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Verification of Speckle Contrast Measurement Interrelation with Observation Distance

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The speckle contrasts of two types of laser projectors were measured at various observation distances and observation lens pinhole diameters using a quantitative measurement technique. We found that the speckle contrast as a function of the observation numerical aperture varies with the projection architecture. In a full-frame projector, it is proportional to the numerical aperture, but it is proportional to its square root in a raster-scanned projector. The difference in speckle contrast as a function of the numerical aperture was analyzed based on Goodman's speckle theory. The obtained results were found to be very useful and applicable for speckle evaluation and display qualifications in an arbitrary observer's position. © 2014 The Japan Society of Applied Physics

Keywords: speckle contrast, laser display, full-frame projection, raster-scanned projection

1. Introduction

In recent years, the study of speckle has been greatly advanced for practical use in laser displays, because the speckle phenomenon is a fundamental issue in coherent light applications and markedly affects the image quality of laser displays. Quantitative measurement and the reduction of speckle are urgent tasks.

In our previous work, a quantitative speckle measurement method was established and speckle noise was reduced markedly using a moving diffuser.[1,2] Based on these results, we have recently released a commercial speckle contrast measurement instrument.[3] In this instrument, the observation distance, the screen, and the alignment of camera were fixed in order to achieve measurement repeatability. However, measurement at the observer's position has recently been required for various laser display applications.

The most useful formula for speckle contrast measurement and reduction derived by Goodman and coworkers is expressed by[1,4]

$$C_S = \sqrt{\frac{M+K-1}{MK}}, \tag{1}$$

where C_S is the speckle contrast, M is the temporal diversity, and K is the spatial diversity. In the case of $M \gg K \gg 1$, C_S can be approximated by[1,4]

$$C_S \approx 1/\sqrt{K} \approx \begin{cases} 1 & NA_{\text{illum}} < NA_{\text{image}} \\ \dfrac{NA_{\text{image}}}{NA_{\text{illum}}} & NA_{\text{illum}} > NA_{\text{image}} \end{cases}, \tag{2}$$

where NA_{illum} is the numerical aperture of the projector illumination lens, NA_{image} is the numerical aperture of the imaging lens, and K is assumed to be proportional to the square of their ratio. Equation (2) essentially implies the dependence of speckle contrast on the projection distance and/or observation distance, which must be considered in practical speckle contrast measurement.

In recent laser display applications, two projection methods have been relatively popular. One is the so-called full-frame projection that transforms the image of a spatial light modulator to the screen through the projection lens. The other is the so-called raster-scanned projection that creates the image by scanning the collimated beam using, for example, a micro-electro mechanical system (MEMS) mirror.

In this paper, we will report speckle contrast measurements of the two types of projectors at arbitrary observation distances, and the results are analyzed using the speckle contrast formula, which is well suited for practical speckle contrast measurements.

2. Experimental Methods

We used the speckle-contrast-measuring equipment SM01VS08 manufactured by OXIDE Corporation in this research. Figure 1 shows the schematics of the measuring system. With this system, C_S can be obtained in a wide dynamic range of values from 0.01 to 1.00. The applied charge-coupled device (CCD) camera is characterized by low noise and high linearity. A pinhole is mounted in front of the camera lens to vary NA_{image}. Available pinhole diameters (*PHD*) are 0.8, 1.0, 1.2, and 1.5 mm. The CCD exposure time is controlled to suppress the photocurrent shot noise corresponding to the incident light intensity. The entire system is controlled by a personal computer.

