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Speckle reduction using deformable mirrors with diffusers in a laser pico-projector

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Abstract: We propose a design for speckle reduction in a laser pico-projector adopting diffusers and deformable mirrors. This research focuses on speckle noise suppression by changing the angle of divergence of the diffuser. Moreover, the speckle contrast value can be further reduced by the addition of a deformable mirror. The speckle reduction ability obtained using diffusers with different divergence angles is compared. Three types of diffuser designs are compared in the experiments. For Type 1 which uses a circular symmetric diffuser the speckle contrast value can be decreased to 0.0264. For Type 2, the speckle contrast value can be reduced to 0.0267 because of the inclusion of an elliptical distribution diffuser. With Type 3 which includes a combination of the circular distribution diffuser and elliptical distribution diffuser, the speckle contrast value can be reduced to 0.0236. For all three types, the speckle contrast value is lower than 0.05. Under this speckle value, the speckle phenomenon is invisible to the human eye.

OCIS codes: (030.6140) Speckle; (290.0290) Scattering; (140.0140) Lasers and laser optics; (110.6150) Speckle imaging

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1. Introduction

In recent years, laser projection display technology has developed significantly [1]. The laser projector has a wide color gamut, long lifetime and high optical efficiency compared with traditional projectors. There are also advantages arising from using a laser as the light source in the projector design, such as the monchromaticity, directionality, brightness and coherence of the light [2]. However, the high coherence of the laser light can lead to a speckle effect caused by interference [3]. This speckle phenomenon damages the image quality of the projection. Therefore, speckle suppression is very important to consider in laser projection displays. An additional element is needed in the projector design to reduce the speckle effect. Many techniques have been developed for speckle suppression in laser projection displays in recent years [4]. The speckle suppression technologies can be divided into three methods. The first method uses wavelength diversity [5], angle diversity, and polarization diversity of the laser for coherence reduction, which can further reduce interference [6]. The second method is to eliminate the degree of temporal coherence of the laser by the inclusion of a vibrating diffuser [7], dynamic deformable mirror [8,9], or electroactive polymers [10]. The third method is spatially varying independent to include dielectric elastomeric actuators (DEA) [11, 12], or rely upon moving the screen [13]. The above methods can reduce the speckle contrast value to between 0.03 and 0.05. However, all of these technologies have disadvantages such as requiring a large system volume and high power consumption, making them unsuitable for laser pico-projector designs and none of these methods can effectively to reduce the value of speckle contrast in the laser projector display to a low enough level that speckle particles are not visible to the human eye.

In this study, we combine two methods for the design of a speckle reduction element which has commercial applications. In the first method, diffusers, a circular distribution diffuser, and an elliptical distribution diffuser, are used to increase the étendue of the laser. This method has already been used in laser projector displays. In order to further reduce the speckle contrast to a level invisible to the human eye, we add a dynamic deformable mirror [9, 14]. This method can generate many uncorrelated speckle patterns, which can further reduce the speckle contrast value. The above two methods are based on the principle of angle diversity.

2. Definition of speckle contrast

The speckle phenomenon is very important for image quality in laser projection displays. The speckle contrast value indicates the amount quantization used to describe the speckle. The speckle contrast is given by [3]

$$C = \frac{\sqrt{<I^2> - <I>^2}}{<I>} = \frac{\sigma_I}{<I>} \tag{1}$$

where speckle contrast C is defined as the ratio of the standard deviation σ_I to the mean intensity <I>. The speckle contrast value is usually between 0 and 1. When the value of speckle contrast C is a little short of one, this is called a fully developed speckle pattern [3].

When the image is not affected by the speckle phenomenon, the value of the speckle contrast is said to be 0. When the value of the speckle contrast is less than 0.05, the speckle phenomenon becomes imperceptible to the human eye [4, 7].

3. Pico-LASER projection layout

The layout of the pico-LASER projection system is shown in Fig. 1. There are three white light laser sources used in the projector display. An X-prism is used to combine the three laser sources. For evaluating for speckle phenomenon, the wavelength of the laser source is 532nm, because the human eye is more sensitive to green light than other colors. First, the laser light passes through a neutral density filter. The neutral density filter is used to maintain the intensity of the laser light at the same laser power level for production of the speckle phenomenon, and to avoid saturation at the detector. The optical light path transfers the laser beam through a deformable mirror. When the deformable mirror is in operation, the randomly-distributed surface deformation creates many uncorrelated speckle patterns. Furthermore, the deformable mirror can also avoid localized temperature increases from becoming too high [14].

