Optically Efficient Homogenization of Laser Illumination

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Abstract

DYOPTYKA’s innovative deformable mirror technology is shown to achieve effective and efficient intensity homogenization of laser illumination and speckle reduction in a projection display optical system. Performance is found to be similar to an approach which uses one stationary and one moving diffuser but with significantly improved optical efficiency.

1 Background

Laser diodes have certain advantages for projection displays in comparison to LEDs, in particular their greater optical power so that fewer sources are required and their lower étendue for more optically efficient coupling into the illumination optical system.

However optical efficiency is not optimized when a diffuser is used to increase étendue to fill the entrance aperture(s) of the illumination homogenization and shaping optical system of microdisplay-based projectors. Even carefully designed and fabricated diffusers with relatively smooth surfaces have Fresnel reflection losses and scatter some illumination at high angles such that it misses the entrance aperture(s).

Another problem arising from the use of diffusers is that they create strong interference patterns in the projected image. These are one manifestation of the phenomenon of speckle [1] which can seriously degrade image quality. The conventional solution to making interference patterns less perceptible is to move the diffuser to create many uncorrelated patterns which sum to a more homogeneous intensity over time, see Figure 1.

2 Objectives

To demonstrate how optical efficiency can be improved by using DYOPTYKA’s phase-randomizing deformable mirror technology (see Figure 2,) without any of diffuser(s,) to increase étendue so as to achieve good homogenization of illumination intensity and reduction of speckle contrast.

3 Apparatus

The projection display parameters chosen for this investigation are those of a near-to-wall television with 150× magnification of a 0.65” DLP® microdisplay for an approximately 100” image through an f/2.4 projection optical system. Although a multi-LD array with about 30 W optical power would be required for sufficient brightness, for ease of laboratory experimentation we used a single 1 W multimode laser diode and a small deformable mirror. The experimental apparatus is shown and described in more detail in Figure 3.

Figure 1: The field illuminated by different configurations of the projection apparatus used in this study. [Above, left] With no diffuser, various inhomogeneities are evident: modal structure of laser diode; interference fringes arising from dust, scratches, and misalignments in the illumination and projection optical systems; incomplete distribution of illumination. [Above, right] With a 2” “engineered diffuser” before homogenizing rod: strong pattern due to diffuser structure; [Below, right] With a second diffuser of the same characteristics positioned after the first: more complete distribution of illumination but strong pattern visible; [Below, left] With second diffuser rotating at approx. 10,000 RPM: significant improvement.

Camera magnification was chosen such that image resolution was approximately equal to that of a human observer located at the nominal screen diagonal distance. Camera lens f/# was chosen such that speckle contrast in the acquired imagery was approximately equal to that perceived by a human observer. This is a highly subjective approach but we felt it appropriate to ensure that speckle is more realistically represented in acquired imagery than is sometimes the case in the published literature.

4 Procedure and results

We operated the apparatus mostly in two different configurations: no diffuser(s) and deformable mirror active; one stationary diffuser, one moving diffuser, and deformable mirror inactive. Table 1 summarizes our measurements and observations which are discussed in
Figure 2: Deformable mirror in inactive and active states. Central region is actuated at hundreds of kHz resulting in randomly-distributed surface deformations which achieve effective and efficient divergence, inter-modal dispersion in waveguides, and the generation of uncorrelated speckle patterns. Reflection efficiency is approximately 98%.

Table 1: Subjective observations about homogeneity of the illuminated field shown in Figure 4. Also mean pixel gray level intensities (relative to maximum sensor value) and speckle contrast ratios of the small regions shown in Figure 5 (values rounded to nearest integers.)

<table>
<thead>
<tr>
<th></th>
<th>Deformable mirror</th>
<th>Diffusers</th>
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<tbody>
<tr>
<td>Intensity</td>
<td>Low gain</td>
<td>47%</td>
</tr>
<tr>
<td></td>
<td>High gain</td>
<td>65%</td>
</tr>
<tr>
<td>Speckle</td>
<td>Low gain</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td>High gain</td>
<td>10%</td>
</tr>
<tr>
<td>Homogeneity</td>
<td>Low gain</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>High gain</td>
<td>Good</td>
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We operated the apparatus also with only one moving diffuser and deformable mirror inactive. However the homogeneity was so poor it was not possible to make a meaningful comparisons with the other configurations.

