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Laser speckle reduction using motionless image conduits

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Abstract We have demonstrated a speckle reduction method using motionless image conduits (MICs). Different experimental conditions by introducing the high-coherence HeNe laser and the low-coherence laser diode (LD) as the illumination light sources, by employing the straight MIC and the curved MIC as the speckle reduction components, and by recording speckle images without (objective speckle) and with (subjective speckle) the imaging lens mounted on the CCD camera are conducted, respectively. The most efficient speckle reduction condition is found by the combination of using the LD and the curved MIC, where the objective speckle contrast ratio is reduced from 0.7378 to 0.1725. Experimental results are discussed, and the causes for these speckle reduction efficiency changes are given.

Keywords Speckle · Speckle reduction · Image conduits

1 Introduction

When a coherent laser beam illuminates onto the surface of a rough object, interference occurs among the scattering lights. Consequentially, the scattering lights cause bright or dark granular intensity distribution, which is named as speckle [1]. As the disturbance in laser displays, speckle must be reduced to improve the image quality [2]. The prevalent speckle reduction technique is using a fast rotating [3–5] or vibrating [6] random diffuser to generate temporally changing speckle patterns; during the integration time of human eyes (∼ 30 ms), different speckle patterns are projected onto the screen and are homogenized by the human eyes, and hence we can achieve speckle reduction. However, the requirement of using motors or actuators working at high frequency makes the optical system bulky and noisy [4]. Other speckle reduction methods include the introductions of wide-band lasers [7, 8], random lasers [9], or specially designed screen, etc. [1], but they have the trade-offs of sacrificing the performances of laser displays, such as narrowing the color gamut, enlarging the etendue, or increasing the cost, respectively. Researchers have also used fiber bundle to split a laser beam into M separated sub-beams, where the fibers lengths are different. When the light delays among individual fibers are longer than the laser coherence length, the M sub-beams can be treated as uncorrelated laser sources. Under proper optical system configuration, speckle is expected to be reduced by a factor of $1/M^{1/2}$ [1, 10].

In this paper, we have demonstrated an optimized speckle reduction technique using motionless image conduits (MICs). The MICs work as the light delay component among individual sub-beams. Different experimental conditions are conducted, such as using straight or curved MICs, using HeNe laser or laser diode (LD), and for the

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measurements of objective speckle and subjective speckle (objective speckle is measured using the CCD camera without the imaging lens mounted, and subjective speckle is measured using the CCD camera with the imaging lens mounted). Experimental results indicate that the curved MIC can reduce speckle more efficiently when using the LD as the illumination light source, where the objective speckle is reduced from 0.7378 to 0.1725. At the end of this paper, reasons for the speckle reduction efficiency difference are discussed.

2 Experiment setup

The MIC is a fused glass fiber rod, where many individual fibers are assembled together [11]. Figure 1a schematically shows the structure of the straight and curved MICs. Figure 1b shows the real-picture of the straight MIC, bought from Edmund Optics [11] and the curved one. The curved MIC is made from the straight one by heating it up and bending it as a circular type. The MIC is 305 mm long with outer diameter equalling to 6.4 mm, and it is composed by 3012 number of fibers. For each fiber, its diameter equals to 100 µm, and the indexes of refraction for the core and the cladding are $n_{\mathrm{core}} = 1.58$ and $n_{\mathrm{cladding}} = 1.49$, respectively.

Figure 2 shows the experimental setup for subjective speckle measurement under with the straight MIC condition. The expanded laser beam illuminates the straight MIC, where in between the beam expander and the straight MIC, we have used an iris with 5 mm in diameter aperture to redefine the laser beam diameter. A diffuser (sandblasted ground glass) working as the transparent screen is placed closely to the exit port of the straight MIC, and speckle formed on the diffuser is captured by a CCD camera with imaging lens mounted ($f = 35$ mm and $F_{\#} = 16$). The distances from the MIC to the diffuser and from the diffuser to the CCD camera are 40 and 70 mm, respectively. We have used a CCD camera with 1280 × 1024 pixels to capture the speckle images (each pixel size is 5.2 µm×5.2 µm). It is known that the speckle grain size is proportional to effective *F*-number of the imaging lens, i.e., the *F*-number of the imaging lens and the distance between the imaging lens and the CCD camera [12, 13]. Though the *F*-number of the imaging lens is not large here, we increased the distance between the imaging lens and the CCD camera to increase the effective *F*-number of the imaging lens and ensure an enough large subjective speckle grain size; thus, the speckle grains are correctly recorded by the CCD camera pixels.