The laser beam is reflected from the deformable mirror to pass through the first diffuser and then through the second diffuser at the end of the light pipe. The multiple-reflections of the laser light within the light pipe generate a uniform homogenization at the end of the light pipe [15]. The first diffuser and the second diffuser are used to increase the étendue of the laser. The passing of the laser light through the diffusers will produce various speckle patterns. A relay lens system is used to build a conjugation relationship between the exit port of the light pipe and the active area of the digital micromirror device (DMD). This relationship allows the relay lens system to superposition the various speckle patterns, further reducing the speckle contrast value. The typical projector elements such as the DMD, total internal reflection (TIR) prism and projection lens are placed after the relay lens system. The light pipe size is 4.5mm × 5.8mm and 30mm in length.

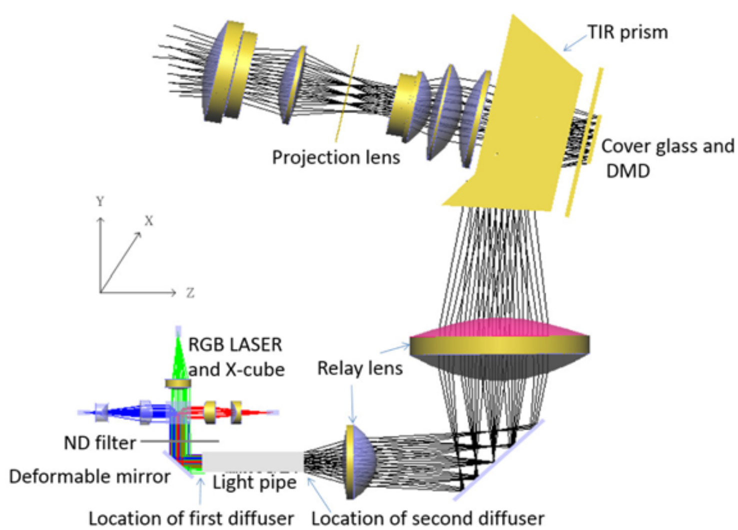

Fig. 1. Layout of pico-LASER projector.

4. Experimental setup and deformable mirror function

The measurement setup is shown in Fig. 2. The Pico-LASER projector and camera lens are located 50cm from the screen. For the speckle contrast ratio measurement, we are specific to low-image-magnification apparatus for 50 cm from projection screen and camera. Thus, the speckle contrast ratio would be higher if the screen was further away. The CCD camera pixel size is 5.2um × 5.2um with a resolution of 1280 × 1024 pixels. The F/# for the camera lens is 1.3 [16]. The integration time of CCD camera chooses 20ms that is close to integration time of human eyes [17].

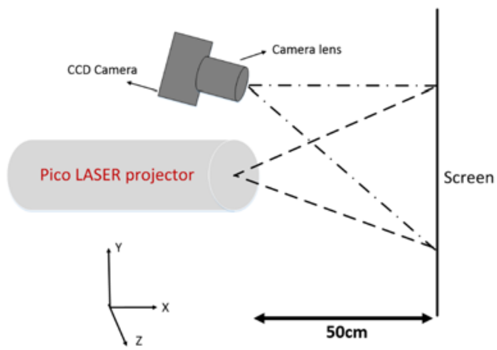

Fig. 2. Experimental setup.

In this experimental setup, the deformable mirror takes the place of the moving diffuser device typically used in anti-speckle technology. The deformable mirror allows a more compact system size than the moving diffuser voice coil motor (VCM) device typically used in the projector system, because the deformable mirror can bend the optical path. Compared with previous designs, the deformable mirror reduces the volume and the complexity of the system [7]. Moreover, the deformable mirror produces uncorrelated speckle patterns, thereby reducing the speckle phenomenon. The working mechanism is comprised of an actuated phase-randomized deformable mirror capable of reaching hundreds of KHz. Figure 3 shows the DYOPTYKA miniaturized phase-randomizing deformable mirror [18, 19]. Figure 3(a) shows an inactive deformable mirror with dimensions of 4.5mm and 6mm. As can be seen in Fig. 3(b), the active deformable mirror has an elliptical working area of 3mm × 4.5mm for the generation of angle divergence [19].

