Laser Beam Modulation with a Fast Focus Tunable Lens for Speckle Reduction in Laser Projection Displays

Zequn Jian[1, 2], Zhaomin Tong[1, 2], Yifei Ma[1, 2], Mei Wang[1, 2], Suotang Jia[1, 2], and Xuyuan Chen[1, 2, 3]

[1]State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Laser Spectroscopy, Shanxi University, Taiyuan, Shanxi 030006, People's Republic of China
[2]Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, Shanxi 030006, People's Republic of China
[3]Faculty of Technology and Maritime Sciences, Department of Micro- and Nanosystem Technology, University of Southeast Norway, Borre N-3184, Norway

Keywords: Speckle reduction, focus tunable lens, angular diversity, spatial diversity.

ABSTRACT

We propose a laser speckle reduction method using a fast focus tunable lens (FTL). Different laser beams are generated after modulating the FTL. Thus, when the laser beams are used to illuminate a diffuser, various speckle images are obtained, and the summed speckle images yield a speckle image with reduced speckle contrast ratio.

1 INTRODUCTION

Lasers are preferred to be used as illumination light sources in displays owing to their good monochromaticity and directionality [1]. Compared with other display technologies, laser displays can provide wider color gamut, increased brightness, and increased optical efficiency [2]. One of the problems associated with the use of lasers in displays is the speckle effect, that is caused by the coherence property of laser manifested as strong grainy interferences when lights are scattered from an object with rough surfaces [3]. The existence of the laser speckle can seriously degrade image quality. Correspondingly, speckle reduction is required in laser displays. Speckle reduction can be achieved by a fast scanning micromirror [4], vibration of diffusers [5], binary micro-mirror arrays [6], and dynamic deformable mirrors [7]. Among these speckle reduction techniques, most of them can effectively suppress speckle. However, some of these are expensive, complicated, or bulky, and hence unsuitable for practical laser display applications.

In this study, we propose a simple and effective laser speckle reduction method by introducing a fast focus tunable lens (FTL). Sinusoidal signals are used to drive the FTL, making the focal length of the FTL change between minimum and maximum values, thus realizing laser beam modulation. When the modulated laser beams are used to illuminate an object with rough surfaces, it produces different speckle patterns. Thus, speckle reduction can be achieved after summing these speckle patterns during the exposure time of the charge-coupled device (CCD) camera. Speckle contrast ratio C is used to characterize the speckle effect. The speckle contrast ratio C is defined as [8],

$$C=\frac{\sqrt{<I^2>-<I>^2}}{<I>}=\frac{\sigma_I}{<I>}, \quad (1)$$

where $<I>$ and σ_I represent the mean value and the standard deviation of light intensity, respectively. For fully developed speckles, the speckle contrast ratio equals one. It is reported that the human eye cannot detect the presence of speckle when the value of speckle contrast ratio is lower than 0.05 [8].

The covariance of light intensity for the two laser beams at different angles of incidence on the diffuser can be written as [8]

$$|\mu_A(\vec{q}_1,\vec{q}_2)|^2=|M_h(\Delta q_z)|^2|\Phi(\Delta q_t)|^2, \quad (2)$$

where $|\mu_A(\vec{q}_1,\vec{q}_2)|^2$ is the covariance of the light intensity, $|M_h(\Delta q_z)|^2$ is the first-order characteristic function of the surface-height fluctuations, and $|\Phi(\Delta q_t)|^2$ is the translation of the speckle pattern when the incidence or observation angle is changed. Additionally, $\vec{q}_1$ and $\vec{q}_2$ are the scattering vectors, and Δq_z and Δq_t are the normal and the transverse components of the scattering vector difference $\Delta\vec{q}=\vec{q}_1-\vec{q}_2$, respectively. Δq_z and Δq_t are given by [8]

$$\Delta q_z=\frac{2\pi}{\lambda}\left[\sqrt{n^2-\sin^2(\theta_{i1}+\Delta\theta)}-\sqrt{n^2-\sin^2\theta_{i1}}\right], \quad (3)$$

$$\Delta q_t=\frac{2\pi}{\lambda}\left[\sin(\theta_{i1}+\Delta\theta)-\sin\theta_{i1}\right]. \quad (4)$$

As the scattering vector difference $\Delta\vec{q}$ increases, the angle difference $\Delta\theta$ between vector $\vec{q}_1$ and $\vec{q}_2$ becomes larger, which makes the intensity covariance $|\mu_A(\vec{q}_1,\vec{q}_2)|^2$ smaller. Thus, the decoherence of the illuminating light source increases, and the speckle contrast ratio can be reduced [8].

