Reduction of the recorded speckle noise in holographic 3D printer

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Reduction of the recorded speckle noise in holographic 3D printer

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Abstract: A holographic 3D printer produces a high-quality 3D image reproduced by a full-color, full-parallax holographic stereogram with high-density light-ray recording. In order to produce a high-resolution holographic stereogram, we have to solve the problem of speckle noise in this system. For equalizing an intensity distribution inside the elementary hologram, the object beam is modulated by a diffuser. However the diffuser typically generates speckles, which is recorded in the holographic stereogram. It is localized behind the reconstructed image as a granularity noise. First we show the problems of some conventional ways for suppressing the granularity noise using a band-limited diffuser, and then we analyze an approach using a moving diffuser for the reduction of this noise. In the result, it is found that recording with a moving diffuser is effective for reducing the granularity noise at infinity of reconstructed image, although an alternative noise occurs. Moreover we propose a new method introducing multiple exposures to suppress the noise effectively.

OCIS codes: (030.6140) Speckle; (090.2870) Holographic display; (230.1980) Diffusers.

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1. Introduction

A holographic 3D printer produces a holographic stereogram (HS) using the three dimensional (3D) data of a subject from a computer and outputs a hardcopy of 3D image like a conventional image printer [1–3]. The image obtained by this system has full-color, full-parallax and high-density light-ray information.

In this system, by use of the optical system shown in Fig. 1, an array of small elementary reflection-type holograms is recorded in a thick recording material. The recording medium is translated horizontally and vertically after each exposure so that the whole surface of the hologram is exposed by an array of small elementary holograms. An aperture is placed to avoid leaking the object beam to the adjacent elementary holograms. The image displayed on a spatial light modulator (SLM), in this case a liquid-crystal display (LCD) panel, is a geometrical projection of the 3D object calculated by a computer-graphic technique. In the reconstruction stage, since each elementary hologram is a volume reflection grating, full-parallax 3D image can be displayed under an ordinary white light illumination.

Since the recording medium is placed on the Fourier plane, the intensity variation on the hologram plane depends on the spatial frequency component of the image displayed on the SLM. This image usually has a small high-frequency component. The phase distribution is almost dependent on the amplitude pattern since the phase is also modulated along with the amplitude by the LCD panel. Therefore the low-frequency component is dominant even in the phase pattern, and the object beam has a strong zero frequency peak. As a result, two problems occur, (1) the recording of a hologram with high efficiency is difficult because the dynamic range of the recording medium is limited, and (2) the reconstructed image is affected by dark spacing between the elementary holograms due to the low aperture ratio.

To solve these problems, several ways have been proposed. To smooth the Fourier spectrum distribution, one may simply move the recording medium slightly away from the focal plane so that the intensity becomes almost uniform by defocus [4]. Then, however, the problem of the low aperture ratio remains.

Another method is to use a phase modulation. Using a diffuser to equalize the Fourier spectrum within the aperture causes a loss of the object beam and generates speckles, which are recorded with LCD image. This recorded speckle pattern appears behind the reconstructed image as a granulated pattern. We call it "granularity noise" in this paper. A granularity noise is originated from speckles, which are generated by a diffuser and recorded in an elementary hologram. Therefore various phase masks called band-limited diffuser, proposed for the holographic memory applications [5–14], have been employed. However, these optimized

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phase masks cannot reduce the granularity noise sufficiently under the terms of equalizing the Fourier spectrum. This is described in the section 2.

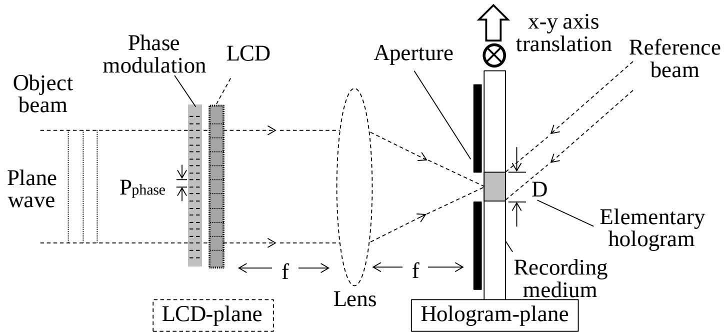

Fig. 1. Optical setup for an elementary hologram recording. A phase modulation means placing a diffuser or a digital diffuser and *Pphase* is a pitch of phase cell of the digital diffuser. *D* is a pitch of the elementary hologram.

In this paper, we analyze a "moving diffuser method". This method was tried in the HS with horizontal parallax only (HPO) [15], but details of the experimental result have not been reported. We first apply this method to holographic 3D printer that generates full-parallax HS. In the result, we found through experiments that this method can reduce the granularity noise localized behind the reconstructed image, although alternative high-frequency noise appeared on the hologram plane. This is described in section 3. To avoid these problems, we discuss introducing multiple exposures in section 4. In this approach, effective granularity noise reduction is possible.