To further change NA_{image}, the distance (L) between the screen and the pinhole was controlled from 517.5 to 1035 mm, which corresponds to the NA_{image} range of 0.00042 to 0.00152. The projection distance S was fixed at 517.5 mm. The CCD pixel size was $6.45 \times 6.45\,\mu\text{m}^2$. The screen used was a conventional one for business projectors. A polarizer was applied in front of the pinhole to eliminate the polarization diversity induced by screen volumetric scattering.[3,5] Since the defocus of the imaging lens affects speckle contrast measurements, focusing was adjusted in each measurement when changing the distance L.[6,7]

We prepared two commercially available laser projectors using different projection schemes. One was a liquid crystal-on-silicon (LCOS) full-frame projection-type mobile

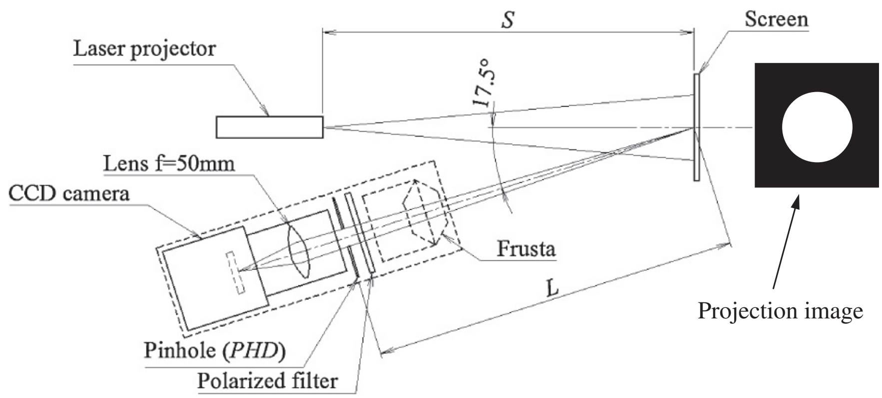

Fig. 1. Schematics of the measurement system. S is the projection distance and L is the observation distance.

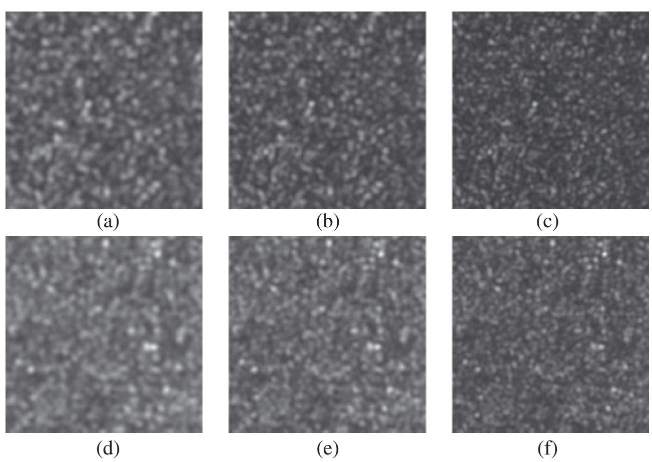

Fig. 2. Observed speckle patterns of raster-scanned projector at various L and PHD values. The first row shows $L = 690$ mm and the second row shows $L = 1035$ mm. The first column shows $PHD = 1.0$ mm, the second column shows $PHD = 1.2$ mm, and the third column shows $PHD = 1.5$ mm. (a) $C_S = 0.384$ at $NA_{image} = 0.00078$. (b) $C_S = 0.426$ at $NA_{image} = 0.00092$. (c) $C_S = 0.478$ at $NA_{image} = 0.00114$. (d) $C_S = 0.274$ at $NA_{image} = 0.00052$. (e) $C_S = 0.311$ at $NA_{image} = 0.00061$. (f) $C_S = 0.360$ at $NA_{image} = 0.00076$.

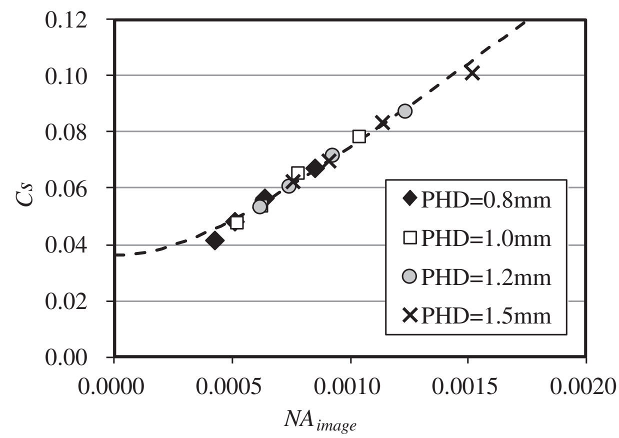

Fig. 3. Measured C_S in full-frame projector. The dotted line shows the theoretical fitting function [Eq. (4)] with $M = 761$ and $NA_{illum} = 0.0153$ (to be discussed).

projector (model FMVNPJ3 manufactured by Panasonic System Networks). The other was a raster-scanned projector (model SHOWXX of Microvision). In our measurement, the projection image was a homogeneous red picture.