2 CHARACTERIZATION of the FTL

The FTL (EL-10-30-TC from Optotune) has a clear aperture of 10 mm and the response time is smaller than 2.5 ms. The FTL is composed of an electromagnetic actuator and an elastic polymer membrane filled with optical fluid [9]. When the electromagnetic actuator works to exert pressure on the container, more fluid fills the clear volume of the FTL, and the deflection of the FTL increases [9]. Therefore, the focal length of the FTL decreases. The maximum and minimum driving currents are 0 mA and 250 mA, respectively. The working frequency of the FTL ranges from 0 Hz to 1kHz. We have used a camera beam profiler (BC106N-VIS/M from Thorlabs) to calibrate the focal length of the FTL. The minimum focal length is f_{min} = 44.5 mm and the maximum focal length is f_{max} = 160.5 mm.

To realize speckle reduction by generating different speckle images and summing them together during the detector integration period, alternating currents are used to drive the FTL to induce temporal-dependent changes of the focal length of the FTL. The tuning range of the focal length varies at different driving frequencies. When the frequency of the driving current equals the resonant frequency of the elastic polymer membrane, the strongest elastic polymer membrane vibration is realized, and the tuning range of the focal length is maximized largest [9]. Figure 1 shows the experimental setup used to characterize the resonant frequency of the elastic polymer membrane.

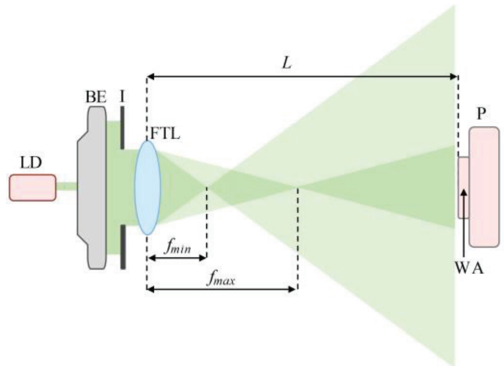

Fig. 1 Experimental setup used to characterize the resonant frequency of the elastic polymer membrane (LD: laser diode, BE: beam expender, I: iris, FTL: focal tunable lens, P: photodetector, WA: working area of the photodetector).

As shown in Fig. 1, we have used a collimated laser diode (L520P50 from Thorlabs) as the illumination light source. A 20× beam expander and circular iris (with a diameter of 8 mm) are introduced to magnify the laser beam and redefine the laser beam width, respectively. After the laser beam passes through the FTL, light intensity is measured by a photodetector (PDA36A from Thorlabs). The photodetector has a rectangular working area of 3.6 mm × 3.6 mm. The distance between the photodetector and the FTL is L = 290 mm. The photocurrent generated by the photodetector has a one-to-one relationship with the change of the focal length of the FTL in this situation. For example, when the driving current decreases from its peak to its valley value, the focal length of the FTL varies from the maximum value f_{max} to the minimum value f_{min}, and the number of photons captured by the working area of the photodetector decreases correspondingly. An oscilloscope (TBS 1052B from Tektronix) was used to measure the peak-to-peak photocurrent generated by the photodetector.

Figure 2 shows the normalized peak-to-peak photocurrent measured by the oscilloscope when the driving frequency of the FTL was changed from 0 Hz to 200 Hz. As shown in Fig. 2, when the driving frequency of the FTL equals 97 Hz, the normalized peak-to-peak photocurrent has a maximum value. Therefore, we choose 97 Hz as the working frequency of the FTL to maximize the tuning range of the focal length of the FTL to achieve the most efficient speckle reduction.

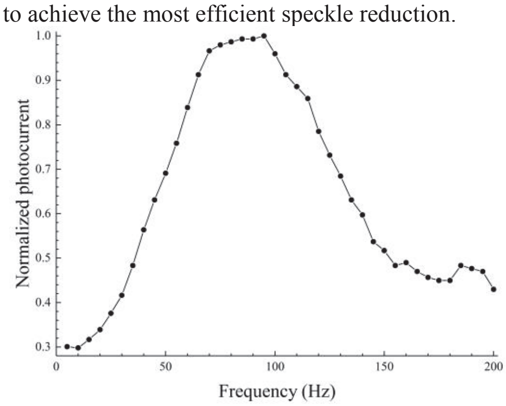

Fig. 2 Relationship between the normalized peak-to-peak photocurrent and the working frequency of the FTL.

