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Speckle reduction by angle diversity using a translucent spatial light modulator

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A translucent spatial light modulator (SLM) and a condenser lens are introduced to suppress the laser speckle effect. The SLM is programmed as a sinusoidal grating with rotating orientation and/or adjustable period. The incident laser beam is diffracted into various diffraction orders after the SLM modulation, and the diffraction light beams with temporally changing incident angles are focused onto a transmission diffuser by a condenser lens. A CCD camera is used to record the speckle patterns in free space, and the speckle effect is reduced after integrating all the speckle patterns together. The speckle reduction principles are discussed, and about 0.3 speckle contrast ratio (CR) is obtained, where the grating rotating orientation span is 5°, and two grating periods have been chosen.

Keywords: spatial light modulator (SLM), grating, speckle reduction.

1. Introduction

When a laser beam hits on a rough object whose surface roughness is comparable with the optical wavelength, because of the temporal/spatial coherence of laser, fluctuations of the light intensity will be perceived by the square-law detector (eye, camera, *etc*.), which is known as speckle [1]. The criterion to characterize speckle is speckle contrast ratio (CR), which is defined as the ratio of the standard deviation and the mean value of the light intensity [1]

$$C = \frac{\sigma}{\langle I \rangle} = \frac{\sqrt{\langle I^2 \rangle - \langle I \rangle^2}}{\langle I \rangle} \tag{1}$$

where C is the speckle CR, and σ, $\langle I \rangle$ and $\langle I^2 \rangle$ are the standard deviation, the mean value and the mean square value of the light intensity. Another method to evaluate the speckle effect is the number of independent speckle patterns (NISP). When the value of NISP is N, and they are added together within the integration time of the detector, the speckle CR is equal to [1]

$$C = \frac{1}{\sqrt{N}} \tag{2}$$

In the applications using laser as the illumination source, for example, in laser displays, the image quality is degraded due to the grainy light intensity distribution and the speckle needs to be suppressed. Generally, speckle reduction can be achieved by introducing polarized screen, which can provide maximum two degrees speckle reduction freedom [1], by destroying the temporal coherence of laser [2–4], and/or by destroying the spatial coherence of laser [5–10]. Furthermore, by compounding several reduction techniques, the speckle can be suppressed more efficiently [1].

The main drawbacks for the existing speckle reduction techniques in laser displays are: wideband laser degrades the color purity [2, 3], laser array requires complicated assembly and is expensive [4], vibrating/rotating random diffuser or Hadamard matrix type binary diffuser needs the mechanical motor [6, 7], orthogonal array type binary diffuser programmed electronically demands two closely overlapping one-dimensional phase plates [8], and the barker or barker like binary codes are only applicable to line-scan system [9, 10].

In our previous publication, a speckle reduction apparatus has been presented, where an SLM is programmed as a sinusoidal grating with rotating orientation and/or changing period. The temporally changed diffraction light beams are used to illuminate a stationary diffuser, which pass a 100 mm lens and overlap on the screen [11]. The theory behind this experiment setup is meant as summing different speckle patterns formed on the diffuser surface due to the movement (non-overlapping or partial-overlapping) of the diffraction spots. A 0.36 speckle CR is obtained experimentally, and it is possible to bring the speckle CR down to 0.08 or less. To achieve the lower speckle CR, one requires avoiding overlapping of the diffraction spots on the diffuser surface, which in turn demands increasing the distance between the microscope objective and the diffuser and/or decreasing the laser beam diameter.

In laser displays, a simple and compact speckle reduction method is preferred. In this paper, a similar method is proposed, where the speckle reduction principle is by *angle diversity* [1]. The optical system can be more compact by introducing a single scattering spot on the diffuser surface, which is generated by the modulated laser beams with diverse diffraction directions and refocused by a condenser lens, compared with the old method relying on the spatial travel of the scattering spots. Experiment results are presented, and the proposed speckle reduction configuration has been analyzed.

