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Dynamic Illumination for Spatio-temporal Integration of Unwanted Interferences in Holographic Displays

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Abstract: *The quality of holographic display imagery is improved using a compact, reliable, optically efficient deformable mirror instead of a moving diffuser. In particular, so-called subjective speckle that can render text and symbols illegible at viewing distances of several meters, is reduced significantly.*

1 Background

Computer-generated holograms presented on phase-only spatial light modulators (SLM) can form high contrast and high optical efficiency imagery suited to applications such as automotive head-up displays and near-eye virtual and augmented reality displays [1]. Lasers are commonly used as their sources of illumination since they have the high spatial coherence and narrow spectral linewidths required. However these characteristics can result in there being a variety of unwanted interferences visible in the imagery, including objective and subjective speckle [2]. Approaches to reduction of objective speckle include presentation of sequences of variations of the hologram. This necessitates additional computation and presentation frequency is limited by SLM interface bandwidth. Approaches to reduction of subjective speckle include moving a diffusing screen located where the image is formed. This requires a motion mechanism that adds to system size and complexity.

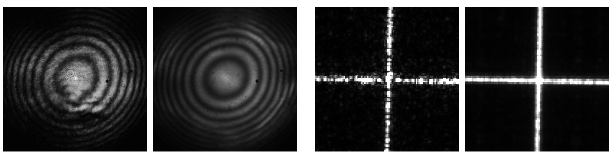

Fig. 1: [Left] Fringes formed by an interferometer with dirt on its lenses (left.) With DM active, only the fringes of interest remain (right.) [Right] Pattern formed on a diffusing screen by a diffractive optical element. Speckle results in an inhomogeneous distribution of intensity (left.) With DM active, intensity distribution is improved without significant loss of resolution (right.)

DYOPTYKA has developed an innovative phase-randomizing deformable mirror (DM) technology that can generate sequences of uncorrelated interferences at high temporal frequencies. Thus their visibility is reduced through their spatio-temporal integration by the observer. In conventional projection display applications this approach results in much improved optical efficiency when used instead of moving and stationary diffusers [3].

A unique characteristic of our technology is that it can preserve sufficient spatial coherence for interference fringes and diffraction patterns, see Figure 1. Herein we address the question of whether it can reduce speckle effectively in holographic displays.

2 Apparatus and Method

We have already demonstrated that a small spot focused onto the surface of the DM is like an extended source from which a beam of reasonable quality can be formed [4]. This inspired the design of our hologram apparatus, as shown in Figures 2, 3, and 4. Rather than collimate the beam, a lens was used to focus the hologram image onto a diffusing screen. This emulates a head-up display configuration where diffusion is necessary to fill the entrance pupil of a combiner optical system. The relatively rough surface of the screen is a cause of subjective speckle.

A narrow linewidth 532 nm DPSS laser source with beam diameter approx. 1 mm was used with an $f = 15$ mm spot focusing lens mounted on a precision linear translation stage. When the translation distance was such that spot size was smallest, approx. 10 µm diameter, not much speckle reduction was observed in the hologram image. Our interpretation was that there was an insufficient combination of DM surface waves within the extent of the spot for the generation of uncorrelated speckle patterns. When the spot was much larger, approx. 500 µm, there was an unacceptable loss of image resolution due to blur. A compromise between these two extremes was found by adjusting the translation stage while looking at the image.

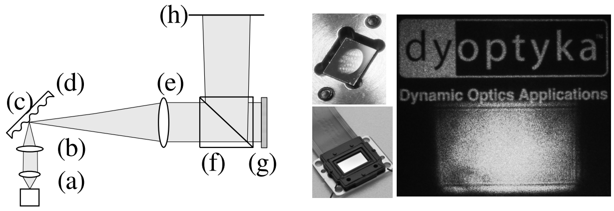

Fig. 2: [Left] Schematic of hologram illumination and display system: (a) coherent source and collimating lens; (b) focusing lens; (c) small spot; (d) deformable mirror; (e) image focusing lens; (f) Polarizing beam splitter cube; (g) reflective SLM; (h) screen. [Center] DYOPTYKA's small uDM deformable mirror in an active state. Elliptical central region of $3 \times 4.5\,\mathrm{mm}^2$ is actuated at hundreds of kHz resulting in randomly-distributed surface deformations (above.) Jasper Display Corporation reflective LCoS SLM (below.) This model JD9554AE7 is not phase-only. Its rubbing angle of 45 deg is a compromise for both phase and amplitude modulation. [Right] Hologram image of company logo formed on screen. Zero order diffraction region can be blocked by a polarizer with appropriate orientation.

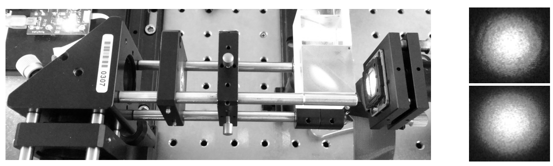

Fig. 3: [Left] Experimental apparatus corresponding to schematic. [Right] Illumination focused by image focusing lens with DM inactive (above.) With DM active (below) there is a minimal increase in extent since increased divergence due to the DM is within the N.A. of the lens.

