Invited Paper

Recent Advances in Tolerancing Illumination Optics

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Abstract: Tolerancing is a critical step in creating successful commercial products. We explore recent advances in tolerancing illumination optics with particular emphasis on surface perturbations and extended sources.
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1. Introduction

Illumination design often involves freeform optical surfaces that provide a desired illuminance and/or intensity distribution. Approaches to compute surfaces that do not possess rotational or translational symmetry have been maturing over the past decades [e.g., 1-3], and advances continue to show up in commercial illumination design software [e.g., 4]. A typical illumination arrangement is a source with a lens or a reflector, as depicted in Fig. 1. The sharpness of the cutoff near the edges of the distribution is typically controlled by the size of the source.

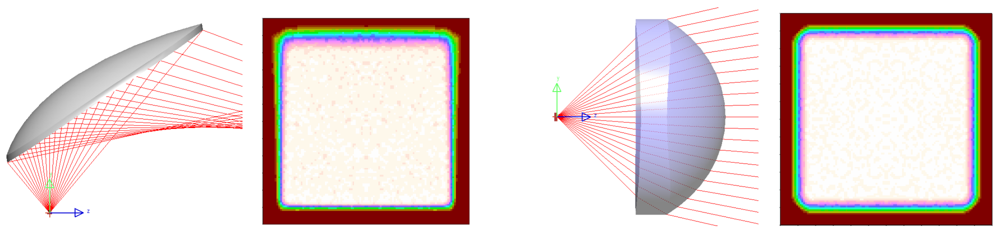

Fig. 1. Reflector (left) and Lens (right) are shown along with simulated illumination distributions.

In parallel with the development of design capabilities, fabrication and metrology also continue to mature [e.g., 5]. These advancements have resulted in corresponding software tool improvements. It is now becoming common for illumination designers to use tolerancing algorithms to simulate multiple perturbed systems and characterize the 'as built' performance. Two common design parameters to tolerance are surface figure and source alignment.

2. Surface Figure and Source Alignment

Differences between the desired and fabricated surface can produce changes in the output irradiance. Recent work [6] showed that irradiance changes are proportional to the Laplacian of the surface perturbation and linearly related to the magnitude of the changes. This means that the second derivative of the shape of the surface perturbation can be used to understand the irradiance distribution change. This Laplacian relationship has also been used to explain how light reflected from 'Oriental Magic Mirrors' provides an image of the surface relief on the backside of the mirror [7].

Consider a lens whose surface shape is designed to produce a uniform irradiance distribution using a point source. Now add a surface perturbation with a Gaussian shape (Fig. 2, left). The resulting irradiance distribution will then have a region corresponding to the surface perturbation that is applied. The shape of the irradiance change, relative to the original uniform irradiance, has a shape that is proportional to the Laplacian of the Gaussian (Fig. 2, right). Similarly, a perturbation with a parabolic shape will produce a top-hat type irradiance change, and a perturbation with a cubic shape will produce a triangular-type irradiance change.

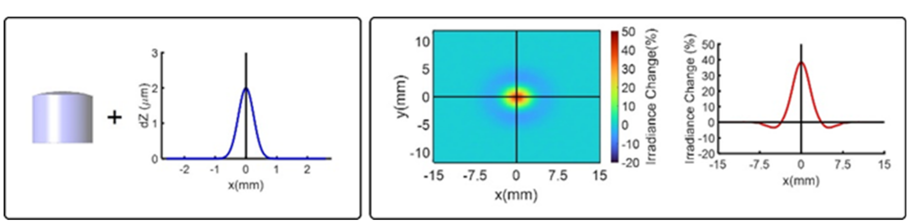

Fig. 2. A lens surface, designed to produce a uniform irradiance distribution, has a Gaussian perturbation added to the surface shape (left). The irradiance distribution change (right) is proportional to the Laplacian of the Gaussian.

Notice that the change in irradiance shown in Fig. 2 has a central peaked region that is surrounded by a region with a negative irradiance change. This is a result of energy conservation because flux from the outer region is shifted into the central region. If the Gaussian surface perturbation is reversed (e.g., a hole/dent instead of a bump), the change in target irradiance also reverses (e.g., reduced in the center and increased in the annular outer region).

This Laplacian relationship is correlated with the result obtained by comparing freeform surfaces designed to create different targets. The radial difference between a freeform designed to produce uniform illuminance over a specified target region compared to one designed for a smaller target shows a quadratic variation in the radial distance between points [e.g., 8]. This matches the Laplacian relationship that a parabolic shape produces a top-hat.

When an extended source is used, the irradiance using a point source can be convolved with the pinholes images to predict the irradiance [e.g., 9]. An example is shown in Fig. 3, where a lens to produce a 250 mm x 200 mm uniform illuminance distribution has a localized parabolic perturbation applied at a position that is offset from the center of the lens. Compared to a point source, the irradiance change with an extended source is smeared in size and its magnitude is significantly reduced.

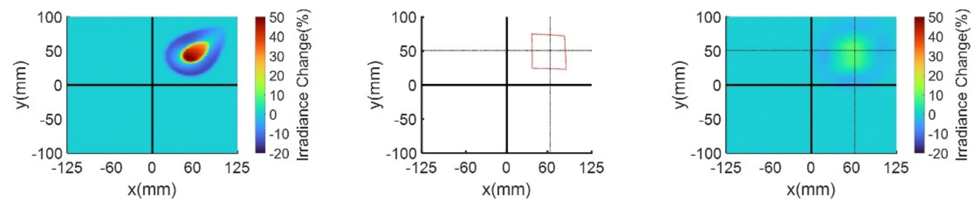

Fig. 3: Irradiance change for lens with decentered parabolic perturbation (left), the pinhole image outlines (middle), and the resulting irradiance change using the extended source (right).

Source position is also a critical parameter to tolerance. An example of three lenses that are designed to produce the same target distribution using a point source is shown in Fig. 4. The difference between the three cases is the shape of the input lens surface (see the upper row of Fig. 4) and that produces significant differences in the size of the pinhole images near the edges of the target (see the middle row of Fig. 4). Interestingly, the lens where the pinhole images have relatively constant size is also the one where shifting the source in Y has the smallest effect (see the lower row of Fig. 4). Constant pinhole image size is also usually related to reduced Fresnel reflections.

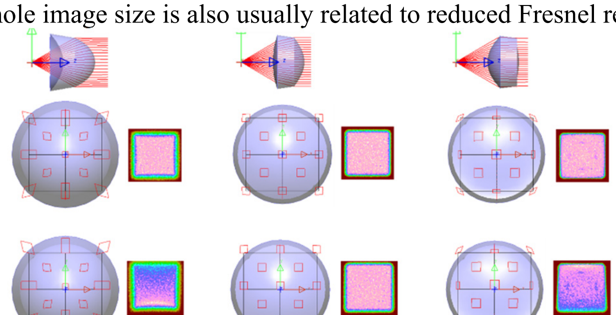

Fig. 4: Three lenses with different input surface shapes (upper row). Pinhole images and irradiance with the source at its nominal location (center row). Impact on the pinhole images and irradiance from the source shifted by half its size (bottom row).

3. Conclusions

Surface figure and source location are critical items to tolerance in an illumination system. Funded in part by the NSF Center for Freeform Optics (IIP-1822049).

4. References

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[4] https://www.synopsys.com/optical-solutions.html and https://www.synopsys.com/optical-solutions/lighttools.html. Simulations were performed using LightTools® and tailoring examples used the LightTools® FreeformDesign Feature.

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