5 Homogeneity

The intensity distribution across the field is not as good with the deformable mirror only as with the two diffusers. It is possible that a longer homogenizing rod would help, as would cleaner and better aligned optics. In our previous work much better homogeneity was achieved through the use of microlens arrays instead of a homogenizing rod [2] but we used a rod here because it is the most common approach for DLP®. However our expectation is that the use of a multi-LD array instead of a single source should lead to a significant improvement.

6 Speckle

The speckle contrast ratios for both configurations are effectively the same. This is in accordance with the theory that the limit is inversely proportional to the sensor spot size divided by the projection lens diffraction-limited spot size [1].

Figure 3: [Above] Experimental illumination and projection apparatus. Components clockwise from below-left: Roithner LaserTechnik 450 nm multimode laser diode delivering approximately 1 W optical power; An $f = 4.51\text{mm}$ lens to reduce divergence so that only the central region of the deformable mirror is illuminated; Kinematic mount holding deformable mirror and first RPC Photonics model EDS2° engineered diffuser; Second 2° engineered diffuser mounted such that it can be rotated at approx. 10,000 RPM; An $f = 4.51\text{mm}$ lens positioned such that the exit $f/#$ of the illumination optical system is approximately $f/2.4$; Homogenizing rod of dimensions $6 \times 8 \times 50\text{mm}^3$. Although this rod has only half the cross-sectional area of a 0.65” microdisplay, it was chosen because of the reduced optical power available; Projection lens from DLP® projector with a rectangular stop added to approximate $f/2.4$; Since the projection lens was not wide angle, the apparatus was positioned approximately 5 m from the illuminated field for 150x magnification. [Below] Region of illuminated field comprising materials with different surface roughness characteristics: paper business card; low gain, relatively rough diffusing surface of painted wall; high gain, polarization-preserving 3-D cinema screen sample (with holes for sound transmission;) and smooth plastic ruler. Note that this image was acquired using broadband, non-coherent, diffuse illumination. When illuminated with monochromatic, coherent, directional illumination through the projection apparatus, the high gain screen sample has a more irregular intensity due to it not being flat, see Figure 4 for example.

7 Optical Efficiency

The deformable mirror only configuration is approximately 1.5 times brighter than the two diffuser configuration for both low-gain and high-gain materials. For increased confidence in our observations we simplified the apparatus by positioning a beam profiler directly after the exit face of the homogenizing rod. The imagery acquired is shown in
Figure 4: [Above] With no diffuser and deformable mirror active. Compare to the [Above, left] image of Figure 1 where the deformable mirror is inactive. [Below] With one stationary and one moving 2° “engineered diffuser.” This is an enlarged version of the [Below, left] image of Figure 1.

Figure 6. This confirmed that the deformable mirror only configuration was indeed approximately 1.5 times brighter than the two diffuser configuration (and approximately 1.25 times brighter than the one diffuser configuration.)

8 Conclusions

A significant increase in the brightness of the projected image was achieved using the deformable mirror only instead of diffusers. Homogeneity was reasonable and speckle contrast was equivalent.

Although more optically efficient diffusers could have been used and followed by a more optimized collecting optical system at the entrance of the homogenizing rod, it is difficult to imagine how any moving diffuser design could improve upon the approximately 98% optical efficiency of the DYOPTYKA deformable mirror solution.

We believe these results to be of significance and that they could lead to brighter and more efficient laser and laser-phosphor [3] projection displays of all sizes.

Figure 5: 50×50 pixel regions from illuminated fields where intensity should be relatively homogeneous. [Left] Low-gain painted surface. [Right] High-gain cinema screen. [Above] With deformable mirror active. [Below] With one stationary and one moving diffuser.

Figure 6: Imagery from Thorlabs BC106-VIS beam profiler camera positioned directly against the exit face of the homogenizing rod. [Left] With deformable mirror only, mean intensity is 35% (relative to maximum sensor value.) Note that in this particular case the mirror was not driven in such a way as to achieve good homogeneity. [Center] With one moving diffuser only, mean intensity is 28%. [Right] With one stationary and one moving diffuser only, mean intensity is 24%.

References