3. Results

3.1 Observed speckle patterns

The observed images of speckle patterns are shown in Fig. 2, where the images in each row correspond to $L = 690$ and 1035 mm, and the images in each column correspond to $PHD = 1$, 1.2, and 1.5 mm. When L is longer, C_S decreases. When PHD is larger, C_S increases and the observed speckle size decreases. As shown in Eq. (2), since C_S is a function of NA_{image}, the measured C_S remains almost constant when NA_{image} takes a closer value in combination of L and PHD, while the average speckle size differs [shown in Figs. 2(a) and 2(f)].

The minimum observed speckle size on the CCD camera was 17 µm in our experiment, which is sufficiently large compared with the resolution of our CCD camera.

3.2 Full-frame projector

Figure 3 shows the speckle contrasts at various L values for every four pinhole diameters. The plot is normalized as a function of $NA_{image} = (PHD/2)/L$. Since this projector is equipped with a speckle reduction device, the observed speckle contrast was low. The measured C_S was proportional to NA_{image}.

3.3 Raster-scanned projector

The result obtained using the raster-scanned projector is shown in Fig. 4. Since this projector is not equipped with speckle reduction components, a higher speckle contrast should be observed. Nonetheless, it was previously found that the scanning beam reduces the speckle contrast in this projection scheme.[8] The speckle contrast is approximately proportional to the square root of NA_{image}. This is obviously different from the NA_{image} dependence in the full-frame projector.

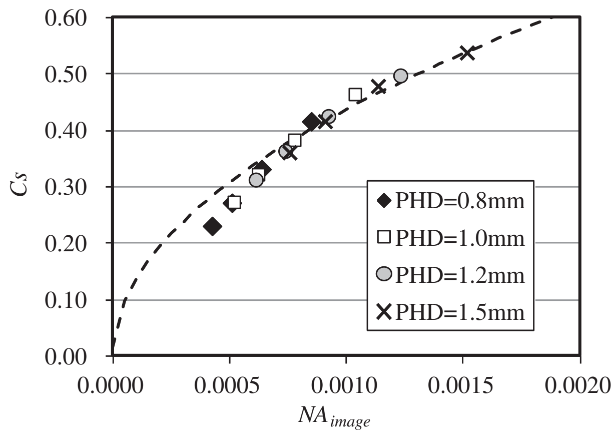

Fig. 4. Measured C_S in raster-scanned projector. The dotted line shows the theoretical fitting function [Eq. (6)] with $NA_{illum} = 0.00532$ (to be discussed).

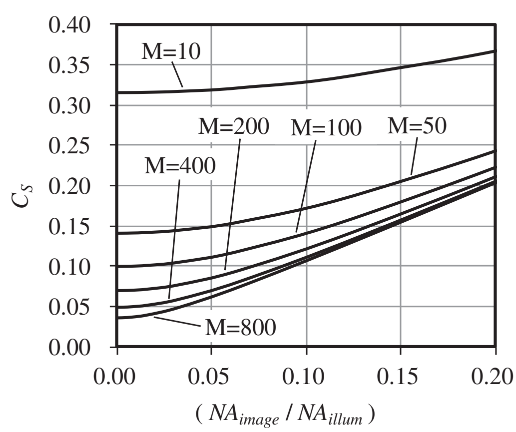

Fig. 5. Theoretical fitting function [Eq. (4)] at various M values in full-frame projection.

4. Discussion

The observed speckle contrast varied depending on the projection method used. We will discuss the reason for this in this section.