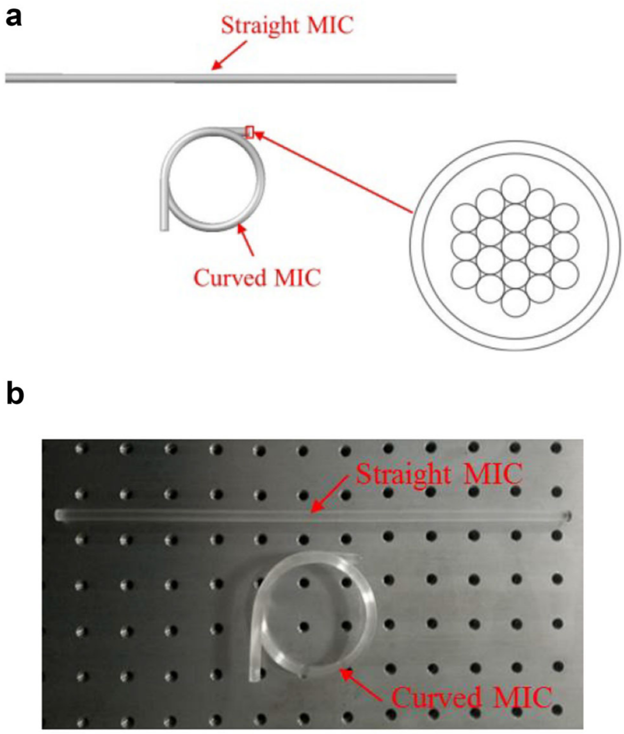

Fig. 1 **a** Schematic diagram of the straight and curved MICs. **b** Real picture of the straight and curved MICs used in our experiments

As shown in Fig. 2, the experimental setup can be modified by unmounting the imaging lens for objective speckle measurement under with the straight MIC condition, by removing the MIC under without the MIC condition (including subjective speckle and objective speckle measurements, depending on the imaging lens is mounted or unmounted onto the CCD camera), or by replacing the straight MIC as the curved MIC under with the curved MIC condition (including subjective speckle and objective speckle measurements, depending on the imaging lens is mounted or unmounted onto the CCD camera), respectively. Two types of laser sources are used, i.e., a 0.8-mW HeNe laser (λ_{HeNe}: 632.8 nm) and a 50-mW green LD (λ_{LD}: 520 nm).

To correctly record the speckle images, the experiment is carried out in the dark room on an optical table, and the exposure time of the CCD camera is adjusted to avoid underexposures or overexposures.

3 Results and discussions

The speckle images under the above mentioned conditions are captured, which are shown in Fig. 3. Table 1 lists the speckle contrast ratio, defined as the ratio between the standard deviation and the mean value of the light intensity [14].

3.1 Influence of laser sources on speckle reduction

Figure 4 shows the spectra of the HeNe laser and the LD measured using a spectrometer (Aryelle Butterfly bought from LTB). According to these spectra, we can calculate