2. Limitation of band-limited diffusers

2.1 The problem: Granularity noise

If HS is recorded with a typical diffuser, a speckle pattern due to a low pass filtering by the aperture in Fig. 1 affects the LCD image and is recorded in the elementary hologram. When using the static diffuser, since a same speckle pattern is recorded in all elementary holograms, this pattern becomes localized at infinity of the reconstructed image as granularity noise. An average size of the granularity depends on the aperture size, and the smaller the aperture size is made for high-density recording of elementary holograms, the more apparent the granularity noise becomes because of larger granularity size. It also means that a granular size doesn't change even though the frequency of the diffuser mask is altered. If we can make the frequency of granularity noise very high, this problem is solved. However, this is unrealizable because to increase the frequency of granularity noise, we have to employ an aperture of large size or a high numerical aperture (NA) lens. The former means large elementary holograms and decrease the HS resolution, and the latter is limited in point of implementation. Therefore this is a critical problem for high-density HS recording. Then, band-limited diffusers have been studied to solve this problem.

2.2 Band-limited diffuser

Band-limited diffusers optimized to Fourier transform holograms have been analyzed for holographic data storage applications [5–12,16] and also have been applied to HS recording [17–19]. However, the problem of this method has not been described in detail. In this paper, we describe the characteristics of one of the band-limited diffusers called digital diffuser, which is designed by a digital process. Digital diffusers can be categorized in two groups: object-independent and object-dependent diffusers [18]. Since the former is more practical in point of implementation, we describe only the former.

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An object-independent diffuser is one of the phase masks, which have rectangular phase cells. It is placed back of the LCD and modulates the phase of the object beam to equalize the Fourier spectrum in the HS recording. The phase is designed not to generate speckles. As the designing method fitting the HS recording, there are pseudorandom phase sequences (PRPS) [11] and iterative Fourier transform algorithm (IFTA) [13].

2.3 Evaluation

We evaluate smoothness within the aperture on the hologram plane and a speckle contrast [20] of the LCD plane after the low pass filtering by a numerical simulation. The smoothness *"S"* and the speckle contrast *"C"* are written as:

$$S = \frac{\langle \mathrm{I_F} \rangle}{\mathrm{I_{F\,max}}}, C = \frac{\sigma_{\mathrm{LCD}}}{\langle \mathrm{I_{LCD}} \rangle}, \tag{1}$$

where I_F and I_{LCD} are the intensity of the Fourier plane and the LCD plane, max means a maximal value, $\langle \ \rangle$ means a spatial average and σ_{LCD} is a standard deviation of I_{LCD}.

2.4 Pseudo random phase sequence (PRPS)

PRPS is simply designed to the adjacent phase difference to be constant. Fitting the aperture size to the main lobe of the Fourier spectrum, it is possible to equalize the Fourier spectrum within the aperture. The results of 4level-PRPS, 6level-complex-PRPS [11] and 2level-random phases [5] are shown in Fig. 2. The phase differences of the adjacent cells generate an intensity difference at the reconstructed light distribution by low pass filtering of the aperture. It makes the characteristic pattern shown in Fig. 2(a)~(c) and affect the LCD image. This pattern is reconstructed as angular distribution, which forms an image at infinity and causes quality reduction.

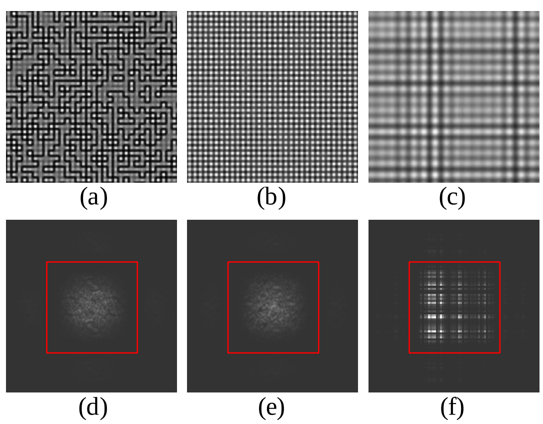

Fig. 2. Simulation results of PRPS: Reconstructed light distribution of HS with (a) 2level-random phase, (b) 4level-PRPS and (c) 6level-complex-PRPS. Fourier spectrum with (d) 2level-random phases, (e) 4level-PRPS, (f) 6level-complex-PRPS and red-rectangle is the aperture size. The Fourier spectrums (d)~(f) are almost equalized although the reconstructed angular distributions (a)~(c) become characteristic patterns.

