Speckle Reduction Using Spatial Light Modulators in Laser Projection Displays

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***Abstract*—Three coherent imaging systems using LCoS spatial light modulators (SLMs) to reduce speckle phenomenon are presented. The use of negatively correlated speckled images achieved considerable speckle suppression without degrading image quality. In addition, the measurement technique of speckles in the projected images and the characterization of LCoS-SLM are also shown.**

***Index Terms*—Speckle, spatial light modulator, speckle measurement, speckle suppression, negatively correlated speckle, speckle contrast ratio.**

I. Full-Frame Laser Projection Displays Using Spatial Light Modulators

Lasers are advantageous in projecting images due to their wider color gamut, higher resolution, and higher light efficiency as compared to incoherent sources. However, the presence of speckles, a random granular appearance in images resulting from the interference of the coherent waves scattered from a rough object, degrades the image quality and results into fine details irresolvable [1,2]. Speckle suppression has been a critical issue and has been widely studied in coherent imaging. Numerous methods have been proposed to reduce speckle noise: using a source of multiple wavelengths, inserting a vibrating or rotating diffuser or ground glass, coupling with a vibrating multimode fiber, moving an optical aperture in the Fourier plane, and spatial averaging in the detection plane. Recently, a new technique of diffractive optical element (DOE) has been widely adopted to reduce speckle noise. Using DOEs in laser scanning displays, the scanning spot was split into several randomly-spread small spots [3], or modulated with phase arrays [4-6]. In systems projecting full-frame images, the DOE functioned as a changing diffuser to generate partially coherent illumination [7-9]. In holographic projection displays, a phase-only DOE is displayed in an LCoS spatial light modulator (SLM), and the image (Fourier transform of the DOE) was projected onto the screen [10-12].

I will describe three projection systems using lasers as the light source and an SLM for implementing DOEs. The first system is a full-frame projection display using an optical Fourier transform apparatus. The LCoS-SLM is used as a dynamical diffuser in the second projection display using a geometrical imaging apparatus. The relationship between the speckle size and the pixel size of the LCoS-SLM is studied. In the third system, an LCoS SLM performs beam shaping and speckle reduction simultaneously in an image projection display. The phase content of DOE was carefully calculated and accurately realized by an SLM to provide effective de-correlation of the light, resulting in low speckle noise.

II. Speckle Measurement

The reduction of the speckles has been a key issue in laser imaging, such as laser projection display, digital holography, and digital microscope [12-15], and other applications such as monitoring blood flow by using time-varying speckles [16], the statistics of the speckles in images is analyzed to characterize the object. It is important to provide correct information of speckles through the coherent imaging system. A frequently-used parameter to evaluate the speckles is the speckle contrast (*SC*), which is defined as [2]

$$SC = \frac{\sigma_S}{\bar{I}_S}, \tag{1}$$

where $\bar{I}_S$ and σ_S are the mean and the standard deviation of the intensity of a speckled pattern with an intensity distribution $I(x, y)$, respectively. The speckle contrast provides not only a proper evaluation to the coherent imaging system but also a reliable reference to the comparisons of the speckle reduction methods.

When reviewing the related articles, we found that the incident power and the size of speckles are the two key factors which affect the measurement of speckles and the *SC* values. We conducted simulations for characterization of the *SC* values using a Matlab program which implemented the method as shown in [2]. The simulation results show the ideal parameters of a measurement system to evaluate the speckles in images. We then setup an optical apparatus to generate objective speckled images and calculated the *SC* values. By analyzing the results of the simulation and experiment, we concluded that:

(i) The ratio of the speckle size to the CCD pixel size, is larger than 3.5, and

(ii) the ratio of the maximum speckle intensity to the CCD saturation intensity, is in the range of 0.3 to 1.0.

Note that it is equivalent to have the maximum gray level in the speckle patterns between 80 and 255.

III. Characterization of Amplitude and Phase Response of Spatial Light Modulators

There have been lots of methods to measure the phase retardation and intensity reflectivity of SLMs with respect to the applied voltages or the input gray levels [17, 18]. In this presentation, we introduce a method to characterize the reflective LCoS SLMs (LC-R2500 and PLUTO, HOLOEYE Photonics AG). By measuring the intensity reflectivity and the power of the first diffraction order generated by a series of binary phase grating patterns, the amplitude and phase responses with respect to the input gray levels are obtained. Several sets of the binary patterns with a great variety of phase levels are applied to measure and confirm the relative phase difference between two phase levels. Only the intensity of the first order diffraction is needed and thus the results are not affected by the variation of the on-axis reflection.

In this method, the field function of a complex-valued binary grating with two complex amplitudes $r_1\exp(j\phi_1)$ and $r_2\exp(j\phi_2)$ can be expressed as

$$t_A(x,y)=\left[r_1 e^{j\phi_1}\ \mathrm{rect}\left(\frac{x+X/2}{X}\right)+r_2 e^{j\phi_2}\ \mathrm{rect}\left(\frac{x-X/2}{X}\right)\right]\otimes \mathrm{comb}\left(\frac{x}{2X}\right), \tag{2}$$

where X is the width of a stripe, and rect and comb denote the rectangular and comb functions [19]. Here, we neglect the finite extend of the grating and assume a normally incident, monochromatic, and plane wave illumination. The first-order diffraction efficiency of the grating is given by the square of the first order Fourier coefficient of (1), and is simplified as

$$\eta_{+1}=\frac{1}{\pi^2}\left[r_1^2+r_2^2-2r_1r_2\cos\Delta\phi\right], \tag{3}$$

where $\Delta\phi = \phi_2 - \phi_1$ is the phase difference of the two complex amplitudes corresponding the input gray level.

IV. Conclusion

As the techniques of LCoS SLM being highly progressed, the application of laser projection display has been widely developed. The image projection by the LCoS SLM can be either in a Fourier-transform or in an image-formation mode. However, speckles in the two types of laser image result into degradation of the image quality. In this presentation, we show the basic apparatus of these two techniques, and an effective means to reducing speckles when using an LCoS SLM as the key component [20].

Evaluation of speckles in laser images is critical in developing the speckle reduction methods. When measuring the speckle effect, the incident power and the relationship between the sizes of digital camera and speckle should be carefully specified in order to compute correct speckle contrast of a speckled image.

It is also important to exactly characterize the amplitude and the phase responses of LCoS SLM. The characterization of LCoS SLM influences not only in using the LCoS SLM as a dynamical diffuser, but also in generating all projection images.

Acknowledgment

The support of the National Science Council, Republic of China, under grant NSC 100-2221-E-027-050 and NSC 101-2221-E-027-102 is gratefully acknowledged.

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