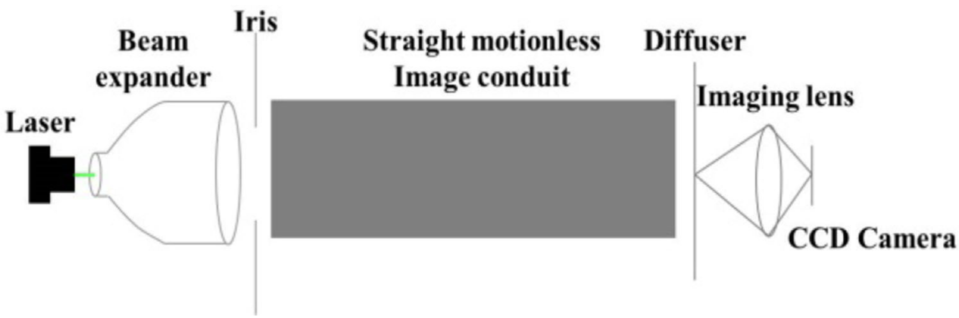

Fig. 2 Experimental setup for subjective speckle reduction by the straight MIC

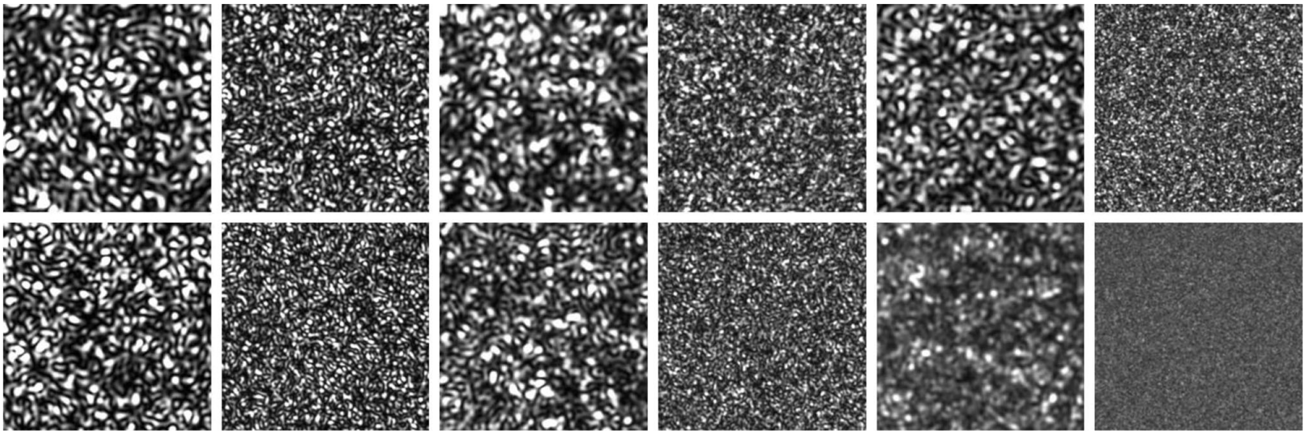

Fig. 3 The speckle images captured on different conditions. First row: HeNe laser, second row: LD; first (subjective speckle) and second (objective speckle) columns: without the MIC, third (subjective speckle) and fourth (objective speckle) columns: with the straight MIC, and fifth (subjective speckle) and sixth (objective speckle) columns: with the curved MIC

Table 1 Speckle contrast ratio under different combinations

Condition	Without the MIC		With the straight MIC		With the curved MIC	
Speckle contrast ratio	Subjective speckle	Objective speckle	Subjective speckle	Objective speckle	Subjective speckle	Objective speckle
HeNe laser	0.8007	0.7424	0.7162	0.579	0.6765	0.4969
LD	0.7994	0.7378	0.6928	0.5449	0.4723	0.1725

the coherence lengths L_c of the HeNe laser and the LD. The value of L_c can be calculated as [15]

$$L_c = \frac{\lambda^2}{\Delta\lambda}, \tag{1}$$

where λ is the central wavelength and $\Delta\lambda$ is the full width at half maximum (FWHM). It can be found from Fig. 4 that the central wavelengths for the HeNe laser and the LD are $\lambda_{\text{HeNe}} = 632.8$ nm and $\lambda_{\text{LD}} = 513.8$ nm, respectively, and the FWHM for the HeNe laser and the LD are $\Delta\lambda_{\text{HeNe}} = 0.04$ nm and $\Delta\lambda_{\text{LD}} = 0.69$ nm, respectively. According to Eq. (1), we can calculate that the coherence lengths of the HeNe laser and the LD are $L_{\text{c\_HeNe}} = 1 \times 10^4$ μm and $L_{\text{c\_LD}} = 383$ μm, respectively.

As listed in Table 1, before introducing the MICs, the speckle contrast ratios for the HeNe laser and the LD are almost the same. However, when the straight MIC or the curved MIC is used, the speckle contrast ratios for the LD are always lower than those for the HeNe laser. Based on our calculations of the coherence lengths of the laser sources, the coherence length of the HeNe laser is about 26 times longer than that of the LD. Thus, under the same light delays, speckle must be reduced more efficiently using the LD than using the HeNe laser.

3.2 Influence of the imaging lens of the CCD camera on speckle reduction

As listed in Table 1, under the same circumstance, we can find that the objective speckle contrast ratio value is always lower than that for the subjective speckle. When a spatially incoherence laser source illuminate a diffuser, the