2.5 Iterative Fourier transform algorithm (IFTA)

The algorithm of IFTA is described in [13,14]. In this algorithm, smoothness *S* can be controlled by changing the clipping level of the Fourier domain constraint. Therefore, we calculated the relation between *S* and *C* in numerical simulations as shown in Fig. 3. A part of results is shown in Fig. 4. These results indicate that there is a trade-off between the smoothness and the speckle contrast. It means that the more increase the aperture ratio, the more the granularity noise appears at infinity. We can understand that this is a limitation of single exposure with digital diffusers.

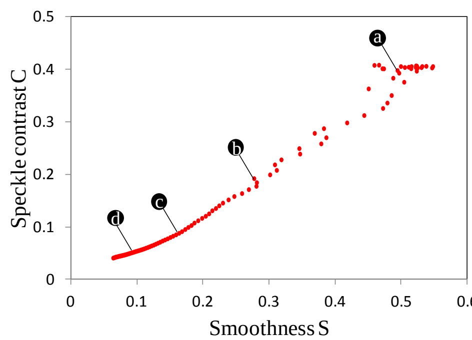

Fig. 3. Simulation results of IFTA: A speckle contrast "*C*" vs. smoothness "*S*" of digital diffusers designed by IFTA. Mark (a)~(d) are corresponding to Fig. 4. There is a trade-off between *C* and *S*. *S* can be controlled by changing the clipping level of the Fourier domain constraint in IFTA.

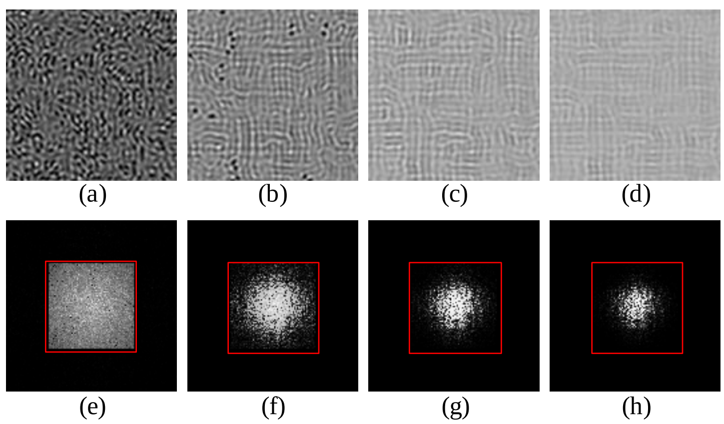

Fig. 4. Simulation results of IFTA: (a)~(d) Reconstructed light distribution of HS corresponding to the mark of Fig. 3(a)~(d). (e)~(h) Fourier spectrum corresponding to (a)~(d) each other. Red-rectangle is the aperture size. IFTA method and the choice of initial phase are same as [14]. This simulation is calculated with 128 × 128 phase cells and the results are made by 50 iterations.

3. HS recording with moving diffuser

3.1 Principle

A moving diffuser method is another way to reduce the granularity noise in HS. Moving a typical diffuser after each exposure step, uncorrelated speckle patterns are recorded in each elementary hologram with the LCD image. When observer focuses on infinity of the reconstructed image, these patterns are superposed at observer's retina since HS is reconstructed with incoherent light as shown in Fig. 5. Superposing the uncorrelated granularity pattern, granularity noise contrast is reduced in inversely proportion to the square root of the number of superposed images like the case of speckle contrast [20]. In this way, the granularity noise contrast at infinity can be reduced.

We evaluate this effect quantitatively through experiments with the granularity noise contrast appeared at infinity and the noise energy at the hologram plane represented by the power spectral density [21]. Figure 6 shows the reconstructed image recorded with and without a moving diffuser. In the result, the moving diffuser could effectively reduce the granularity noise at infinity as shown in Fig. 6(d), and this effect almost agreed with the theoretical value. However, when the observer focused on the hologram plane, alternative noise was perceived as shown in Fig. 6(c). Following sections describe the detail.

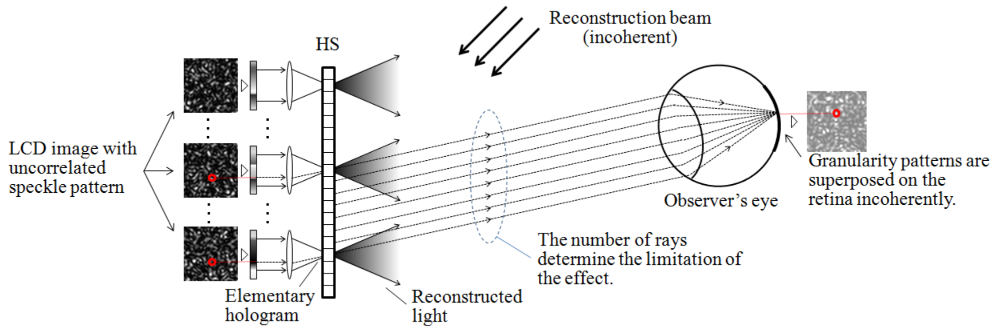

Fig. 5. Principle of reducing the granularity noise perceived at infinity by a moving diffuser. Each elementary hologram reconstructs the LCD image with the uncorrelated speckle pattern as the angular distribution. When the observer focuses on infinity of the reconstructed image, these patterns superposed at the retina incoherently, and then granularity noise contrast can be reduced.