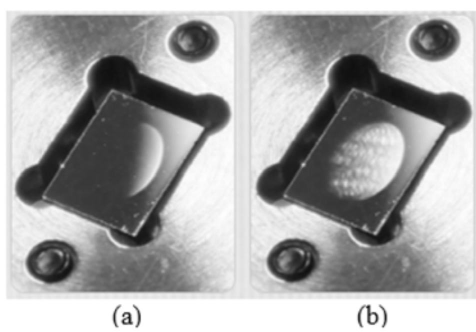

Fig. 3. DYOPTYKA miniaturized phase-randomizing deformable mirror (a) inactive (b) active state [18].

The relation between the vibration frequency of the deformable mirror and the divergence angle of the laser obtained in this study is shown in Fig. 4. The driving frequency of the deformable mirror in the range of 0 to 350 KHz. When the deformable mirror is operating at high frequency, there is an approximately 2 degree increase in the degree of divergence of the laser beam compared to the inactive state. Moreover, the rate of change in the divergence angle is independent in the X and Y directions. The profile of the laser beam after reflection by the deformable mirror is elliptical. As can be seen in Fig. 4, the rate of change in the angle of divergence is not stable. We use curve fitting to study changes in the divergence angles in

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the X and Y directions. The results show that the divergence angle increases with the working frequency of the deformable mirror. The rates of increase of the divergence angle in the X and Y directions are 0.079 deg./KHz and 0.041 deg./KHz for frequency ranges of 0Hz and 10 KHz, respectively, and 0.005 deg./KHz and 0.0027 deg./KHz for frequency ranges of 10Hz and 350 KHz, respectively. The initial divergence angles in the X and Y directions are 0.968 and 1.181, respectively. The divergence angle of the laser is based on the intrinsic property of the vibration of the deformable mirror. Moreover, the elliptical divergence angle profile in the Y direction will change to an elliptical divergence angle profile in the X direction with increasing vibration frequency. Around a vibration frequency of 75 KHz, the profile of the elliptical divergence angle becomes circular. This angle of divergence is more stable for a laser projector design based on symmetrical principles with this relay lens design and light pipe arrangement.

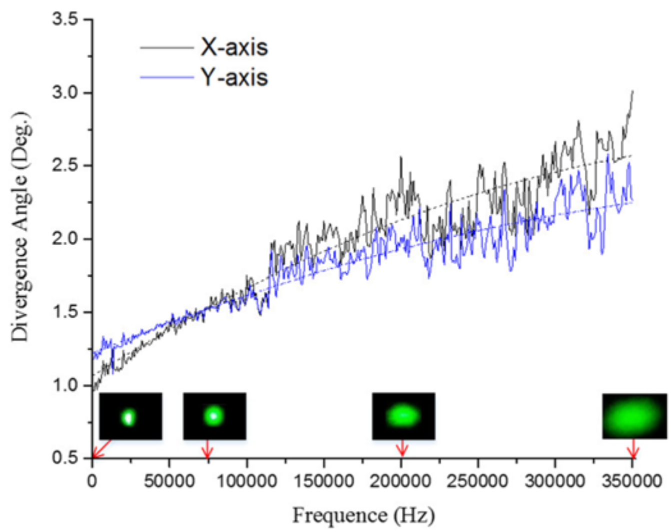

Fig. 4. Relation between vibration frequency of the deformable mirror and divergence angle of the laser.

