Speckle Noise Suppression Algorithm of Holographic Display Based on Spatial Light Modulator

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Holography has emerged as one of the most attractive three-dimensional display technologies. With the technological development of computer science and coherent light source, the computer-generated holography has been applied in many fields. However, the speckle noise of the holographic reconstructed image seriously affects the viewing experience. In this paper, the cause of speckle noise generation in holographic display is introduced. Then, discussions about the speckle noise suppression methods are provided. The discussions are categorized into iterative and non-iterative approaches. Besides, we also introduce other speckle noise suppression techniques which are proposed from the perspective of light coherence, human visual system and optical system. Finally, the prospects of different types of approaches are summarized.

Keywords: speckle noise, computer-generated holography, holographic display, three-dimensional display, speckle noise suppression method

INTRODUCTION

Holography was first proposed by D. Gabor in 1948 (Gabor, 1948). It can record and reconstruct the entire wave-front information of the object. In 1965, A.W. Roman successfully made the first computer-generated hologram (CGH) and the theoretical foundation of CGH was established (Brown and Lohmann, 1966). In this period, the researchers mainly focused on the hologram encoding methods, and the main device for producing holograms was a plotter. Then, Lohmann proposed three different forms of circuitous phase-encoded holograms (Brown and Lohmann, 1969). Subsequently, Paris applied the fast Fourier transform (FFT) algorithm to speed up the calculation of the Fourier hologram, which greatly shortened the calculation time (Lohmann and Paris, 1967). After the 1980s, various types of spatial light modulators (SLMs) and new recording materials were developed (Zhan et al., 2020), which created new opportunities for holographic display. Many researchers gradually paid attention to the display effects of the different types of SLMs, and the researchers focused on the various hologram generation algorithms. So, different methods were developed, such as the look-up table method (Lucente, 1993), stereo holography method (Yamaguchi et al., 1992) and integrated holography method (St. Hilaire et al., 1992). Since 2000, liquid crystal on silicon (LCoS) has become a new research hotspot. The LCoS uses electrical signals to control the deflection of liquid crystal molecules for achieving modulation of the incident light phase (Chen et al., 2018). Then, the focus of researches was to improve the calculation speed of holograms by using GPU acceleration and optimizing physical models based on the LCoS (Nishitsuji et al., 2018; Lin et al., 2021). In addition, an increasing number of researchers paid attention to the field of view (FOV) and image quality of the holographic display (Maimone et al., 2017; Shi et al., 2017; Jang et al., 2018; Wang et al., 2020a; Zhao et al., 2020; Wu and Zhang, 2021; Yoo et al., 2021).

FIGURE 1 | Principle of CGH display based on the phase-only SLM.
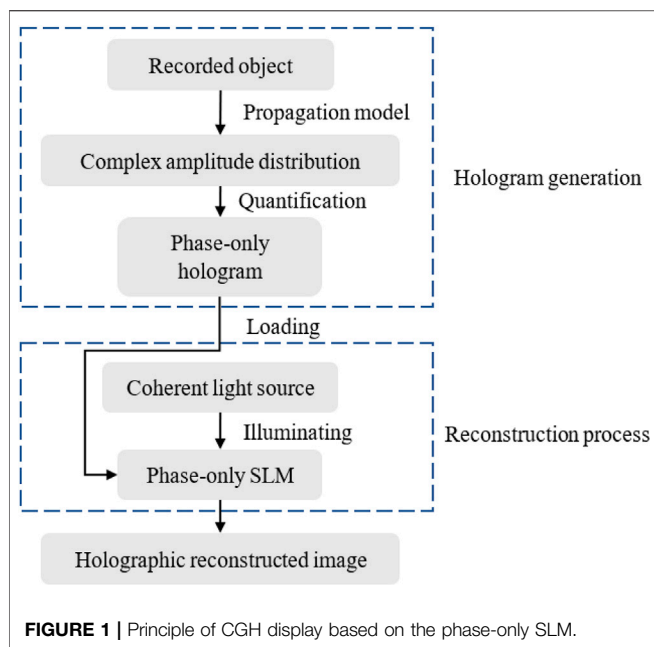
Although CGH has many advantages, there still exists many problems needed to be solved in the display field. One of the key issues is the speckle noise because it seriously affects the viewing experience. It is generally considered that the speckle noise in holographic displays is generated from the quantization error and the spatial coherence. In the past 20 years, more and more researchers have focused on the method for speckle noise suppression. Recently, the requirements to improve the quality of reconstructed images become more urgent. There are a large variety of methods for speckle noise reduction.