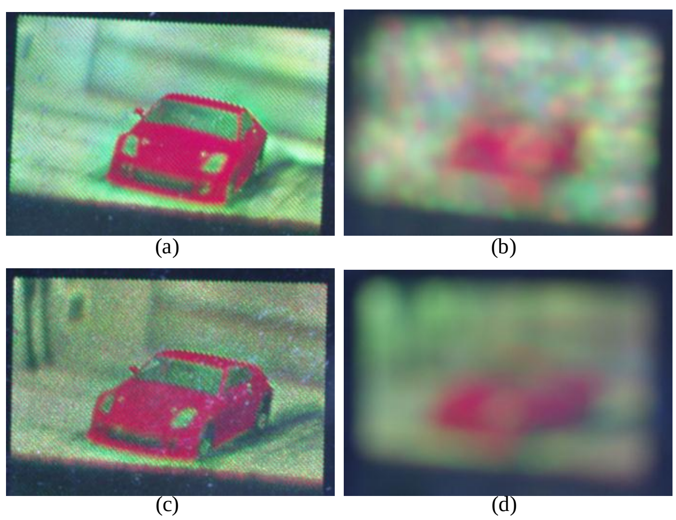

Fig. 6. Reconstructed image with a static diffuser (M = 1) focus on (a) the hologram plane and (b) infinity, and with a moving diffuser (M = 250) focus on (c) the hologram plane and (d) infinity.

3.2 Granularity noise at infinity

The infinity noise is evaluated through experiments quantitatively in a setup like Fig. 7(a). The pattern on the observer's retina when it focuses on infinity is optically simulated on a charge-coupled device (CCD) image sensor, and granularity noise contrast is calculated with Eq. (1) that is the same definition as speckle contrast. Then we also use "C" as granularity noise contrast. In this case the elementary hologram size D is 200μm. A diffuser is vertically translated after each exposure by a z-axis stage. A diode pumped solid state laser of 532nm is used for HS recording in the experiment. Figure 7(b) shows the relation between the granularity noise contrast C and the number of phase patterns M, which correspond to the number of illuminated positions on the diffuser. Figure 8 shows the examples of the granularity noise images captured by the experiment. The granularity noise contrast at infinity reduces in proportion to $1/\sqrt{M}$ theoretically because this is the same as the case of full-developed speckle [20]. Then a theoretical value C_{theo} can be calculated by

$$C_{theo} = \sqrt{\left(\frac{C_{init}}{\sqrt{M}}\right)^2 + C_{syst}{}^2}, \tag{2}$$

where C_{init} is an initial granularity noise contrast (corresponding to M = 1) and C_{syst} is the contrast of the noise originated from the optical systems, which is measured with a white plate instead of the HS. To reduce the effect of unevenness of the object beam distribution before the LCD, the contrast is averaging by small segments. This result shows that the granularity noise contrast (depicted as C_{single}) is almost reduced in proportion to $1/\sqrt{M}$ fitting to the theoretical value. Because of the dynamic range limitation and nonlinearity of the recording medium, while the speckles in the HS recording is a full-developed speckle, C_{init} doesn't become unity.

The number of rays toward the same direction entering the observer's pupil determines the limitation of the granularity noise reduction by this approach as shown in Fig. 5. When the diameter of the pupil is 3.5mm and the pitch of the elementary hologram is 200μm, about 250 rays superposed on the retina, so that the limitation of the granularity noise reduction effect becomes $1/\sqrt{250} \approx 0.063$.

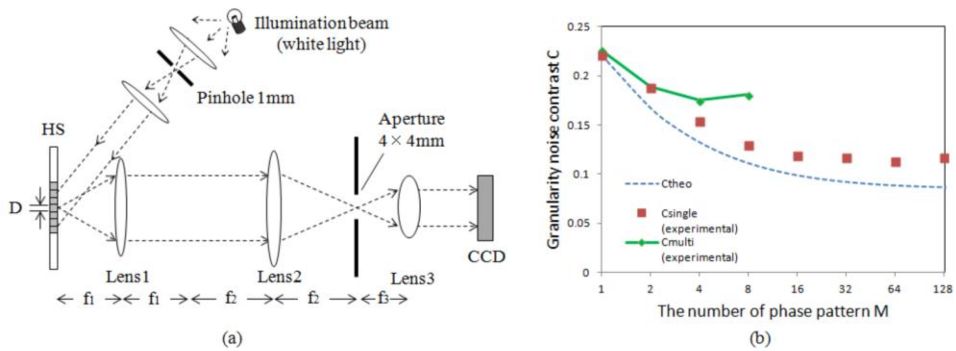

Fig. 7. (a) Optical setup for the granularity noise evaluation of HS at infinity, f1 = 80mm, f2 = 150mm and D = 200μm. (b) Granularity noise contrast at infinity with a moving diffuser (the cases of single exposure "*Csingle*" is described in section 3.2 and multiple exposures "*Cmulti*" is described in section 4.1). Dot-line is the theoretical value, where *Csyst* = 0.085. Granularity noise contrast is evaluated by averaging the divided 3 × 3 segments to reduce the effect of unevenness of the object beam distribution.