4.1 Full-frame projection

In Eqs. (1) and (2), the spatial diversity K of the full-frame projection is expressed by[1)]

$$K = \left(\frac{NA_{\rm illum}}{NA_{\rm image}}\right)^2. \tag{3}$$

By substituting Eq. (3) for K in Eq. (1), C_S is expressed by

$$C_S = \sqrt{\frac{1}{M} + \left(1 - \frac{1}{M}\right)\cdot\left(\frac{NA_{\rm image}}{NA_{\rm illum}}\right)^2}. \tag{4}$$

Figure 5 shows the plots obtained using Eq. (4) for various M values. Each plot is normalized as a function of the numerical aperture ratio $NA_{\rm image}/NA_{\rm illum}$. The temporal diversity M mainly depends on the performance of the speckle reducer equipped in the projector. If we aim at a target C_S value of less than 0.05, it is impossible to reach this target value of C_S, by only improving the speckle reducer performance. To achieve less speckled images, however, the projection optical design should be modified in such way that $NA_{\rm image}/NA_{\rm illum}$ becomes less than 0.04.

The dotted line in Fig. 3 shows the theoretical fitting function [Eq. (4)] obtained using the least-squares method, and we obtained the fitting parameters of $M = 761$ and $NA_{\rm illum} = 0.0153$. K calculated by substituting 0.0153 for $NA_{\rm illum}$ in Eq. (3) was varied from 104 to 1156 in the measurement results of Fig. 3. Since K is comparable to M, it is necessary to apply Eq. (4) rigorously, rather than the approximation in Eq. (2). We could not confirm the reason for the gentle curve part of C_S that would be observed at a particularly small $NA_{\rm image}$ under our experimental condition. In order to confirm this part experimentally, it is necessary to increase the observation distance, or $NA_{\rm illum}$. To reduce the C_S of this full-frame projector further, it is necessary to increase both K and M, because K is comparable to M.

We estimated the projection lens diameter to be about 16 mm from the fitting result of $NA_{\rm illum} = 0.0153$. Since the actual lens diameter is about 8 mm, this result is consistent in order of magnitude. We speculate that the difference is due to the some perturbations, such as the roughness and depolarization of the screen.

4.2 Raster-scanned projection

The value of K for the raster-scanned projection is expressed by[8)]

$$K = \frac{NA_{\rm illum}}{NA_{\rm image}}. \tag{5}$$

By substituting Eq. (5) for K in Eq. (1), C_S is expressed by

$$C_S = \sqrt{\frac{1}{M} + \left(1 - \frac{1}{M}\right)\cdot\left(\frac{NA_{\rm image}}{NA_{\rm illum}}\right)}. \tag{6}$$

In the case of $M \gg K \gg 1$, C_S can be approximated by

$$C_S \approx \frac{1}{\sqrt{K}} = \sqrt{\frac{NA_{\rm image}}{NA_{\rm illum}}}. \tag{7}$$

The measured C_S, which is proportional to the square root of $NA_{\rm image}$ in the raster-scanned projector, is explained by Eq. (7).

Figure 6 shows the plots obtained using Eq. (6) for various M values. In the raster-scanned projection, we assume that M is reasonably determined by

$$M = f_R \cdot T_e, \tag{8}$$

where f_R is the projector scanning frame rate and T_e is the exposure time of the measurement system. In general, f_R for the commercially available display is about 60 Hz and the human eye response time, corresponding to T_e, is about 0.5 s. Therefore, M becomes approximately 30 when the usual display is observed by the human eye.

As shown in the plot of $M = 30$ in Fig. 6, C_S for the usual raster-scanned projector, which is not equipped with a speckle reducer, decreases to only about 0.2. The de-

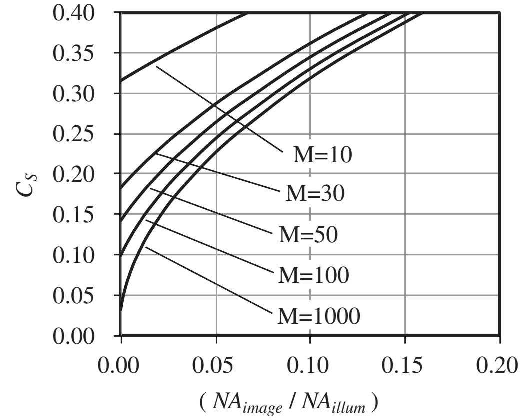

Fig. 6. Theoretical fitting function [Eq. (6)] at various M values in raster-scanned projection.