2. Experiments

Experiment setup is shown in Fig. 1. The polarizer and the analyzer are calibrated in such a manner that the 0° position blocks horizontally polarized light and transmits

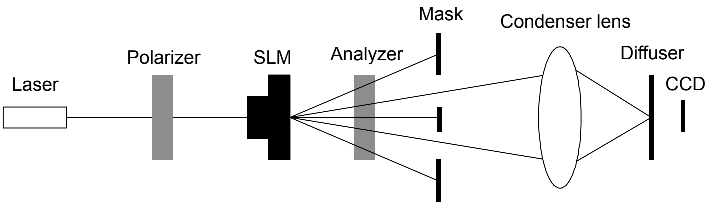

Fig. 1. Experiment setup, where an SLM and a condenser lens are used to introduce diverse laser beams.

vertically polarized light [12]. The SLM is programmed as a sinusoidal grating whose orientation and/or period are changing in real-time, and a circular mask is placed closely after the SLM and the analyzer to let the ±1st diffraction light beams pass through and block the others. The condenser lens is used to collect the diffraction laser beams and focus them on the diffuser surface. The focal length and diameter of the condenser lens are 50 mm, and its transmission efficiency is larger than 99.6%. The diffuser is a commercial quality sandblasted glass with a 120-grit spray, and its diffusing angle is ±10°. Because when the SLM is programmed as different sinusoidal phase gratings, the transmitted light intensity will also change [12], and to maintain the validity of our experiment, we have set the CCD camera at various exposure times to ensure that the CCD sensors work in their linear region.

The SLM (LC 2002) is from HOLOEYE Photonics AG with 800×600 display resolutions and 32 μm×32 μm pixel pitch, and it works in monochrome mode where its optical efficiency is larger than 20% with a typical response time of 42 ms. Laser source is JDS Uniphase He-Ne, type 1108P with $\lambda = 632.8$ nm wavelength. The CCD camera is DMK 21F04 having 659×494 effective pixels, and each pixel size is 5.6 μm×5.6 μm.

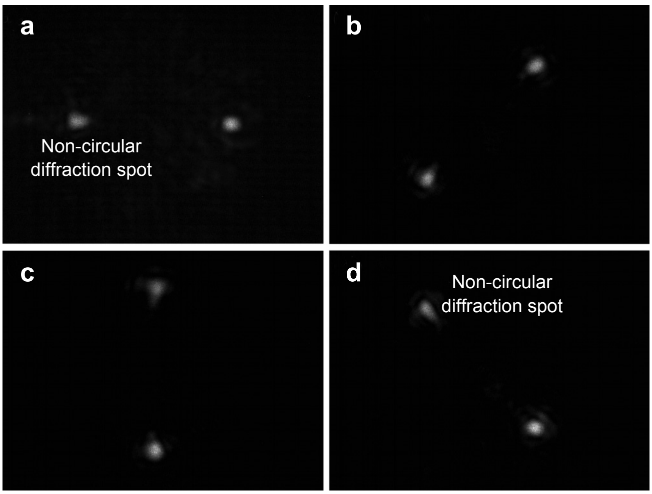

Fig. 2. The 1st order diffraction spots with different grating orientation. 0° (**a**), 45° (**b**), 90° (**c**), and 135° (**d**).

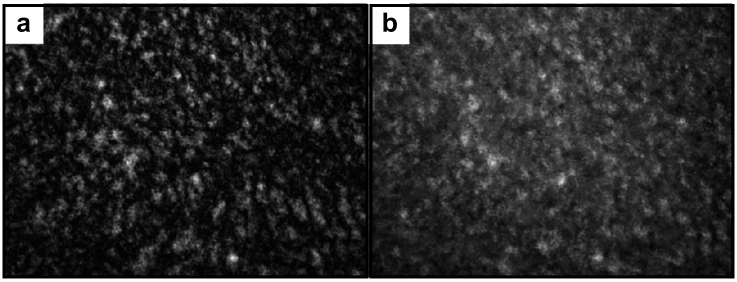

Fig. 3. Speckle images in free space before and after the summation. Individual speckle image (**a**), and summed speckle image (**b**).

Figure 2 shows the diffraction spots on the entrance surface of the condenser lens with rotating grating orientation. The period of the grating is fixed at d_1 = 128 μm, and its orientation is programmed as 0°, 45°, 90°, and 135°, respectively. In this configuration, the distance from the SLM to the condenser lens is 550 mm, and the distance from the condenser lens to the diffuser is 55 mm. The CCD camera is placed after the diffuser, where their distance is 30 mm.