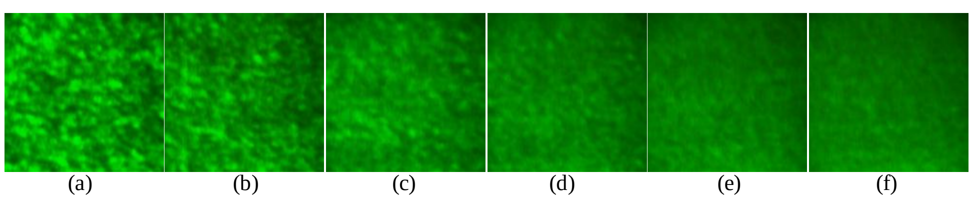

Fig. 8. Granularity noise in the reconstructed image at infinity captured by the experiment shown in Fig. 7. (a) M = 1, (b) M = 2, (c) M = 4, (d) M = 8, (e) M = 16, (f) M = 32.

3.3 High-frequency noise at hologram plane

As mentioned in the section 3.1, it was found that a high-frequency noise appeared on the surface of the reconstructed HS (hologram plane) as shown in Fig. 6(c). The quantitative

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evaluation of the noise at the hologram plane was carried out by the setup of Fig. 9(a). We evaluated the image captured by a CCD camera, which focus on the hologram plane, using one dimensional power spectral density. The noise energy is calculated by the sum of the power spectrum in the frequency range lower than the elementary hologram pitch, excluding zero-order. In this experiment, the camera was adjusted to the same condition that HS was placed at 200mm from an observer whose eye pupil was 3.5 mm diameter. The relation between the number of phase pattern M and the energy of this noise are shown in "Single exposure" of Fig. 9(b).

When recording by a static diffuser, a very low frequency noise appears at the hologram plane, and this noise does not bother the reconstructed image while the infinity noise is more noticeable. When using a moving diffuser, since each elementary hologram reconstructs the granulated pattern that is different from each other, observer perceives a luminance variation at the elementary holograms when focusing on the hologram plane as shown in Fig. 10. This noise is perceived when the value of M becomes large to some extent as shown in Fig. 9(b), and the pitch of the elementary hologram determines the maximum frequency. Also, since this high frequency noise is originated from the granularity pattern recorded in each elementary hologram, we cannot suppress it by increasing the frequency of the diffuser as described in section 2.1. In addition, when moving the point of view, the high-frequency noise is perceived as a flicker. This is the problem of the moving diffuser method.

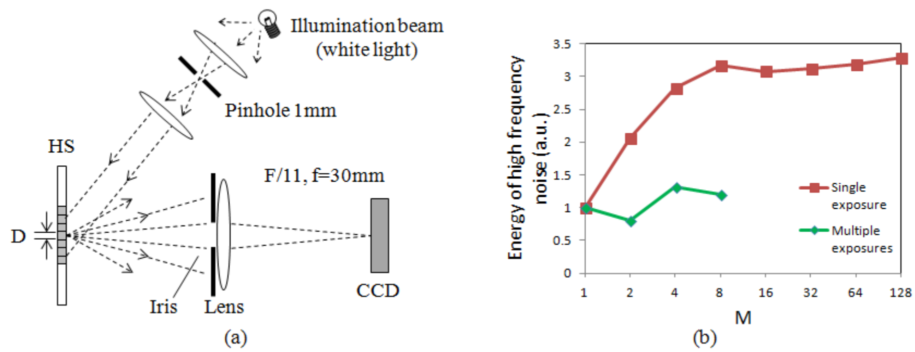

Fig. 9. (a) Optical setup for the noise evaluation of the hologram plane. (b) High-frequency noise at the hologram plane with the moving diffuser. ("Single exposure" is described in section 3.3 and "Multiple exposures" is described in section 4.1).