This paper gives the overview on the speckle noise suppression of holographic display based on spatial light modulator, and the main body is divided into the following sections. Firstly, the reason for speckle noise in CGH is described. Meanwhile, three criteria for quantizing the effect of speckle noise in the holographic reconstruction are provided. Besides, we introduce the speckle noise suppression process by considering various strategies. The described speckle noise reduction methods are mainly categorized into iterative method and non-iterative methods. In addition, other speckle noise suppression techniques are also introduced, which are proposed from the perspective of light coherence, human visual system and optical system. Finally, the prospects of these methods are summarized.

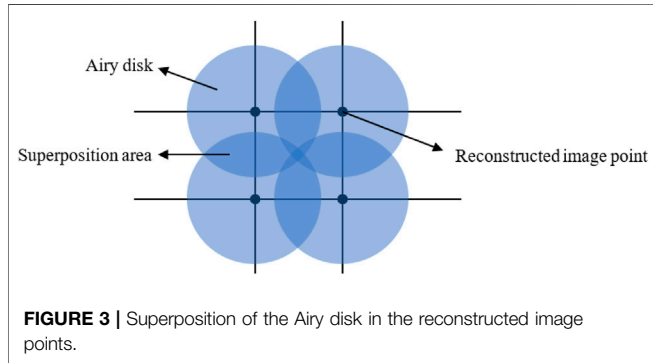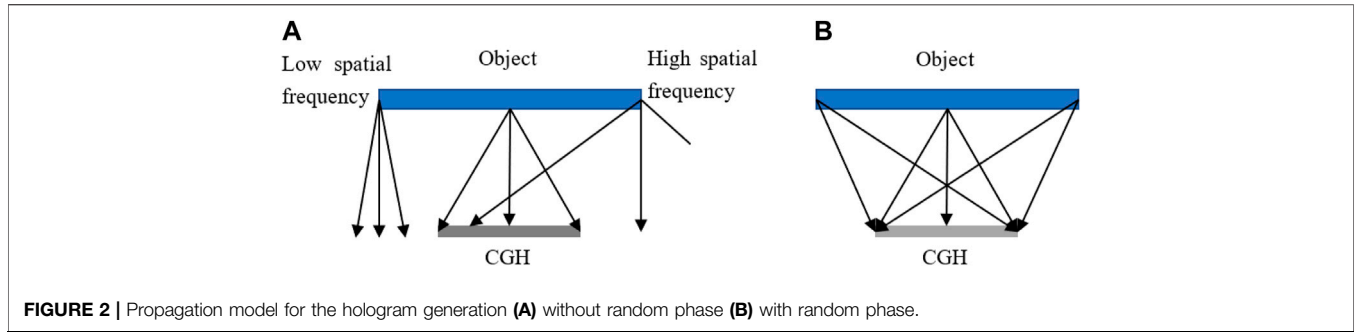## SPECKLE NOISE PROBLEM IN HOLOGRAPHIC DISPLAY

Since the commercial SLMs are either phase-only type or amplitude-only type, the holograms need to be encoded into phase-only or amplitude-only type to fit the type of SLM. Among them, the phase-only SLM has higher diffraction efficiency, so it is currently widely used in the holographic display. The principle of CGH display based on the phase-only SLM is shown in **Figure 1**.

In the hologram generation process, the complex amplitude distribution of the recorded object can be obtained by using the point-based propagation model. Then, the phase-only hologram can be generated by encoding the complex amplitude distribution of the recorded object. The encoding process can also be regarded as a quantization process, which is the sampling and approximation of the complex amplitude distribution. In the reconstruction process, the phase-only SLM is needed to realize the optical reconstruction of the CGH. By loading the phase-only hologram on the phase-only SLM and illuminating it with the coherent light source, the image can be reconstructed.

In general, the speckle noise in holographic display is considered generated from the perspective of software and hardware. The software and hardware refer to the computer generation process of the hologram and the optical reconstruction process, respectively. Speckle noise results from the interference. In encoding process, the approximate sampling is regarded as the quantization error of the holographic reconstruction and it is inevitable. Due to the quantization error, the speckle noise is generated by the uncontrolled coherence effects of the reconstructed image. When the phase in the reconstructed image is a random distribution, the reconstructed image points will disturb each other and produce a randomly changed intensity because of the phase difference. In order to simulate the scattered light on the surface of the recorded object, the random phase is added to the recorded object in hologram algorithms. As shown in **Figure 2**, the recorded object consists of parts with low frequencies and high spatial frequencies. For a recorded object without random phase, only high-frequency and part of low-frequency of the information can be recorded on the CGH, while the edge of the low-frequency cannot be recorded. Although the random phase is a generator to ensure that the recorded object information spread completely over the CGH, it is also the main cause of the speckle noise generation (Shimobaba and Ito, 2015).

Moreover, during the optical holographic reconstruction, coherent light sources and optical devices are also the causes of the speckle noise generation. The reconstructed points exist in the form of Airy disks because of the limited aperture of the optical elements and the diffraction effects, as shown in **Figure 3**. The speckle noise becomes more serious with increasing of the superposition area. The optical reconstruction process is imperfect since the dust, scratches in the lens and aberrations can produce additional speckle noises. Different from the quantization error, this kind of error caused by the hardware is called systematic error.