3 EXPERIMENTS and DISCUSSION

3.1 Speckle Reduction in Free-space Propagation

Figure 3 schematically shows the experimental setup for the speckle reduction measurement in free-space propagation using the FTL. Herein, a similar optical configuration was used to that shown in Fig. 1. A rotating polarizer is employed to control the laser beam intensity, and a 50 mm × 50mm square diffuser (sandblasted glass from Edmund Optics) is placed after the FTL. During the experiment, the distance from the FTL and the diffuser L_1 is changed from 45 mm to 165 mm. Speckle patterns propagating in free-space are recorded by a CCD camera. The exposure time of the CCD camera is set to 30 ms, which is close to the time required by the human eyes to integrate the visual signal [8]. The CCD camera has a resolution of 1280 × 1024 pixels, and each pixel has a dimension of 5.2 µm × 5.2 µm. The brightness of the speckle images recorded by the CCD camera is modulated by the rotating polarizer to avoid overexposure and underexposure. The working frequency of the FTL equals its resonant frequency at 97 Hz. The diffuser and the CCD camera are mounted on a precision translation stage. Accordingly, the distance between the FTL and the diffuser can be accurately controlled. The distance from the diffuser and the CCD camera is constant with a value L_2 = 260 mm.

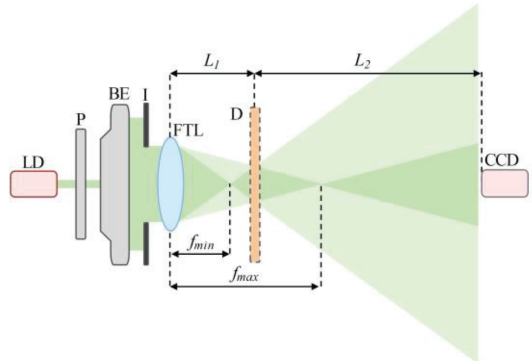

Fig. 3 Schematic of the optical path of the FTL in the case of sinusoidal signal modulation. The diffuser is placed at

the position (the regions inside the dotted black lines) at which the beam diameter is the smallest (LD: laser diode, P: polarizer, BE: beam expender, I: iris, FTL: focal tunable lens, D: diffuser, CCD: charge-coupled device camera).

When the distance L_1 is changed, speckle images are captured by the CCD camera. Equation (1) was used to calculate the speckle contrast ratio C. Figure 4 shows the relationship between the distance L_1 and the speckle contrast ratio C.

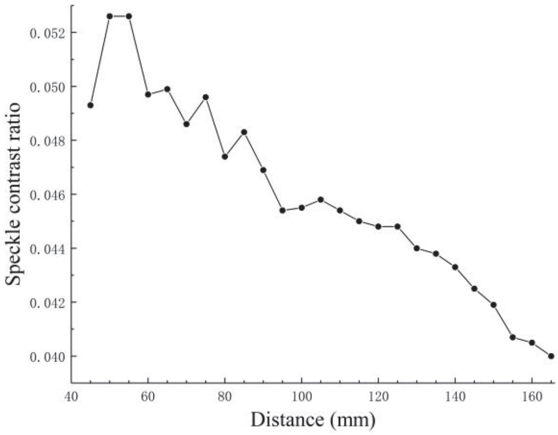

Fig. 4 Experimental results showing the variation of the speckle contrast ratio as a function of distance.

As shown in Fig. 4, when the distance L_1 becomes larger, the speckle contrast ratio exhibits sequential rising and falling edges. When the distance L_1 equals 60 mm, the speckle contrast ratio has a maximum value. The laser beam size on the diffuser changes by moving the diffuser, which alters the coherence properties of the laser beam which propagates on the diffuser. Accordingly, we have that [10]