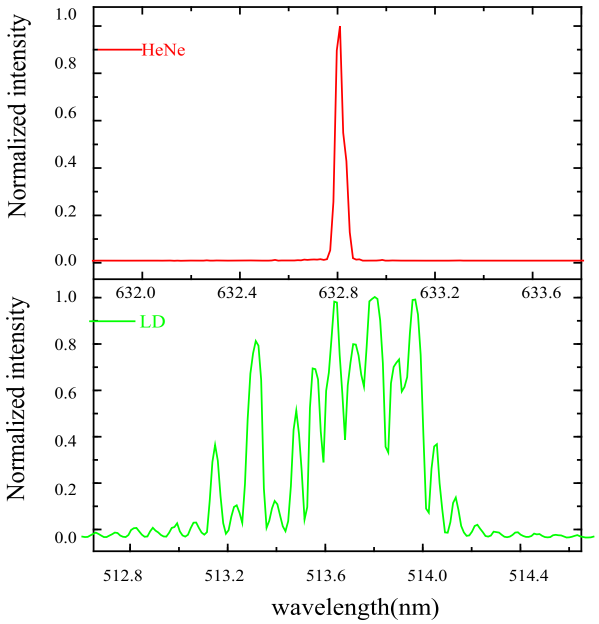

Fig. 4 The spectra of HeNe laser and the LD

equations to calculate objective speckle contrast ratio C_{obj} and subjective speckle contrast ratio C_{sub} can be written as follows [1]

$$C_{\mathrm{obj}} \approx \sqrt{\frac{A_{\mathrm{c}}}{A_{\mathrm{D}}}}, \tag{2}$$

$$C_{\mathrm{sub}} \approx \sqrt{\frac{A_{\mathrm{c}}}{A_{\mathrm{s}}}}, \tag{3}$$

where A_{c} is the coherence area of the light incident on the diffuser, A_{D} is the area that the diffuser is illuminated, and A_{s} is the equivalent area of the spread function of the imaging lens. A_{s} can be further written as [1]

$$A_{\mathrm{s}} = \left(\frac{\lambda z}{\pi P}\right)^2, \tag{4}$$

where $z = 70$ mm is the distance between the diffuser and the CCD camera, and P is the diameter of the entrance pupil. The equation to calculate P can be written as

$$P = \frac{f}{F_{\#}}, \tag{5}$$

where $f = 35$ mm and $F_{\#} = 16$ are the focal length and the F-number of the imaging lens, respectively. According to Eqs. (4) and (5), $A_{\mathrm{s\_HeNe}} = 41.5\ \mu\mathrm{m}^2$ and $A_{\mathrm{s\_LD}} = 27.4\ \mu\mathrm{m}^2$ are obtained for the HeNe laser and the LD, respectively. The effective area that the diffuser is illuminated can be directly measured, such as $A_{\mathrm{D\_straight}} = 3.8 \times 10^7\ \mu\mathrm{m}^2$ and $A_{\mathrm{D\_curved}} = 1.3 \times 10^8\ \mu\mathrm{m}^2$ using the straight MIC and the curved MIC, respectively.

Based on Eqs. (2) and (3), and by the facts that A_{c} is a fixed value and A_{D} is larger than A_{s}, we can conclude that $C_{\mathrm{obj}} < C_{\mathrm{sub}}$. It should be known that Eqs. (2) and (3) are inappropriate for quantitatively analyzing the experimental results; the laser beams are partially incoherent at the output face of the straight/curved MIC, where in Eqs. (2) and (3) derivations, the source is assumed as totally incoherent [1].

3.3 Influence of MICs on speckle reduction

As shown in Fig. 3 and listed in Table 1, under the same circumstance, we can achieve speckle reduction after introducing the straight/curved MICs; moreover, we can find that the speckle contrast ratios after using the curved MIC are lower than those using the straight MIC.

Because of the intermodal dispersion in multimode fibers, large numerical aperture and long fiber can increase the speckle reduction efficiency [16, 17]. The temporal pulse spreading $\delta\tau$ result from the intermodal dispersion can be written as [1]

$$\delta\tau = \frac{(\mathrm{NA})^2\sqrt{LL_{\mathrm{c}}}}{2n_1 c}, \tag{6}$$

where NA, L, L_{c}, and n_1 represent the numerical aperture, the length, the mode coupling length, the core refractive index of the multimode fiber, respectively, and c is the speed of light in vacuum. The speckle contrast ratio at the end of the multimode fiber is given by [17, 18]

$$C(L)^2 = \left[1 + \frac{1}{2}(2\pi\Delta v)^2 T_{\mathrm{g}}^{\prime 2}\right]^{-1/2}, \tag{7}$$

where $|\Delta v|$ and T'_{g} represent the Gaussian spectral profile with *1/e* half-width and the modal dispersion parameter, respectively. Expressions for *NA*, $|\Delta v|$ and T'_{g} are

$$\mathrm{NA} = \sqrt{n_{\mathrm{core}}^2 - n_{\mathrm{cladding}}^2}, \tag{8}$$

$$|\Delta v| = \frac{c}{\lambda^2} \cdot \Delta\lambda, \tag{9}$$

$$T'_{\mathrm{g}} = \frac{\delta\tau}{\sqrt{3}}, \tag{10}$$

where $\delta\tau$ is the temporal pulse spreading in Eq. (6).