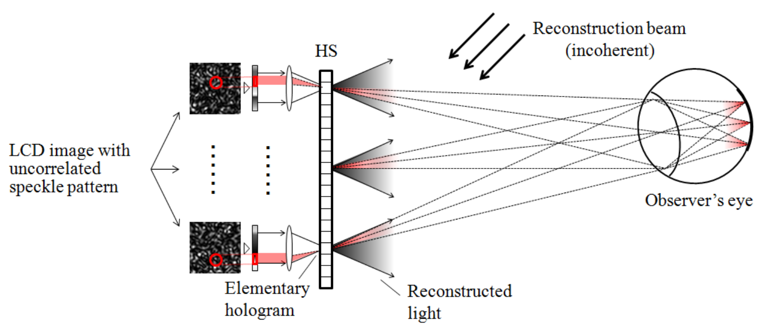

Fig. 10. Principle of appearing the high-frequency noise at the hologram plane. Each elementary hologram reconstructs the uncorrelated speckle pattern, and the observer perceives a luminance variation at the elementary hologram as high-frequency noise.

4. HS recording with multiple exposures

4.1 Multiple exposures with uncorrelated random phase

The moving diffuser method is effective to reduce the granularity noise behind the reconstructed image, but has the problem of the high-frequency noise at the hologram plane. In this section, we propose a new method to solve this problem. Recent years, a number of studies about photo-polymers have been developed for holographic data storage applications, which uses multiple exposures. Therefore, we consider applying the multiple exposures to reduce the granularity noise in HS. For example, an elementary hologram is recorded by multiple exposures to several times (M times) while the diffuser is shifted after each exposure. Then, if each speckle pattern recorded in the single elementary hologram is uncorrelated, the granularity noise reconstructed from the single elementary hologram reduces in proportion to $1/\sqrt{M}$ so that the noise on the retina also reduced. Then high-frequency noise at the hologram plane does not appear in case of the multiple exposures using same sets of positions on the diffuser. In this way, only the granularity noise behind the reconstructed image can be reduced without increasing the high-frequency noise on the hologram plane. The result of experimental evaluation is shown in "C_{multi}" of Fig. 7(b) and *"Multiple exposures"* of Fig. 9(b). These results indicate that the multiple exposures with uncorrelated phases can reduce the granularity noise contrast in proportion to $1/\sqrt{M}$ without the high-frequency noise until 4 times exposures, although cannot reduce when 8 times exposures. The reason can be considered that the exposure condition becomes difficult as increasing the number of multiple exposures since the linearity of the sensitivity in recording medium is limited. Therefore, the number of multiple exposures cannot be increase so much because it takes a large recording time to shift the diffuser and the diffraction efficiency is affected by multiple exposures. It means that the factor of $1/\sqrt{M}$ is inefficient. If it is possible that each speckle pattern recorded by multiple exposures have a negative correlation, we can reduce the speckle contrast effectively smaller than $1/\sqrt{M}$. In the application of a laser display, this concept has already been proposed [22].

4.2 Proposed method

According to the concept described above, we propose a new method for the granularity noise reduction in HS. Let us consider the phase modulation with a digital diffuser designed by 4level-PRPS. It has the random phase sequences in which the phase step at each boundary is either + π/2 or -π/2. When the size of the elementary hologram D is $2\lambda f/p$, where f, λ *and* p denote the focal length, the wavelength and the pitch of phase cell respectively, the reconstructed image recorded by 4level-PRPS becomes a dot-like pattern as shown in Fig. 2(b). Exposing an elementary hologram four times with shifting the diffuser half-length of the phase cell pitch, the dot-like pattern reconstructed from the elementary hologram is superposed incoherently as shown in Fig. 11. Then, since the dot-like pattern and its shifted pattern have a negative correlation, the speckle contrast is effectively reduced.

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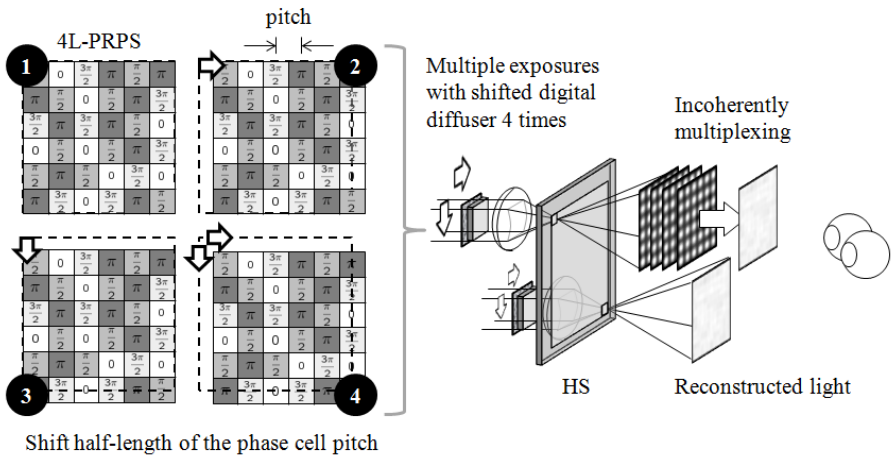

Fig. 11. Concept of the proposed method: Speckle reduction by multiple exposures with 4level-PRPS. Multiple exposing an elementary hologram four times with shifting the diffuser half-length of the phase cell pitch, the dot-like pattern reconstructed from the elementary hologram is multiplexed incoherently.