Finally, to assess the speckle noise suppression effect, three criteria can be used to investigate: the peak signal-to-noise ratio (PSNR), structural similarity (SSIM) index and speckle contrast (SC). Besides, the foveal perception, wirtinger flow method and subjective quality evaluation can also be used for evaluation (Bolek and Makowski, 2019; Chakravarthula et al., 2021). PSNR is the most commonly used objective measurement method for evaluating image quality, which can be defined as follows:

FIGURE 2 | Propagation model for the hologram generation **(A)** without random phase **(B)** with random phase.

FIGURE 3 | Superposition of the Airy disk in the reconstructed image points.

$$PSNR = 20 \cdot \lg \left(\frac{255}{\sqrt{\frac{1}{mn} \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} \left\| X(i,j) - Y(i,j) \right\|^2}} \right), \quad (1)$$

where X and Y represent the object image and the reconstructed image, respectively, m and n represent the resolutions. The unit of PSNR is 1dB. A higher value of the PSNR usually means the effect of speckle noise suppression is better.

SSIM is also a very important parameter for evaluating the reconstructed image quality. For the holographic reconstructed image x and recorded object y, the SSIM of the two images can be expressed as follows:

$$SSIM(x,y) = \frac{\left(2\mu_x \mu_y + c_1\right)\left(2\sigma_{xy} + c_2\right)}{\left(\mu_x^2 + \mu_y^2 + c_1\right)\left(\sigma_x^2 + \sigma_y^2 + c_2\right)}, \quad (2)$$

where μ_x and μ_y are the average of image x and image y, respectively. σ_x^2 and σ_y^2 are the variance of image x and image y, respectively. σ_{xy} is the covariance between images x and y. $c_1 = (k_1 L)^2$ and $c_2 = (k_2 L)^2$ are two constants used to maintain stability and L is the dynamic range of pixel values, where K_1 equals to 0.01 and K_2 equals to 0.02 (Duan et al., 2019).

SC is the simplest parameter to evaluate the speckle noise of the reconstructed image, and it satisfies the following equation:

$$C = \frac{\sigma}{\bar{I}}, \quad (3)$$

where σ and $\bar{I}$ represent the standard deviation of intensity and the average of intensity, respectively. The lower SC indicates the less speckle noise in the reconstructed image.
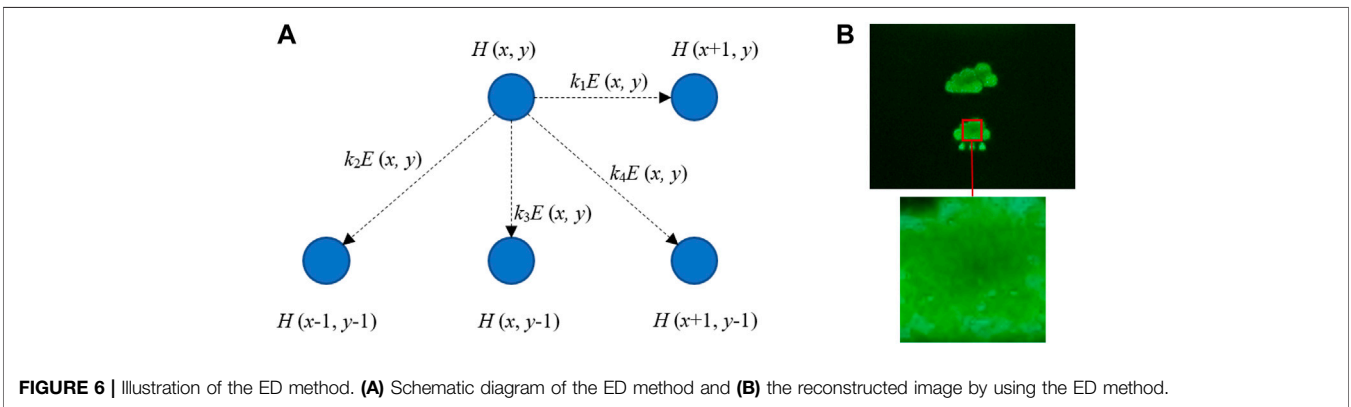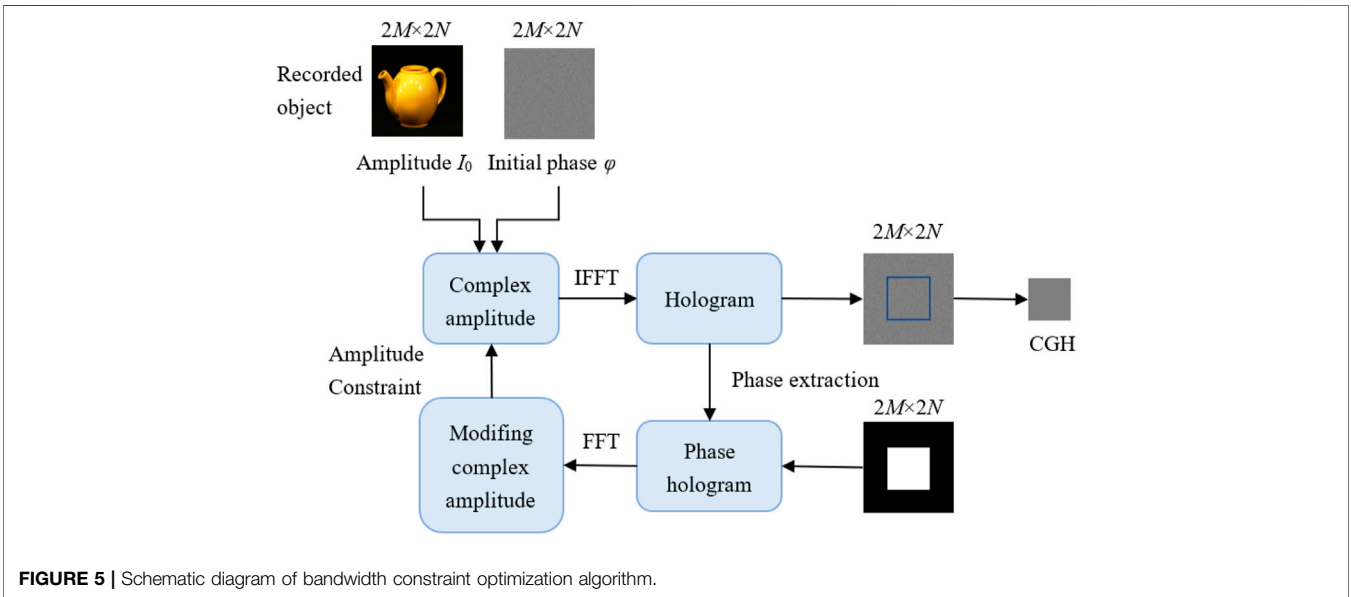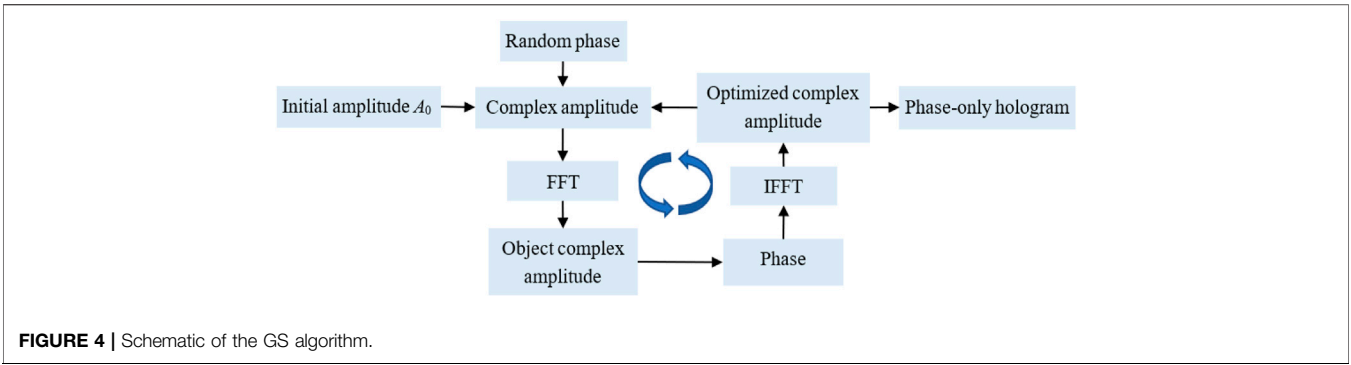
METHODS OF SPECKLE NOISE SUPPRESSION

There are many kinds of methods for suppressing the speckle noise, and they can be discussed based on the hologram generation process and the reconstruction process. Based on the hologram generation process, the CGH algorithm can be divided into two categories: iterative and non-iterative methods. Based on the reconstruction process, we also introduce other speckle noise suppression techniques which are proposed from the perspective of light coherence, human visual system and optical system.

Iterative Methods

Among the iterative methods that can generate phase-only holograms, the iterative Fourier transform algorithm is a representative method. The characteristic of this type of algorithm is the iterative propagation in two planes by using the Fourier transform (Bu et al., 2021). The most famous and mostly used method is the Gerchberg-Saxton (GS) algorithm (Gerchberg and Saxton, 1972). As shown in **Figure 4**, the amplitude constraint is imposed on the object plane and hologram plane, then the phase is continuously iterated between the hologram plane and object plane. After several iterations, the phase distribution on the hologram plane converges to an optimal value. Therefore, the amplitude information of the object can be encoded into the phase-only hologram. Moreover, it is also possible to use the Fresnel transform instead of the Fourier transform to simulate light field propagation.