5. Speckle reduction by a deformable mirror with different diffusers

Different diffusers are used with the deformable mirror for speckle reduction in the experiments. The setup of the optical system for speckle reduction comparison can be divided into three types based on the type of diffuser. Type 1 uses a diffuser with a circular distribution, Type 2 uses diffuser with an elliptical distribution and Type 3 uses two diffusers, one with a circular distribution and one with an elliptical distribution. Only one diffuser is used in Type 1 and Type 2. The second diffuser is removed from the Pico LASER projector design used in the speckle testing experiments to make it more compact in size. Two diffusers are used in Type 3 for comparison with previous studies [7, 20]. The divergence angles of the circular distribution diffusers are 5 degrees (5X5), 10 degrees (10X10) and 30 degrees (30X30) and the divergence angles of the elliptical distribution diffusers are 5 degrees and 30 degrees (5X30), 10 degrees and 50 degrees (10X50), and 20 degrees and 80 degrees (20X80), described as the angle of the full width at half maximum (FWHM) of the bidirectional transmittance distribution function (BTDF) in the X and Y directions.

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5.1 Type 1: Circular distribution diffuser

The circular distribution diffuser is used as the first diffuser located at the entrance of the light pipe. The passage of laser light through the deformable mirror produces divergence resulting in an elliptical profile with the long side corresponding to the X direction. Moreover, the light pipe element has a long side and a short side, so the light pipe arrangement can be divided into two modes. The light pipe arrangement for an optical system with a first diffuser of “30°X30°” is shown in Fig. 5. In Fig. 5(a), “LPL X_30°X30°” indicates the case where the long side of the light pipe corresponds to the X direction and the first diffuser is “30°X30°”; “LPL Y_30°X30°” indicates that the long side of the light pipe corresponds to the Y direction with a diffuser of “30°X30°” as shown in Fig. 5(b).

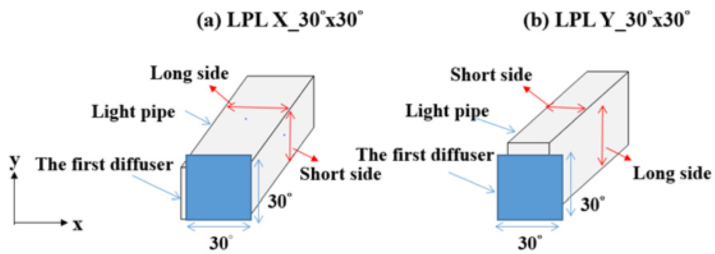

Fig. 5. The laser beam produces an elliptical profile because of the deformable mirror. The light pipe arrangement can be divided into two modes: (a) LPL X_30°X30°; (b) LPL Y_30°X30°.

The speckle contrast value measurement results are shown in Fig. 6. When the deformable mirror is inactive (frequency at 0 Hz) and the long side of the light pipe corresponds to the X direction (LPL X), the speckle contrast values are 0.1141, 0.2364 and 0.3579 for first diffusers of 30X30, 10X10 and 5X5, respectively. When the deformable mirror works at a frequency of 0 Hz and the long side of the light pipe corresponds to the Y direction (LPL Y), the speckle contrast values are 0.1299, 0.265 and 0.3879 for first diffusers of 30X30, 10X10 and 5X5, respectively. We can see that the speckle value is larger when the deformable mirror is inactive.

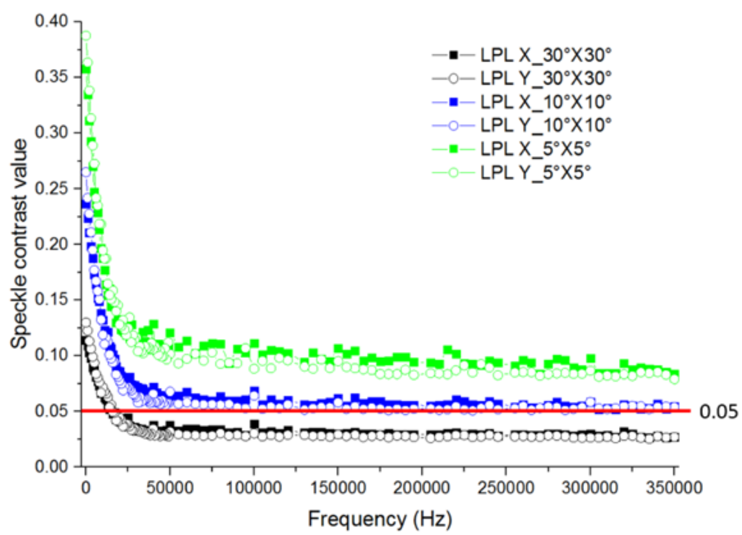

Fig. 6. Dependence of the speckle contrast value on the applied frequency for a circular distribution diffuser.