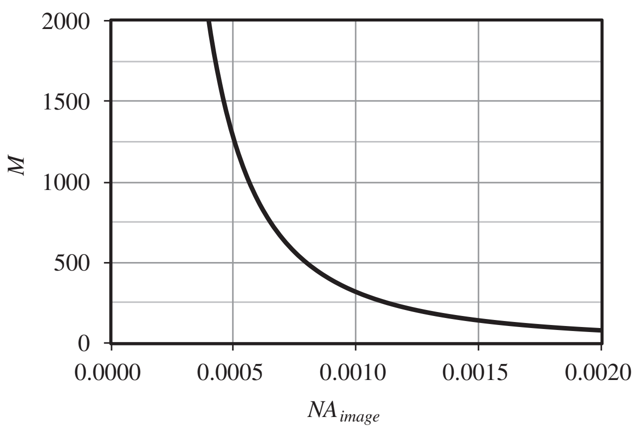

Fig. 7. M as function of NA_{image} in the raster-scanned projector in this experiment.

pendence of $NA_{\mathrm{image}}/NA_{\mathrm{illum}}$ in the raster-scanned projector is larger than that in the full-frame projector. Thus, it is easy to decrease C_{S} by increasing NA_{illum} if M is large.

In particular, in our experiment, the temporal diversity M in Eq. (6) can be determined by NA_{image} even though M is not directly related to the spatial diversity parameters. This is because T_{e} is optimized for the incident light intensity in our equipment, and when we vary the measurement distance L and PHD, the incident light intensity varies depending on NA_{image} given by the equation $NA_{\mathrm{image}} = (PHD/2)/L$.

The dotted line in Fig. 4 shows the fitting function of theoretical Eq. (6), which is included in the relation in Fig. 7. First, the least-squares method was used to obtain $NA_{\mathrm{illum}} = 0.00532$. Then, M calculated by the relation shown in Fig. 7 ranged from 137 to 1800, and K calculated by substituting 0.00532 for NA_{illum} in Eq. (5) ranged from 3.5 to 12.5 in the measurement result in Fig. 4. Since M is much larger than K, the dotted line in Fig. 4 is consistent with Eq. (7).

To reduce C_{S} for this raster-scanned projector further, it is necessary to increase K, because C_{S} is represented by Eq. (7).

Moreover, it is necessary to discuss NA_{illum} for the raster-scanned projector. Since K for the raster-scanned projector is equal to the ratio of the eye resolution diameter to the projector beam spot diameter,[4] NA_{illum} is not equal to the numerical aperture determined by the projector's collimated beam divergence. However, we assumed that NA_{illum} is equal to the collimated beam's numerical aperture if the beam waist of this collimated beam is located on the screen. According to Miller et al.,[9] the collimated beam of this projector's engine has the beam waist at the position of 500 mm. Therefore, the projection distance S is nearly equal to the beam waist in this experiment. From the fitting result of $NA_{\mathrm{illum}} = 0.00532$, the beam divergence is 0.30° in half angle at 13.5% of the peak. We estimate the projection lens diameter to be about 5.3 mm. This result is consistent with the actual lens diameter of about 5 mm speculated from the projection window.

5. Conclusions

The speckle contrasts of two types of laser projectors were measured at various observation distances and observation lens pinhole diameters using a quantitative measurement technique. The fact that the speckle contrast is a function of the numerical aperture can be confirmed experimentally by measuring the speckle contrasts for various sets of observation distances and pinhole diameters while keeping their numerical aperture ratio constant, and the difference in speckle contrast caused by the projection architectures can be revealed. In the full-frame projector, the speckle contrast is proportional to the numerical aperture, but it is proportional to its square root in the raster-scanned projector. The measurement results were analyzed based on the speckle contrast formula. We confirmed that these results are consistent with Goodman's speckle theory in an arbitrary observer's position.

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