Many improved CGH algorithms have been developed based on the GS algorithm. The GS algorithm with weight coefficients (GSWC) has been proposed to improve the convergence rate and suppress the speckle noise (Kuzmenko et al., 2011; Wu et al., 2021a). The GSWC algorithm replaces the original constraint with the weight coefficients multiplied by the amplitude of the recorded object. The quality of the reconstructed image using the GSWC algorithm is improved by 75% compared with the GS algorithm. Moreover, the uniform random phase generator used

FIGURE 4 | Schematic of the GS algorithm.

FIGURE 5 | Schematic diagram of bandwidth constraint optimization algorithm.

FIGURE 6 | Illustration of the ED method. **(A)** Schematic diagram of the ED method and **(B)** the reconstructed image by using the ED method.

by the GS algorithm is also an important cause of the speckle noise. To optimize the random phase generator, an iterative method with bandwidth constraint strategy has been proposed (Chen et al., 2021a). As shown in **Figure 5**, in order to suppress the speckle noise and provide effectively controls of the reconstructed intensity fluctuations, the iterative method can

optimize the phase of the CGH by using the bandwidth constraint strategy of the reconstructed image and quadratic initial phase. The SC of the method with bandwidth constraint strategy is 46% lower than that of the GS method.

Different from the iteration between the object plane and the hologram plane, the error diffusion (ED) method is another type

of iterative algorithm, which iterates between the pixels of the hologram (Barnard et al., 1989). As shown in **Figure 6**, H represents a pixel of the CGH, (x, y) represents the pixel coordinate point, E and k represent the quantization error of the pixel point and the weight coefficient, respectively. Since the ED method diffuses the quantization error to adjacent pixels of the phase-only hologram and homogenizes them, the speckle noise generated by the quantization error can be suppressed. However, the calculation time of the ED method increases proportionally with the resolution of the hologram.

Based on the ED method, some researchers have introduced two enhanced methods which are known as the localized error diffusion and redistribution (LERDR) and bidirectional error diffusion (BERD). In these methods, the conversion of a complex Fresnel hologram to a phase-only hologram can be conducted in a parallel manner (Ysang et al., 2014). Compared with the localized error diffusion (LERD) algorithm, the PSNR of the reconstructed image by using LERDR and BERD algorithm is nearly 10 dB higher on average. Besides, the combination of the ED and the digital lens has been proposed (Chang et al., 2015; Wang et al., 2020b; Jiao et al., 2020; Li et al., 2020). The suppression effect of speckle noise can be improved by more than 60% on average compared with the ED method.

Recently, with the rapid development of the camera and computation, the camera with an algorithm can be used to optimize the phase distribution of the CGH. Camera-in-the-loop (CITL) holographic algorithm has been proposed to reduce the gap between the numerical simulation and optical reconstruction, since the optical system is imperfect. However, the direct current (DC) noise from the SLM cannot be eliminated in CITL on-axis setup. To solve this problem, a holographic display system has been proposed by using a new CITL optimization and two phase-only SLM (Choi et al., 2021a). This display system is inspired by the design of Michelson interferometers, so that called Michelson holography (MH). Compared with the double phase-amplitude coding (DPAC) method, the PSNR of the reconstructed image by using MH method is about 6 dB higher in the optical experiment. Nonetheless, the calculation time of the MH method is too much for the multi-depth recorded object. To solve this problem, a multi-depth holographic display method has been proposed by using stochastic gradient descent (SGD) with complex loss function (Chen et al., 2021b). For the recorded object with 20 depth layers, the calculation time of the proposed method is faster 94.36% than that of the SGD based on amplitude loss method.
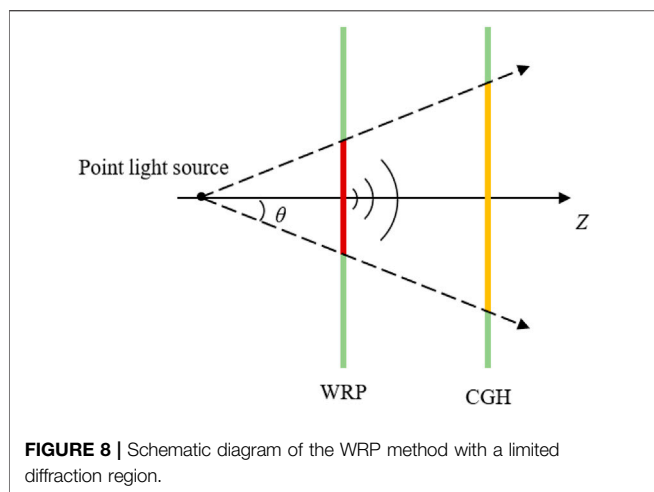
Non-Iterative Methods