After activation of the deformable mirror, the speckle value gets smaller for all conditions. When the first diffuser is 5X5 and the driving frequency of the deformable mirror is 350 KHz, the speckle contrast value can be reduced from 0.3579 to 0.0839 for “LPL X” and from 0.387 to 0.079 for “LPL Y”. When the first diffuser is 10X10 and the driving frequency is 350 KHz, the speckle contrast value can be reduced from 0.2364 to 0.0546 for “LPL X” and from 0.265 to 0.0538 for “LPL Y”. In addition, when the first diffuser is 30X30 and the driving frequency is 350 KHz, the speckle contrast value can be reduced from 0.1141 to 0.0273 for “LPL X” and from 0.1299 to 0.0264 for “LPL Y”. The lowest speckle value is 0.0264 obtained under the condition of “LPL Y_30°X30°” with a deformable mirror frequency of 350 KHz. When the speckle contrast value is lower than 0.05, the speckle phenomenon becomes invisible to the human eye. Figure 7(a) shows the speckle image produced with an inactive mirror and Fig. 7(b) shows that produced with an active mirror.

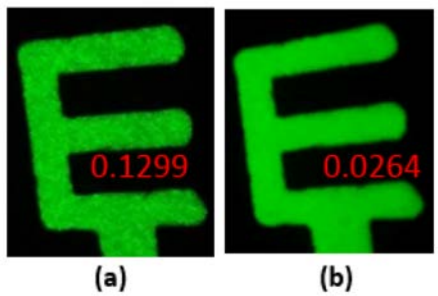

Fig. 7. Image quality of the first diffuser “30X30” with a speckle contrast value of (a) 0.1299 for an inactive mirror; (b) 0.0264 using a deformable mirror and a driving frequency of 350 KHz.

Based on the above results, we can see that the speckle contrast value decreases towards a constant value as the driving frequency gradually increases. In addition, we also find that the speed of decrease is larger at a low driving frequency (0 Hz to 50 KHz) than for a high driving frequency (50 KHz to 350 KHz). The speckle reduction ability of the different diffusers is different. The speckle reduction ability of a first diffuser with a large divergence angle is higher, because the large divergence angle in the light pipe leads to the creation of more speckle patterns [7,21]. The speckle patterns are superposed on the image plane by the relay lens system thereby reducing the speckle contrast value. Furthermore, the speckle contrast value is less in the “LPL Y” mode than in the “LPL X” mode. This reason for this is the reflection of the elliptically distributed laser beam by the active deformable mirror. The deformable mirror functions to change the circular distribution of the laser beam into an elliptical distribution, thus causing differences in the amount of light bounce for the different light pipe modes.

5.2 Type 2: Elliptical distribution diffuser

In the second type of design, an elliptical distribution diffuser is placed at the entrance of the light pipe. As for Type 1, the arrangement of the elliptical distribution diffuser and the light pipe can be divided into four modes. An example of an optical system with a first diffuser of “80°X20°” is shown in Fig. 8. Figures 8(a)-8(d) show the arrangements for “LPL X_80°X20°”, “LPL X_20°X80°”, “LPL Y_80°X20°”, “LPL Y_20°X80°”, respectively.

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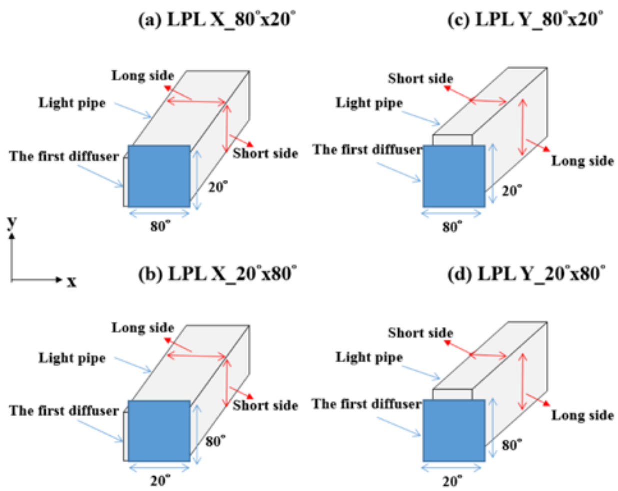

Fig. 8. Arrangement of the elliptical distribution diffuser and light pipe which can be divided into four modes: (a) LPL X_80°X20°; (b) LPL X_20°X80°; (c) LPL Y_80°X20°; (d) LPL Y_20°X80°.