$$\theta_{\mathrm{coh}} = \frac{\lambda}{\pi r_{di}}, \tag{9}$$

where the coherence divergence angle θ_{coh} depends on the beam radius r_{di} on the diffuser. The laser beams are captured by the CCD camera after propagating through the diffuser, and the size of the coherence area on the CCD camera is $A_{coh} = \pi(L_2 \tan\theta_{coh})^2$. Thus, the coherence area on the CCD camera is inversely proportional to the laser beam radius r_{di} of the diffuser. According to the geometrical optics principle, the various sizes of the laser beam on the diffuser exhibit a falling trend followed by a rising trend when the distance L_1 increases from 45 mm to 165 mm. The smallest size of the laser beam is 4.5 mm when the distance L_1 equals to 69.7 mm. Therefore, the coherence area on the CCD camera exhibits a rising trend followed by a falling trend as the distance L_1 increases. Consequently, the speckle contrast ratio has a maximum value at L_1 = 69.7 mm owing to the spatial diversity. However, the speckle contrast ratio is maximized at L_1 = 60 mm, as shown in Fig. 4.

We define the direction of the incident beam on the diffuser as positive when the normal line rotates at the incident angle in the anticlockwise direction, and when the normal line rotates at the incident angle in the clockwise direction, the direction of incident beam on the diffuser is negative. When the distance L_1 becomes equal to f_{min}, the direction of the incident beam at every spot (expect the focal spot) on the diffuser has single direction (positive or negative). When the position of the distance L_1 is ≥ 69.7 mm, the incident beam has positive and negative directions at all the illuminated points on the diffuser. Therefore, the angular diversity increases as a function of the distance L_1 when it is ≤ 69.7 mm. The directional diversity has a constant value when the distance L_1 is ≥ 69.7 mm.

As shown in Fig. 4, the speckle contrast ratio is increased owing to the decrease of the size of the coherence area on the CCD camera when the distance L_1 is less than 60 mm. When the distance L_1 ranges between 60 mm and 69.7 mm, the angular diversity is the dominant speckle reduction mechanism. The speckle contrast ratio is decreased owing to the increased directional diversity. When the distance L_1 is ≥ 69.7 mm, the dominant speckle reduction mechanism is attributed to the spatial diversity. The speckle contrast ratio is decreased owing to the increased spatial diversity. Considering the problem of the optical power loss, we need to place the diffuser at the position where the beam diameter is the smallest to utilize light. Accordingly, we placed the diffuser at the distance L_1 = 69.7 mm. Figures 5(a) and 5(b) show the speckle images before and after the speckle reduction when the distance L_1 = 69.7 mm. The speckle contrast ratios are 0.84 and 0.04 for Figs. 5(a) and 5(b), respectively.

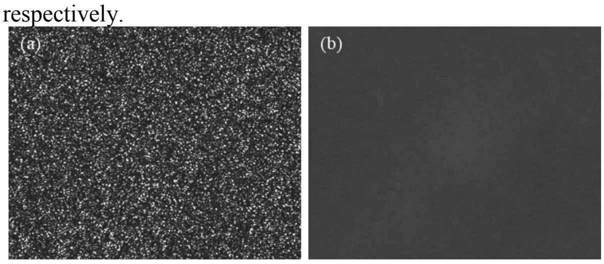

Fig. 5 Recorded speckle images using the CCD camera before (a) and after (b) the speckle reduction.

3.2 Application in Laser Projection Displays

Figure 6 shows a simplified optical system exemplifying the application of this method in laser projection displays. The distance between the diffuser and the FTL is 69.7 mm. A light pipe is placed closely after the diffuser. The dimension of the rectangular entrance surface of the light pipe is 5 mm × 6 mm, which is larger than the laser beam diameter (4.5mm) at this position. Therefore, the light pipe can collect all the scattered light from the diffuser, and the optical power loss can be minimized. With the help of the combination of the diffuser and the light pipe, the optical field is homogenized for uniform illumination. A relay lens and a field lens are used to transfer the optical field at the exit surface of the light pipe to a digital micromirror device (DMD). The image information generated by the DMD is projected onto a screen by a projection lens. The focal length and F-number of projection lens are 24 mm and 2.41, respectively. A CCD camera mounted with an image lens is used to capture the enlarged image on the screen. The focal length of the image lens is 35 mm, and the F-number is 4. The distance between the projection lens and the screen is 1000 mm. The distance between the CCD camera and the screen is 1600 mm. The exposure time of the CCD camera is set to 30 ms.