As non-iterative methods, the multi-random phase method and multiple fractional Fourier transform method have been used for reducing the speckle noise (Jun et al., 1995; Zheng et al., 2009; Wang et al., 2020c). These methods are effective in speckle noise suppression, but they are time-consuming. To reduce the calculation time and suppress the speckle noise at the same time, the random phase-free method has been proposed by multiplying the recorded object with the virtual convergence light (Shimobaba and Ito, 2015; Nagahama et al., 2019). As

FIGURE 7 | Random phase-free CGH by using the convergence light.
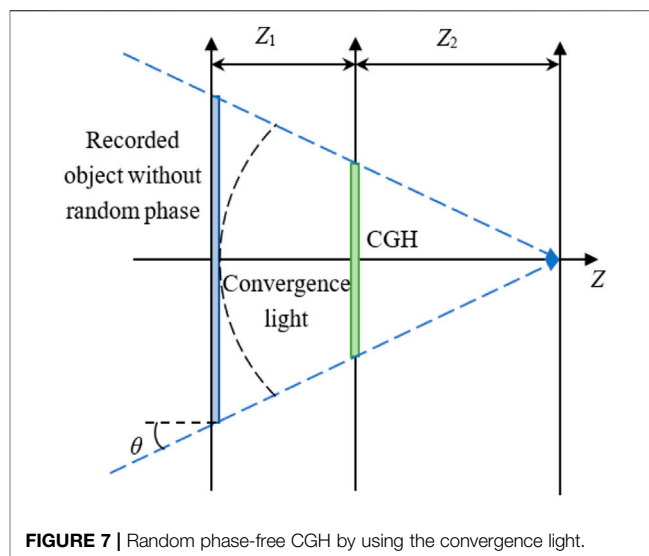
shown in **Figure 7**, the recorded object multiplies with the virtual convergence light instead of the random phase. The recorded object information is completely diffused in the CGH by using the virtual convergence light. The virtual convergence light also avoids the speckle noise generated by the random phase. It should be noted that the incident angle θ of the convergence light must be smaller than the maximum diffraction angle of the SLM to avoid the aliasing error. Compared with the random phase method, the PSNR of the numerically reconstructed image using the random-phase-free method is nearly 30 dB higher.

Since the random phase could lead to the excessive diffusion of information and degrades the image quality, the gradient-limited random phase (GL-RP) addition method and the limited-random-phase (L-RP) time average method have been developed to avoid excessive diffusion of the object information (Ma et al., 2017; Zhao et al., 2019). In the numeral simulation of the GL-RP method, the PSNR and SSIM of the reconstructed image increase by 10 and 13%, respectively. The L-RP method finds that the random phase of the recorded object has an appropriate range, which is limited to 1.2π–1.5π. When the limited random phase is applied in the hologram generation process, the speckle noise can be reduced significantly.

The pixel separation method is also one of the most famous methods. The recorded object is separated into different point groups by pixel separation. For each point group, the sub-CGHs with independent initial random phases are generated. Then, the speckle noise is reduced by the time average (Mori et al., 2014; Liu et al., 2019; Masaya and Yuji, 2019). Compared with the non-separation method, the speckle contrast of the reconstructed image by using these methods is reduced by more than 80%. Therefore, a combination of the pixel separation method and the time average can suppress the speckle noise effectively. However, the high-refresh SLM is necessary for these methods since the time average reduces frame rates of the holographic display. The speckle noise can be further suppressed with the increase of the separated interval and the number of the sub-CGHs.

FIGURE 8 | Schematic diagram of the WRP method with a limited diffraction region.

In the generation process, the Fresnel CGH can be binarized in a non-iterative manner through down-sampling the recorded object with a grid lattice prior. Meanwhile, the down-sampling method can suppress the speckle noise as well. However, the results of the down-sampling method have a prominent texture of regularly that is spaced voids in the shaded regions. To solve this problem, an enhanced method based on grid-cross down-sampling (GCD) has been proposed (Cheung et al., 2011; Tsang et al., 2013). The reconstructed images of these methods have proved that the speckle noise can be suppressed effectively. However, a sparse appearance with many empty voids is generated in reconstructed image when using the GCD method. To suppress the speckle noise and the sparse appearance at the same time, a combination of the GCD and a time-division comb filtering (TDCF) approach has been proposed (Liu et al., 2020; Tsang et al., 2020). The PSNR of the reconstructed image by using the LRDS method can reach almost 30 dB. Moreover, the intermediate angular-spectrum method (IASM) has been proposed by avoiding the numerical circular convolution (Chen et al., 2019). Compared with the zero-padding method, the PSNR of the reconstructed image based on the IASM method can be improved by 36%.