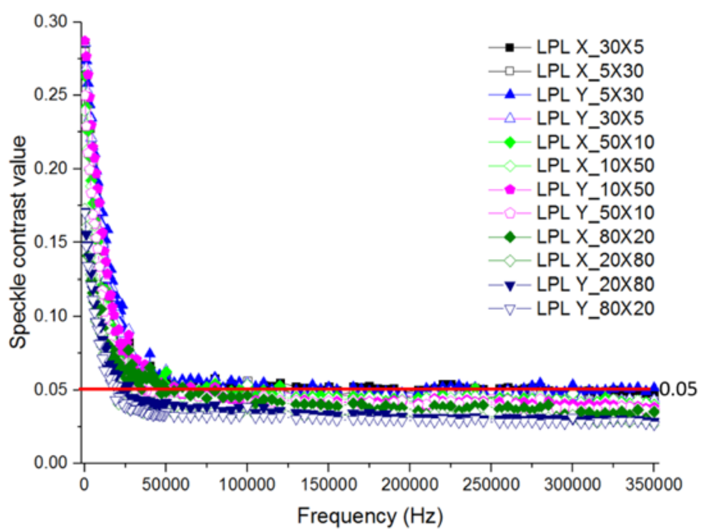

Fig. 9. Dependence of the speckle contrast on the applied frequency for elliptical distribution diffuser diffusers.

The measurement results for the speckle contrast value are shown in Fig. 9. Using a "30°X5°" diffuser as the first diffuser, the speckle contrast values for the four arrangement modes can be reduced from 0.286 to 0.048 for "LPL X_30°X5°", 0.280 to 0.0425 for "LPL X_5°X30°", 0.286 to 0.0492 for "LPL Y_5°X30°" and 0.286 to 0.0412 for "LPL _30°X5°". Using a "50°X10°" diffuser as the first diffuser, the speckle contrast values for the four arrangement modes can be reduced from 0.263 to 0.0401 for "LPL X_50°X10°", 0.240 to 0.0396 for "LPL X_10°X50°", 0.287 to 0.0377 for "LPL Y_10°X50°" and 0.250 to 0.0310 for "LPL Y_50°X10°". Using an "80°X20°" diffuser as the first diffuser, the speckle contrast value for the four arrangement modes can be reduced from 0.171 to 0.0310 for "LPL X_80°X20°", 0.173 to 0.0271 for "LPL X_20°X80°", 0.171 to 0.0288 for "LPL Y_20°X80°" and 0.170 to 0.0267 for "LPL Y_80°X20°". The lowest speckle contrast value is obtained for the "LPL Y_80°X20°" arrangement, as shown in the speckle image in Fig. 10. Figure 10(a)

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shows the speckle image obtained with an inactive mirror and Fig. 10(b) shows the image obtained with an active mirror.

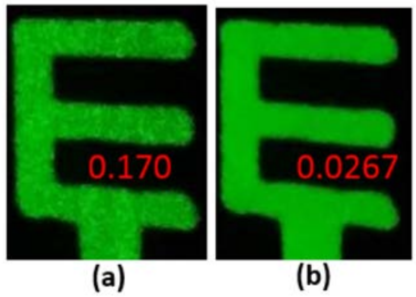

Fig. 10. System image quality obtained with a first diffuser of “80X20” with a speckle contrast value of (a) 0.170 for an inactive mirror; (b) 0.0267 for a deformable mirror and a driving frequency of 350 KHz.

Comparison of the test results in Figs. 6 and 9 shows that the speckle contrast value is lower for Type 2 than for Type 1. For a more detailed explanation please see the following: the difference is speckle reduction ability occurs because the long axis of the elliptical laser beam corresponds to the short side of the light pipe and the large divergence angle of the elliptical distribution diffuser also corresponds to the short side of the light pipe. This increases the number of reflections within the light pipe. This phenomenon can further reduce the speckle contrast value by the superposition of the speckle pattern. This result has been shown in our previous research [7]. Therefore, the “LPL Y_80°X20°” mode has a lower speckle contrast value than the other modes. This overall trend for Type 2 is similar to that for Type 1.