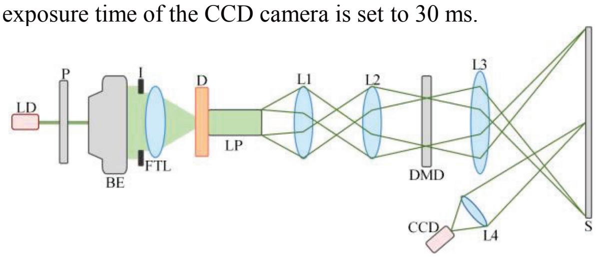

Fig. 6 Speckle measurement and reduction setup in laser projection displays (LD: laser diode, P: polarizer, BE: beam expender, I: iris, FTL: focal tunable lens, D: diffuser, LP: light pipe, L1: relay lens, L2: field lens, L3: projection lens, L4: image lens, DMD: digital micromirror device, CCD: charge-coupled device camera, S: screen).

Figure 7 shows the projected pictures captured by the CCD camera using the optical system shown in Fig. 6 before and after driving the FTL. Speckle contrast ratios are calculated by selecting areas with uniform brightness (the regions inside the solid red lines). After driving the FTL, the speckle contrast ratio is reduced from 0.16 to 0.09.

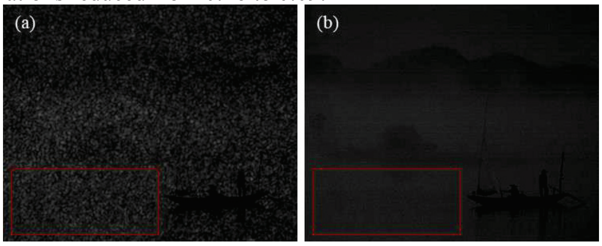

Fig. 7 Projected images on the screen in laser projection displays captured by the CCD camera before (a) and after (b) driving the FTL.

4 CONCLUSIONS

In conclusion, a laser speckle reduction method using the FTL has been proposed in this study based on which we have demonstrated laser speckle reduction in laser projection displays. Because the focal length of the FTL was changed when the FTL was driven by the sinusoidal signal, different angles of incidence were obtained when the modulated laser beam was used to illuminate the diffuser, and the laser beam size on the diffuser changed during the exposure time of the CCD camera. Therefore, the speckle reduction mechanisms were realized based on angular and spatial diversities. To achieve the most efficient speckle reduction, the FTL was driven using a resonant mode to maximize the vibration amplitude of the elastic polymer membrane and the tuning range of the focal length. In consideration of the dimension of the entrance surface of the light pipe, the diffuser was placed at an optimized position to minimize the optical power loss. In these circumstances, the objective speckle contrast ratio was reduced to 0.04 in the case of free-space propagation, and the subjective speckle contrast ratio was reduced to 0.11 in the case of the laser projection system. In comparison with other speckle reduction methods, the method proposed in this study is simple and effective, and can be used in practice in laser projection displays.

REFERENCES

[1] Svelto O, Hanna DC. Principles of lasers. New York: Plenum press, 1998.

[2] Chellappan KV, Erden E, Urey H. Laser-based displays: a review. Appl Opt 2010; 49(25): F79-F98.

[3] Akram MN, Chen X. Speckle reduction methods in laser-based picture projectors. Opt Rev 2016; 23(1): 108-120.

[4] Akram MN, Tong Z, Ouyang G, Chen X, Kartashov V. Laser speckle reduction due to spatial and angular diversity introduced by fast scanning micromirror. Appl Optics 2010; 49(17): 3297-3304.

[5] Pan JW, Shih CH. Speckle reduction and maintaining contrast in a LASER pico-projector using a vibrating symmetric diffuser. Opt Express 2014; 22(6): 6464-6477.

[6] Tong Z, Chen X. Laser speckle reduction by using a Binary Micro Mirror Array (BMMA): theory and design. In: 2011 International Conference on Optical MEMS and Nanophotonics (OMN); 2011. P. 195-6.

[7] Tran TKT, Chen X, Svensen Ø, Akram M N. Speckle reduction in laser projection using a dynamic deformable mirror. Opt Express 2014; 22(9): 11152-11166.

[8] Goodman JW. Speckle phenomena in optics: theory and applications. Englewood. Colorado, USA: Roberts and Company Publishers; 2006.

[9] Blum M, Büeler M, Grätzel C, Aschwanden M. Compact optical design solutions using focus tunable lenses. Proc SPIE 2011; 8167: 81670W.

[10] Mandel L, Wolf E. Optical coherence and quantum optics. Cambridge university press; 1995.