Figure 3**a** shows the captured speckle image in free space using the diffraction spots shown in Fig. 2**a**, and the speckle CR is $C_i = 0.86$. In principle, for fully developed speckle, the orthogonal polarization orientations of the diffuser provide two degrees of the speckle reduction freedom, and the speckle CR is about 0.7 [1]. The 0.86 speckle CR may be caused by the non-circular diffraction spots as shown in Fig. 2, where the light intensity distributions are not uniform. The corresponding scattering light affects the statistic properties of the speckle, and hence the speckle CR is increased. In the future, more work will be done to eliminate the non-circular diffraction spots. In Figure 3**b**, the temporally changing speckle patterns are added together with $\Delta\theta = 5°$ sinusoidal grating rotating angle span, and the total speckle pattern is obtained with $C_s = 0.32$ speckle CR. Comparing Fig. 3**b** with Fig. 3**a**, suppression of the grainy speckle effect is obvious.

3. Results and discussions

In our experiment setup, the principle to achieve the speckle reduction is the illumination angle diversity on the surface of the diffuser. When the wavelength of the laser and the observation angle of the CCD are both fixed, the intensity covariance of two observed speckle patterns is known to be determined by the illumination angle diversity, such as [1]

$$|\mu_A(\mathbf{q_1}, \mathbf{q_2})|^2 = |M_h(\Delta q_z)|^2 \, |\Psi(\Delta \mathbf{q_t})|^2 \tag{3}$$

where M_h is the first-order characteristic function of the diffuser surface height fluctuation, Ψ is the normalized Fourier transform of the intensity distribution across the scattering spot, $\mathbf{q_1}$ and $\mathbf{q_2}$, which are defined as the differences between the observation wave vector and the illumination wave vector, are the scattering vectors, Δq_z is the magnitude of the normal component of the scattering vectors difference $\Delta\mathbf{q} = \mathbf{q_2} - \mathbf{q_1}$, $\Delta\mathbf{q_t}$ and is the transverse component of $\Delta\mathbf{q}$. For a diffuser surface with Gaussian surface-height fluctuations and a uniform circular scattering spot, expressions of $|M_h(\Delta q_z)|^2$ and $|\Psi(\Delta\mathbf{q_t})|^2$ are given in [1], such as

$$|M_h(\Delta q_z)|^2 = \exp\left(-\sigma_h^2 \Delta q_z^2\right) \tag{4a}$$

$$|\Psi(\Delta\mathbf{q_t})|^2 = \left[2\,\frac{J_1\left(D\Delta\mathbf{q_t}/2\right)}{D\Delta\mathbf{q_t}/2}\right]^2 \tag{4b}$$

where σ_h is the rms surface-height fluctuations of the diffuser, J_1 is the first kind of Bessel function, order one, D is the diameter of the scattering spot on the diffuser.

Because the SLM is programmed as phase gratings with different orientation and/or period, dynamic ±1st diffraction orders are generated which follow circular route and/or stretch along the radius. The recollected diffraction laser beams have different incidence angles, and hence angle diversity kind speckle reduction mechanism is introduced. Table 1 is the speckle CR of the summed speckle image, number of total speckle patterns (NTSP) and NISP with increasing rotating angle span of the sinusoidal grating, where the periods of the grating are set at d_1 = 128 μm and d_2 = 224 μm.

As listed in Table 1, NISP approaches NTSP when the rotating angle span of the grating $\Delta\theta$ is increasing. This is because larger $\Delta\theta$ makes the intensity covariance in Eq. (3) closer to zero, *i.e.*, the speckle patterns are less correlated; while by the combination of gratings with rotating orientation and dynamic period, the speckle effect is reduced more efficiently.

T a b l e 1. Experiment results showing the relationships of rotation angle span of the grating $\Delta\theta$ [deg] with the speckle CR and NISP at different grating periods d [μm].