5.3 Type 3: circular distribution diffuser and elliptical distribution diffuser

In Type 3, the experimental setup includes two diffusers. The first diffuser is placed at the entrance of the light pipe and the second diffuser is placed at the exit of the light pipe. From the above discussion, we find that for Type 1 and Type 2, the “30°X30°” and “80°X20°” diffusers, respectively, have the highest speckle reduction ability. In the experimental setup, we choose to discuss the speckle contrast reduction for the “30°X30°” and “80°X20°” diffusers. For example, using a first diffuser of “80°X20°” and a second of “30°X30°” we examine four modes, as shown in Fig. 11. Figures 11(a)-11(d) show the arrangement modes “LPL X_80°X20°, 30°X30°”, “LPL X_20°X80°, 30°X30°”, “LPL Y_80°X20°, 30°X30°”, “LPL Y_20°X80°, 30°X30°”, respectively.

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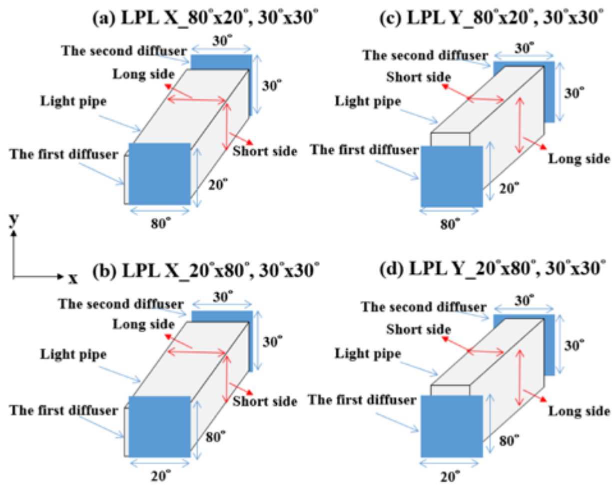

Fig. 11. The first diffuser is an elliptical distribution diffuser and the second diffuser is a circular distribution diffuser. The light pipe arrangement can be divided into four methods: (a) LPL X_80°X20°, 30°X30°; (b) LPL X_20°X80°, 30°X30°; (c) LPL Y_80°X20°, 30°X30°; (d) LPL Y_20°X80°, 30°X30°.

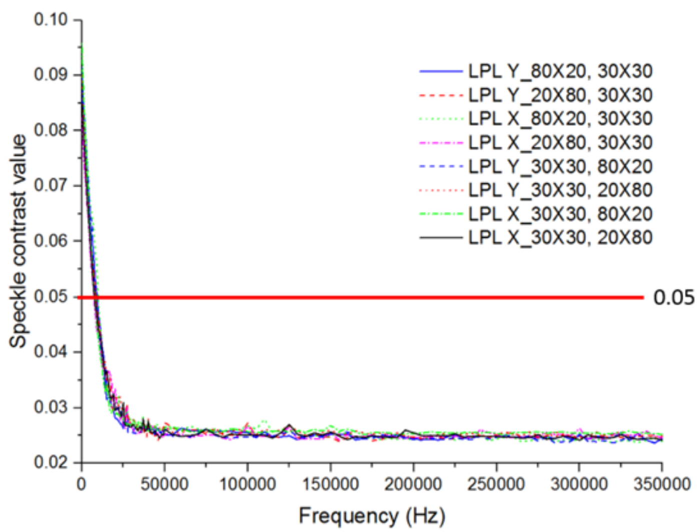

Fig. 12. Dependence of the speckle contrast on the applied frequency using both a circular distribution diffuser "30X30" and an elliptical distribution diffuser "80X20".