Based on Eqs. (6–10), we can find that the speckle contrast ratio is proportional to the numerical aperture of multimode fiber NA and the multimode fiber length L; thus, we conclude that the usage of multimode fiber can reduce speckle.

The reason for using the curved MIC can obtain more efficient speckle reduction comparing with the straight MIC are as follows: for the curved MIC, we can calculate the fiber length difference ΔL between the outer fiber and the inner fiber according to

$$\Delta L = \pi(d_{\mathrm{outer}} - d_{\mathrm{inner}}) \cdot t, \quad (11)$$

where $d_{\mathrm{outer}} = 72.38$ mm and $d_{\mathrm{inner}} = 60.34$ mm are the outer diameter and the inner diameter of the curved MIC, respectively, and $t = 1.25$ is the circle number. According to Eq. (11), we can calculate that the fiber length difference between the outer fiber and the inner fiber is $\Delta L = 47.3$ mm.

When the expanded laser beam illuminates the curved MIC, optical path differences are generated between the sub-beams guided by each fiber. If the optical path differences induced by the fibers are greater than or equal to the coherence length of the laser, the temporal coherence among the sub-beams will be completely destroyed; thus, speckle can be reduced. Because the curved MIC has a fiber length difference at $\Delta L = 47.3$ mm between the outer fiber and the inner fiber, which is much larger than the coherence length of the HeNe laser at $L_{\mathrm{c\_HeNe}} = 1 \times 10^4$ µm and the LD at $L_{\mathrm{c\_LD}} = 383$ µm, speckle reduction can be achieved more efficiently using the curved MIC comparing with the straight MIC.

The changes of effective numerical aperture and refractive index of the MIC when it is bent from the straight type to the curved type may also influence the speckle contrast ratio [19, 20]. For example, if the refractive indexes of a fiber before and after bending are constant, the first order approximation of the effective numerical aperture NA* of the bent fiber can be written as [19]

$$\mathrm{NA}^* = \sin\theta^* = \sqrt{[n_{\mathrm{core}}^2 - n_{\mathrm{cladding}}^2(1 + R/d)^2]}, \quad (12)$$

where θ^* represents the effective acceptance angle, $R = 100$ µm is the fiber diameter, d is the diameter of the bending circle, and $n_{\mathrm{core}} = 1.58$ and $n_{\mathrm{cladding}} = 1.49$ are the indexes of refraction for the core and cladding, respectively. By substituting $d_{\mathrm{outer}} = 72.38$ mm and $d_{\mathrm{inner}} = 60.34$ mm into Eq. (12), we can find that the effective numerical apertures for the outer and inner fibers of the curved MIC are the same, such as $\mathrm{NA}_{\mathrm{outer}}^* = \mathrm{NA}_{\mathrm{inner}}^* = 0.52$. According to Eq. (8), the numerical aperture of the straight equals to $\mathrm{NA} = 0.53$. Therefore, the changes of the numerical aperture NA on speckle contrast ratio are ignorable compare with the significant optical path differences between the sub-beams guided by each fiber.

4 Conclusions

In conclusion, we have used straight and curved MICs to demonstrate the speckle reduction. By comparing different experimental conditions, it is obvious that using LD as the light source can reduce speckle more efficiently than using HeNe laser as the light source. This is because the LD has a wider spectral bandwidth than that of the HeNe laser, i.e., the LD is less coherent than the HeNe laser; we have also observed that the values of subjective speckle contrast ratios are greater than that of the objective speckle contrast ratio values. By comparing the areas that the diffuser is illuminated and the equivalent area of the spread function of the imaging lens, we explained these differences. Finally, the reason for speckle reduction efficiency difference between using the straight MIC and the curved MIC is discussed, where the fiber inside the curved MIC causes an extra light delay. The most efficient speckle reduction is found by the combination of LD as the light source, curved MIC as the speckle reduction component, and recording objective speckle by the CCD camera, where the speckle contrast ratio is reduced from 0.7378 to 0.1725.

The method demonstrated here provides a new approach for speckle reduction. Future works include the optimization of speckle reduction efficiency using the MICs and the integration of this method in laser projection system.

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