On the other hand, the size of the diffraction region affects the quality of the reconstructed image. In order to reduce the speckle noise caused by the useless diffraction region, a wave-front recording plane (WRP) method with a limiting diffraction region has been proposed (Yanagihara et al., 2020). As shown the green area in **Figure 8**, the useless diffraction region can be avoided in CGH generation process. The experimental results demonstrate that the speckle noise can be reduced efficiently by using the WRP method with the limited circular diffraction region. Besides, a method to suppress the speckle noise in the holographic display based on effective utilization of two phase-only SLMs has also been verified availably (Wang et al., 2019). This method combines the pixel separation, the time multiplexing and the limit diffraction region to reduce the speckle noise. Compared with the conventional point-based method, the speckle contrast of the reconstructed image by using this

method is reduced by 21.57%, and the calculation time is reduced by 48.53%.

The speckle noise can also be efficiently suppressed by using the complex amplitude encoding method. For the speckle reduction, an efficient coding method by using lossy compression has been verified (Bernardo et al., 2021). Both the effect of the speckle noise caused by the encoding process and the speckle noise caused by the compression in the recorded object have been discussed in this method. In addition, a combination of the time-multiplexing and the hologram optimization approach has been proposed (Hamann et al., 2018). This approach suppresses the speckle noise by an alternating direction method of multipliers optimization. The simulation demonstrates a significant improvement in the PSNR of the reconstructed image under higher rank factorization. Besides, the double-phase hologram (DPH) provides a better approximation to encode complex amplitude fields. Recently, the speckle-less holographic display based on DPH method has been proposed (Mendoza-Yero et al., 2014; Qi et al., 2016). In DPH method, the complex amplitude information is encoded as two-phase values, then the two phase values are combined into the pixel of the phase-only CGH by using two binary complementary chessboard masks. Since the two-phase values can be synthesized into the corresponding complex amplitude values, the quantization error is reduced and the speckle noise is suppressed. Furthermore, these methods can suppress the speckle noise and reduce the calculation time at the same time because of the free of iteration. Compared with the iterative Fourier transform algorithm, the speckle contrast of the reconstructed image by using the DPH method is reduced by more than 60%.

The hologram generation method based on deep learning is also a non-iterative method, which has great potential to realize real-time and speckle-free holographic display (LeCun et al., 2015; Horisaki et al., 2018; Eybposh et al., 2020; Lee et al., 2020a; Curtis et al., 2021; Park and Park, 2020). The convolutional neural network (CNN) has been demonstrated usefully in revealing the deep relationships between the input object and output hologram (Lee et al., 2020a). The learned CNN has the advantages of speckle reduction and fast calculation speed. Recently, a combination of the CNN and a modified double phase approach has been proposed to achieve a high-quality real-time holographic display (Shi et al., 2021). As shown in **Figure 9**, they introduce an anti-aliasing double phase method (AA-DPM) to generate the hologram dataset, which can reduce both high-frequency noise and speckle noise. The CNN is utilized to learn the relationship between the input 3D object and the Fresnel hologram dataset. The loss function in the training period consists of two types of loss functions: one is to measure the error of the predicted hologram, and the other one is to measure the quality of the reconstructed 3D object. Through the training strategy, the CNN can learn the characteristic of the hologram with high precision, so as to eliminate speckle noise effectively (Chakravarthula et al., 2020; Peng et al., 2020; Choi et al., 2021b; Wu et al., 2021b).
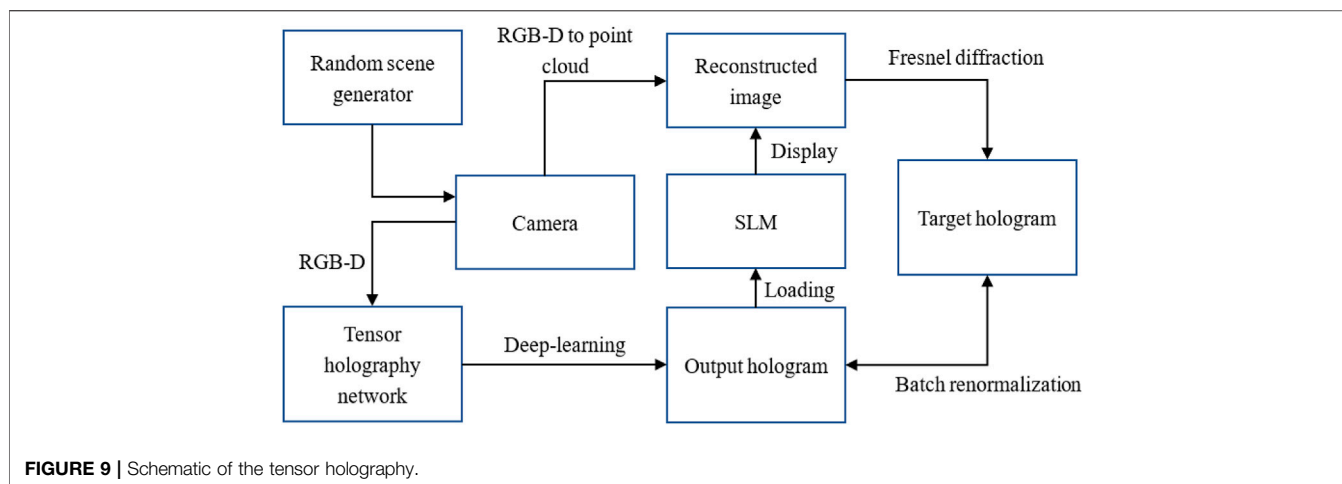
FIGURE 9 | Schematic of the tensor holography.

