a somewhat larger 6.6-mm pupil. Thus the agreement among the PSF estimated from aberrations, the spot diagrams, and the directly recorded PSF is not exact but looks reasonable. Interestingly, the agreement in visual resemblance and shape seems better for the LRT method.

In conclusion, we have proposed and developed a novel laser ray-tracing method for measuring the aberrations of optical systems as an experimental implementation of computational ray tracing used by optical designers. Thus, this method may be useful for facilitating direct comparison between design and testing stages. Results obtained in different tests and experiments (with a high-quality lens alone, with spherical and cylindrical lenses, and with an aberrating plate) were satisfactory. In particular, we obtained a reasonably good match between aberrations measured with the two methods, despite the difficulty of reproducing the same experimental conditions (alignment, focusing, etc.) in both sets of measurements. We interpret this agreement as a mutual validation of the two techniques, because they provided approximately equivalent results. However, since the two methods have very different features, they may reveal different advantages and drawbacks depending on the application.

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