	Speckle CR			NISP			NTSP	
$\Delta\theta$	d_1 = 128	d_2 = 224	$d_{1,2}$ = 128 and 224	d_1 = 128	d_2 = 224	$d_{1,2}$ = 128 and 224	One period	Two periods
5	0.3189	0.3172	0.298	7.44	7.42	8.46	36	72
10	0.337	0.3363	0.3107	6.66	6.60	7.79	18	36
15	0.3546	0.3544	0.3133	6.02	5.94	7.66	12	24
20	0.3699	0.381	0.3213	5.53	5.14	7.28	9	18
30	0.4201	0.4352	0.3552	4.29	3.94	5.96	6	12
45	0.4813	0.4956	0.3939	3.27	3.04	4.84	4	8
60	0.5212	0.5389	0.4176	2.79	2.57	4.31	3	6
90	0.6601	0.704	0.5118	1.74	1.51	2.87	2	4

The possible reasons for the inconsistence of the calculation and experiment results are: *i*) not fully blocked zero order diffraction spot, whose existence caused the formation of a constant speckle pattern and further decrease of the speckle reduction effect; *ii*) lens defocus, which affects the calculation accuracy and introduces the inconsistence; *iii*) light intensity difference for each captured speckle image due to the concomitant amplitude modulation besides the phase modulation of the SLM; *iv*) varying refractive index of the twisted nematic cells when it is modulated; and *v*) electronic noise of the CCD sensor.

One should know that the demonstration in this paper only gives a first impression of the speckle reduction by illumination angle diversity in free space. In a real laser projector system, lights scattering by the diffuser surface shown in Fig. 1 can be used as an illumination source. Homogenizing optics such as a rod integrator will be placed closely after the diffuser to make the optical field uniform, which will be further projected onto the screen by the projection lens. The speckle on the screen is a compound speckle, where the speckle reduction efficiency will be lower than the efficiency obtained on the diffuser surface due to the limited aperture of the human eye or the image lens of the CCD [13]. Moreover, because the integration time of human eye is approximately 30 ms, the response time of the SLM should be short enough to provide sufficient diffraction laser beams with diverse angles. For example, it is a good direction to follow by using the OptoCeramic thin film material such as the materials composed of $Pb_{1-x}La_x(Zr_yTi_{1-y})_{1-x/4}O_3$ (PLZT) or $Pb(Mg_{1/3}Nb_{2/3})O_3$––$PbTiO_3$ (PMN-PT), where they have high electro-optic (EO) coefficient and fast response time (10 ns) [14]. Currently, SLMs made by these fast EO materials are not commer-cially available. Besides, diffraction efficiency of the 0th diffraction order should be designed as low as possible to minimize the light loss. For example, the Fraunhofer diffraction efficiency of a thin sinusoidal phase grating is [15]

$$\eta_m = J_m^2\left(\frac{n}{2}\right) \tag{5}$$

where η_m is the diffraction efficiency of the q-th order, J_m is a Bessel function of the first kind, order m, and n represents the peak-to-peak change of the amplitude transmittance. If we set $n = 4.8$, lights mainly distribute at the ±1 and ±2 diffraction orders and the 0th order diffraction efficiency is zero, which means that the mask in Fig. 1 can be neglected.

4. Conclusions

We have used a programmable SLM and a condenser lens to introduce incident angles diversity of the laser beams, where the SLM works as a sinusoidal grating with rotating orientation and/or differing period. Different speckle patterns form on the diffuser surface, and the summed speckle image becomes less grainy, *i.e.*, the speckle effect is suppressed. Using this de-speckle technique, pictures before and after speckle suppression are presented, and the measured minimum speckle CR is about 0.3 in free space with two grating periods and the grating rotating angle span $\theta = 5°$.

We have analyzed our speckle reduction configuration theoretically, and the de-correlation angle (de-correlation period) is found to be determined by the refractive index of the liquid crystal material, the distance between the SLM and the lens, the lens focal length, the grating period (the rotating angle span), and the diameter of the laser beam. Besides the liquid crystal material, the electro-optic materials such as the OptoCeramic thin film materials composed of PLZT or PMN-PT are preferred to be used in the future, which have much higher working frequency. More work will be done later to demonstrate the speckle reduction apparatus in a laser projector (not practically in use due to the slow response time of the liquid crystal material) and optimize the experiment to bring the speckle CR lower than 5%, which cannot be detected by the human eye.

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