4.3 Simulation and experiment

Figure 12(a,d) shows the result of proposed method by numerical simulation. The granularity noise contrast is reduced almost 0.105 even as $1/\sqrt{4}$ = 0.5 in the case of using uncorrelated phases with M = 4. This means that it is effective compared to the approach with a typical moving diffuser (uncorrelated phases) and multiple exposures.

Next, we confirm the effect of the proposed method by experiments. We introduce a diffractive optical element (DOE) designed by 4level-PRPS [11, 17], which is set to the x-y translation stage in the optical system of holographic 3D printer, and record the HS by the proposed method. We evaluate the granularity noise contrast at infinity and the energy of high frequency noise at hologram plane in the same way as section 3.2 and 3.3 respectively. As the DOE used in this experiment is designed for the wavelength of 633nm, we used He-Ne laser and the reconstructed image is evaluated by red light.

At first, we describe the experimental result of granularity noise at infinity qualitatively. We can see that the reconstructed light distribution of HS recorded with the DOE shown in Fig. 12(b) becomes a periodic dot pattern likewise the simulation shown in Fig. 12(a). Then, we can see that recorded by 4 times multiple exposures with shifted DOE shown in Fig. 12(e), the dot pattern are superposed incoherently to fill the gap between each dots likewise the simulation shown in Fig. 12(d). The effect is not very apparent, but it can be confirmed that the intensity in the gaps becomes higher in (e) than (b). The reason why the gaps can be still observed is the difference between diffraction efficiencies of four holograms recorded by multiple exposures with shifted DOE. It is required to adjust the exposure balance of multiple exposures to improve the effect of the proposed method. But, we can confirm that a HS recorded with the proposed method realizes a better visual effect of the reconstructed image at infinity than single or multiple exposures with moving diffuser shown in Fig. 12(c) or (f).

An upper line of Table 1 shows the evaluation results of the granularity noise contrast. The contrast of the proposed method is slightly smaller than the multiple exposures with moving diffuser (uncorrelated phases). Here, it is to be noted that the periodic structure shown in Fig. 12(a, b) is reflected in the granularity noise contrast, while the structure is not so obstructive for visual observation. Although the simulation of our proposed method with an ideal condition indicates that the reduction factor of the granularity noise contrast is higher than $\sqrt{M}$, it is unrealized in this experiment because of the non-optimal exposure balance in

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the multiple exposure as mentioned above. Therefore, the optimization of exposing conditions is required for more effective noise reduction.

We also demonstrate the high frequency noise on hologram plane. Figure 13 shows the image focused on hologram plane. This results indicate that the proposed method can suppress the high frequency noise as compared to the single exposure with moving diffuser as shown in Fig. 13(a, b). Moreover, the evaluation of the noise energy is shown in the lower line of Table 1. We can see that the noise in the proposed method is smaller than the single exposure with moving diffuser. From these results, we can confirm the validity of our proposed method using multiple exposures with shifted DOE. Finally, the results of the experiments are summarized in Fig. 14.

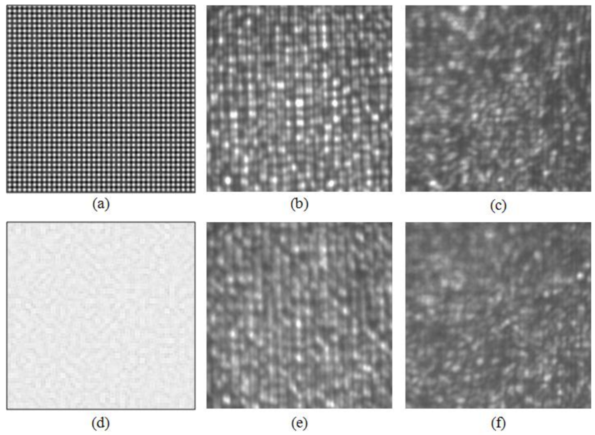

Fig. 12. Simulation and experimental results of the granularity noise reduction (red channel). Reconstructed light distribution by (a) single exposure and by (d) 4 times shifted and multiple exposures (proposed method) with 4level-PRPS generated by numerical simulation. The granularity noise contrast of (d) is 0.105. (b) and (e) are experimental results of (a) and (d), respectively. (c) Is a granularity noise by single exposure with static diffuser and (f) is granularity noise by multiple exposures with moving diffuser (uncorrelated phase pattern).