The measurement results for the speckle contrast value are shown in Fig. 12. When the deformable mirror is inactive (frequency of 0 Hz), the speckle contrast value is lower for Type 3 than for Type 2 or Type 1. The main reason is the two diffusers used in the experimental setup for Type 3. The speckle contrast reduction ability is higher for Type 3 than for Type 2 or Type 1. Moreover, the tendency for speckle change is the same for Types 3, 2 and 1. According to the results, the lowest speckle contrast value is 0.0236 obtained for modes "LPL Y_80X20, 30X30", but it is difficult to distinguish differences in the speckle contrast value for Type 3. The main reason is that the speckle spots are smaller than the CCD camera pixel size. Under this condition, the CCD camera cannot detect the changes in irradiance caused by the speckle spots. In a word, the speckle contrast value measurement is limited by the CCD pixel size. Thus, the change in tendency of speckle contrast values for

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different arrangements in Type 3 is the same. The speckle image under the arrangement mode "LPL Y_80X20, 30X30" is shown in Fig. 13. The image speckle obtained with an inactive mirror is shown in Fig. 13(a) and that obtained with an active mirror is shown in Fig. 13(b).

In other words, although the speckle contrast value of Type 3 is lower than for Type 1 or Type 2, in terms of cost, compactness of size and relay lens cone angle matching [7], the "LPL Y_30X30" mode of Type 1 is the most suitable setup for a laser pico-projector.

Among the three type diffuser arrangements, the speckle contrast vale is decreased with deformable mirror vibration frequency increasing. The lowest speckle value for three type conditions is shown in Table 1.

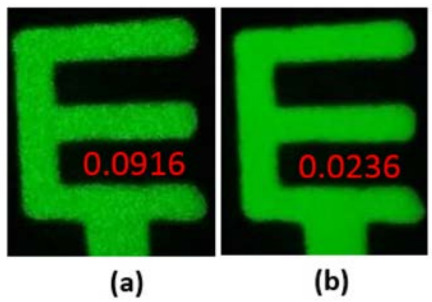

Fig. 13. System image quality of the first diffuser "80X20" and the second diffuser "30X30" with a speckle contrast value of (a) 0.170 for an inactive mirror; and (b) 0.0267 for a deformable mirror with a driving frequency of 350 KHz.

Table 1. The lowest speckle value for three type conditions

	Type 1	Type 2	Type 3
Arrangements type	LPL Y_30°X30°	LPL Y_80°X20	LPL Y_80°X20°, 30°X30°
Deformable mirror off state	0.1299	0.170	0.0916
Deformable mirror on state	0.0264	0.0267	0.0236

6. Conclusion

In this paper, we discuss speckle suppression for designs using deformable mirrors and different diffuser arrangements. The use of diffusers with different angles of divergence affects the speckle reduction ability. The main reason is the larger number of reflections within the light pipe for the large divergence angle diffusers than for the small divergence angle diffusers. The use of a deformable mirror can efficiently decrease the speckle contrast by generation many uncorrelated speckle patterns. The measurement results for Type 1 clearly show that the "LPL Y" mode produces a smaller speckle value than the "LPL X" mode. The main reason is that the deformable mirror produces an elliptical laser beam, so that the speckle contrast value is smaller when the long axis of the elliptical laser beam corresponds to the short side of the light pipe. With an active deformable mirror, the speckle contrast values for "LPL Y_30°X30°" for Type 1, "LPL Y_80°X20°" for Type 2 and "LPL Y_80°X20°, 30°X30°" for Type 3 are 0.0264, 0.0267 and 0.0236, respectively. For the three arrangement modes and three types, the lowest speckle contrast values are all less than 0.05, at which point the speckle phenomenon becomes invisible to the human eye. The above arrangement modes are thus all effective for speckle reduction in a laser pico-projector, however, for mass production, the issue of cost is most important. Thus, "LPL Y_80°X20°, 30°X30°" arrangements are not suitable owing to the use of two diffusers for speckle reduction even though their speckle reduction ability is the same as for the one diffuser setup in Type 1. There is no advantage to using two diffusers as in the Type 3 designs. Comparison between

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Type 2 and Type 1 in terms of the cone angle by relay lens cone angle matching shows a mismatch of cone angles for the "LPL Y_ 80°X20°", meaning that the laser light cannot be collected overall by the relay lens. This decreases the efficiency of the system. Therefore, the "LPL Y_30°X30°" mode is more suitable for a laser pico-projector.

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