Methods Based on the Light Coherence and Optical System

During the optical holographic reconstruction, the coherent light source is one of the main causes of speckle noise generation. Therefore, reducing the coherence of the light source is helpful to suppress the speckle noise. To reduce the coherence, a random laser has been demonstrated usefully (Redding et al., 2012). In conventional coherent light sources, the low spatial coherence and the laser-level intensity are mutually exclusive. As a new kind of light source, the random laser is ideal for display because it has both properties.

Furthermore, in conventional holographic display, the reconstructed images suffer from the trade-off between the speckle noise and the resolution. To alleviate the trade-off problem, the theoretical models for quantifying the effect of the low-coherence have been introduced (Lee et al., 2020b). In this theoretical model, an optimal coherence light source with the maximum effect of the speckle suppression can be found. However, although the light source is optimized for considerable speckle noise suppression, the sacrifice of the resolution and the depth of field is inevitable. Then, this method has been demonstrated to alleviate the trade-off. Moreover, by combining the tunable-focus lens and the local illumination module, a speckle reduced holographic display prototype has been built (Lee et al., 2020c). In order to reduce the speckle noise while maintaining resolution, depth of field and frame rate, the tomographic synthesis method has been applied. The experimental results demonstrate that this method can suppress the speckle contrast averagely by 37.8% while keeping the resolution and depth of field unchanged.

Besides, a novel CGH encoding method based on a low-coherence light source has also been proved feasible for speckle noise reduction (Duan et al., 2019). Compared with the angular spectrum method, the PSNR of the reconstructed image by using this novel encoding method is improving by more than 60%. It is meaningful that this novel encoding method can be combined with other algorithms based on the

low-coherence light source. The previous methods of suppressing speckle noise do not take the perceptual characteristics of the human visual system (HVS) into account (Chakravarthula et al., 2021). Considering the HVS, a method by incorporating anatomically-informed model of human perception has been proposed to reduce the speckle noise. Some users have been invited to evaluate the reconstructed image by using the proposed method.

Finally, we summarize the prospects of three types of methods. Iterative algorithms based on GS method have good flexibility to suppress the speckle noise. However, the computational speed of these algorithms is limited by the number of iterations, which makes it difficult to implement real-time holographic display. As another iterative method, the ED method requires fewer computational resources and reduces the speckle noise well. However, it is not suitable for the CGH with random phase involved because of the limited complex amplitude information correction ability.

As the non-iterative algorithms, the random-phase-free method, the pixel separation method, the down-sampling method, the double phase method and the deep learning method can suppress the speckle noise and improve the quality of the reconstructed image. Generally, the non-iterative algorithms are suitable for the real-time holographic display because they occupy less computational resources. Among them, deep-learning-based hologram generation methods are the most promising one because of the effectiveness in the speckle noise suppression. However, although the speckle noise suppression method based on the current deep-learning-based algorithms is impressive, the whole display system is still a bit huge and complex to commercialization.

On the other hand, reducing the coherence of the light source and systematic errors are also helpful to suppress the speckle noise. However, the low-coherence light source has drawbacks, which are the serious impact on the sharpness and contrast of the reconstructed image (Memmolo et al., 2014; Montrésor et al., 2019). It is important to find an intermediate point balance value between the coherence and incoherence of the

light source. In practice, the strategy can include one or more of these methods.

CONCLUSION

In this paper, the reason of the speckle noise generation in holographic display is provide by analyzing the hologram generation process and the reconstruction process. Meanwhile, the evaluation criteria for speckle noise in holographic display is introduced. In addition, the speckle noise suppression methods are introduced by considering the hologram generation process and the reconstruction process. Based on the hologram generation process, the discussed methods are divided to the iterative and non-iterative methods. In the reconstruction process, other speckle noise reduction methods are also introduced based on the perspective of light coherence, human visual system and optical system. Finally, we summarize the prospects of each type of method.

AUTHOR CONTRIBUTIONS

Conceptualization: N-NL and DW; writing-original draft preparation, N-NL, CC, DW, BL, and Q-HW.

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