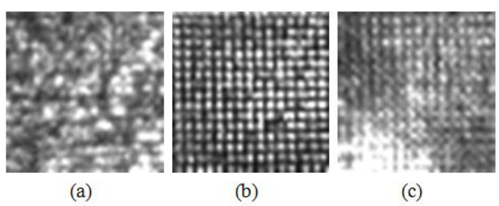

Fig. 13. The image focused on hologram plane (red channel). (a) The case of "single exposure with moving diffuser (M=4)", (b) "proposed method", and (c) "single exposure with static diffuser". The proposed method (b) can suppress the high frequency noise in contrast to the moving diffuser method (a).

Table 1. Experimental Results of the Proposed Method

	Single exposure with static diffuser (M = 1)	Single exposure with moving diffuser (M = 4)	Multiple exposures with moving diffuser (M = 4)	Proposed method (multiple exposures with shifted PRPS)
Granularity noise contrast (infinity)	0.358	0.194	0.270	0.265
High frequency noise (hologram plane)	1	2.16	1.35	1.16

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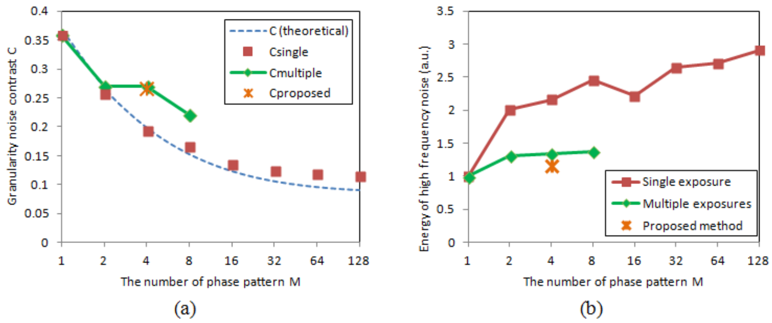

Fig. 14. Comparison between the proposed method and the moving diffuser method. (a) Granularity noise contrast at infinity and (b) high frequency noise at hologram plane. Since the DOE used here is designed for wavelength of 633nm, these results are measured using HS's recorded with a He-Ne laser (633nm) different from Fig. 7(b) and Fig. 9(b) that are recorded with a "green" laser (532nm).

5. Discussions

In the proposed method, there are some issues for the optical implementation. The digital diffuser can be implemented by DOE fabricated on a glass plate or a phase only SLM. In the former case, which is used in the experiment of previous section, as it is necessary to move the DOE mechanically, it requires longer moving time and introduces vibration to the recording system. In addition, when producing the full-color HS, three DOE for RGB and complicated optical system are needed. In contrast, the latter case, there are not problems described above. However, in the case of a phase only SLM such as PAL-SLM [23], a pixel crosstalk of phase modulation is concerned as shown in Fig. 15. In this case, the pixel crosstalk between $3\pi/2$ and 0 phase modulation in 4level-PRPS is the critical problem. Therefore we consider that it is necessary for achieving the proposed method more effectively to study combining the proposed method with the techniques to avoid the pixel crosstalk such as [24], or study another type of phase only SLMs such as Liquid Crystal on Silicon (LCoS) SLM, which is known as a smaller crosstalk. Moreover, we have to consider the effect of a phase modulation by LCD used for amplitude modulation, although LCD is not used in the experiment of previous section.

The evaluation of human visual perception of a speckle noise is another issue for future investigation. Considering a human perception is necessary for the granularity noise evaluations of the HS in addition to the contrast and the noise energy described in section 3 since a relation between human perception and these evaluation values is not understood. It has been already studied for laser projection systems [25]. In addition, the appearance of noise depends on the focus of the observer in the case of 3D display.

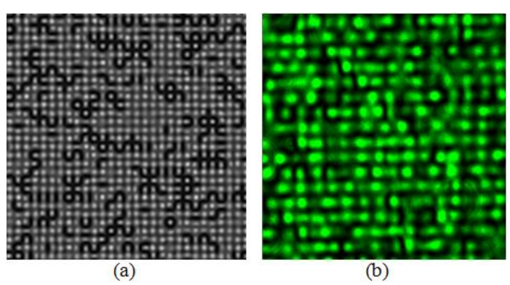

Fig. 15. Example of a pixel crosstalk of a phase only SLM: The reconstructed light distribution of HS with 4level-PRPS, (a) the simulation result and (b) the experimental result. A boundary between $3\pi/2$ and 0 phase modulation have high frequency due to the pixel crosstalk. The crosstalk is calculated by convoluting a gauss function to the original phase pattern in this simulation [23]. (b) is the result of PAL-SLM [22].

6. Conclusions

We discuss mainly two methods for the reduction of a granularity noise in holographic 3D printer. First we evaluated the moving diffuser method and found that this method is effective to reduce the granularity noise behind the reconstructed image, although the problem of the high-frequency noise at the hologram plane appears. Second we proposed a new method using multiple exposures to solve this problem. This approach is shown to be effective by the numerical simulation and the experiment.

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