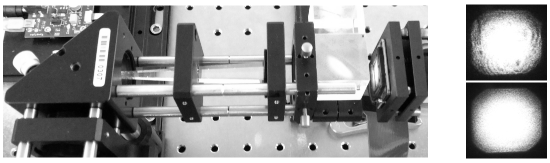

Fig. 4: [Above] Variation of experimental apparatus. A tapered light guide with square profile is used to shape the illumination to better match SLM shape, to improve homogeneity of intensity, and to reduce divergence. [Right] Illumination focused by image focusing lens with DM inactive (above) and active (below.) Unwanted interferences effectively smoothed. Note that the corners of square face of the light guide are blocked by its circular holder.

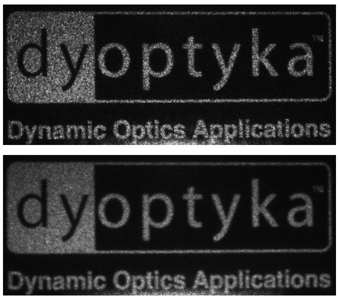

Fig. 5: Hologram image of width 10 cm focused onto paper screen at distance 180 cm. Imaged acquired by camera with lens f=12 mm and aperture stop $f/8$, positioned 50 cm from screen. [Above] DM inactive. Objective and subjective speckle visible. [Below] DM active. Speckle contrast reduced.

Speckle perceived by an observer in reality has higher dynamic range and higher spatial resolution than can be acquired by a typical camera. However the imagery presented herein provides a relatively authentic representation. It was chosen by an observer through a process of adjusting camera lens magnification and aperture parameters such that the camera image displayed on a computer screen approximately matched the observer's perception of the focused hologram image.

3 Results

Figures 5, 6, 7, and 8 show significant improvements in image quality. Particularly noteworthy is the improvement text legibility at the further viewing distance. This is important in head-up and augmented reality displays where the combiner presents text and symbols at virtual distances of several meters.

It is not straightforward to interpret the reduction in speckle contrast ratio as a measure of image quality improvement because a certain amount of inhomogeneity is an inevitable consequence of holographic image formation. For the near viewing distance imagery it is approx. 39% and 32% with DM inactive and active respectively, and for the further distance it is approx. 44% and 34%.

Note that the zero order diffraction region visible in Figure 2 is much brighter than the focused hologram image. The contrast between the brightest and darkest regions of the hologram imagery presented herein is approx. 5:1. Further efforts will be made to improve hologram image contrast (for example using a phase-only SLM and better polarizers) before an investigation is undertaken into whether the action of the DM has any negative effect on contrast.

4 Conclusions

Significant improvements in focused hologram image quality, without any moving diffuser(s) in the illumination or imaging

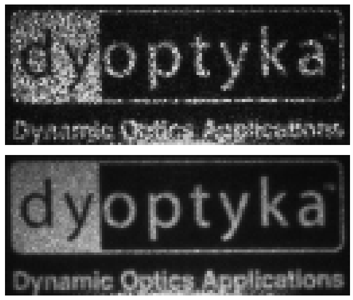

Fig. 6: Same hologram image acquired by the same camera with the same lens parameters but positioned 180 cm from screen. [Above] DM inactive. Speckle worse due to hologram image field being smaller relative to the N.A. of the lens. [Below] DM active. Speckle contrast significantly reduced.

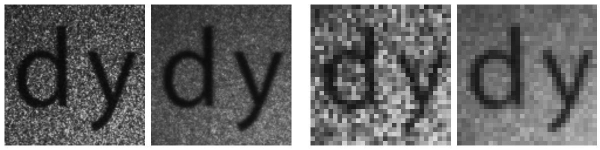

Fig. 7: Regions from the four images described above. Granular texture remains even when subjective speckle contrast is reduced.

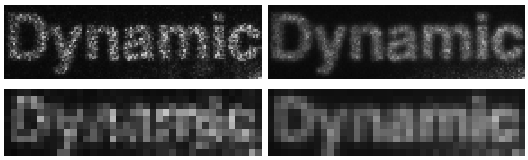

Fig. 8: Smaller text from the same imagery. Size was chosen to be at the limit of observer's visibility at the further viewing distance.

optical systems, have been demonstrated using our deformable mirror. Our understanding of its behavior is: (i) it acts like an extended source, reducing spatial coherence such that speckle contrast is reduced with little degradation of image resolution. See [5] for a related discussion; (ii) it generates uncorrelated speckle patterns over time that are integrated by the observer such that a more homogeneous intensity is perceived.

Acknowledgments

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[3] Shevlin, F., "Optically efficient homogenization of laser illumination," in [*International Display Workshop (IDW '15)*], Institute of Image Information and Television Engineers (ITE), Society for Information Display (SID) (December 2015).

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