

# Improvement of the signal-to-noise ratio in digital holography

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A fundamental problem in optical and digital holography is the presence of speckle noise in the reconstruction process, which essentially diminishes the signal to noise ratio (SNR). For many applications, that reduction of the SNR makes the digital holography impractical, so great number of approaches have been carried out in order to overcome such a problem. They range from modifying the spatial coherence of the illumination to the application of image processing techniques. In this paper we propose the merged use of digital image processing techniques in order to increase this SNR by reducing the speckle noise in the digital reconstruction of optically recorded Fresnel's holograms. The proposed techniques are illustrated with experimental results.

*Keywords:* Digital holography; speckle free reconstruction; Fresnel's holograms.

Un problema fundamental en holografía óptica y digital es la presencia de ruido *speckle* en el proceso de reconstrucción, el cual disminuye considerablemente la relación señal ruido (SNR). Para muchas aplicaciones, esta reducción de la SNR hace que la holografía digital sea impráctica, de modo que gran número de alternativas se utilizan con el propósito de superar este problema. Estas alternativas van desde modificar la coherencia espacial de la iluminación a la aplicación de técnicas del procesamiento de imágenes. En este artículo proponemos el acople de técnicas del procesamiento digital de imágenes con la intención de incrementar esta SNR por medio de la reducción del ruido *speckle* en la reconstrucción digital de hologramas de Fresnel registrados ópticamente. Las técnicas propuestas son ilustradas con resultados experimentales.

*Descriptores:* Holografía digital; reconstrucción libre de *speckle*; hologramas de Fresnel.

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## 1. Introduction

The swift development of digital computers and CCD cameras has made possible the implementation of Goodman's idea of registering and reconstructing holograms by digital means [1]. This development has propelled an important field of the contemporary optics called digital optics, and particularly digital holography as it was conceived by Goodman many years ago.

Naturally, digital holography has inherited both desirable and undesirable characteristics from its optical counterpart. Among the desirable inherited characteristics, we could mention its capability to reconstruct wavefronts, the applicability of typical setups in-line and off-line, etc. However, some undesirable characteristics such as the zero diffraction order and the speckle noise present in the reconstructed images were also inherited and have an unfavorable effect on the signal-to-noise ratio of digitally reconstructed holograms.

Great effort has been focused in of getting rid of the existence of the zero diffraction order and speckle noise in the reconstructed images in both fields of holography [2-8]. These two drawbacks have more devastating effects in digital than in optical holography, which is due to the fact that the systems

of recording and visualization used in digital approach are extremely sensitive to them or may even increase them. As a result, a lot of effort has been invested in the digital holography to overcome these drawbacks, and by taking advantage of the great versatility of the digital systems, important results on the increasing of the SNR of the digital reconstructed holograms have been achieved.

In this work we deal with the problem of reduction of speckle noise in digitally recorded and reconstructed Fresnel's holograms, thus their SNR will be increased. Essentially, we attempt this problem from a digital image processing standpoint by applying well known filtering kernels as well as some other digital approaches presented here for the first time as far as we know. Initially we will introduce some basic ideas about digital holography, and afterwards we will develop and apply the procedures addressed to reach the goal of reducing speckle noise in digital holography reconstruction, and consequently increasing the SNR.

## 2. Fundamentals

Conceptually, digital holography can be outlined by two diffraction processes, one from the object plane to the holo-

gram plane (CCD plane), and the other from the hologram plane to the image one, as it is shown in Fig. 1.

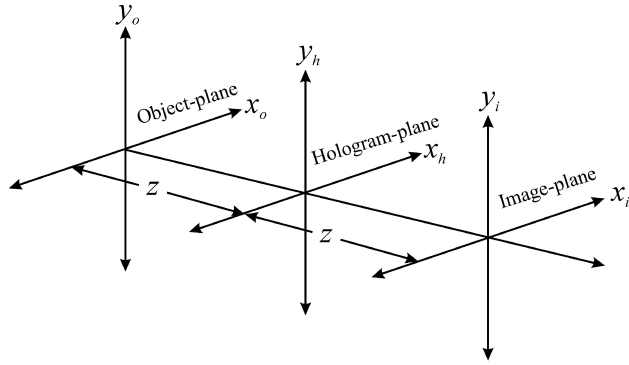


FIGURE 1. The most important planes in digital holography.

The object located at the plane  $z = 0$  is coherently illuminated and the optical field scattered by it interferes with the plane reference wave in such a way that the interference pattern is recorded in a CCD camera located at a distance  $z = d$ . At this plane, only the intensity  $I(x_h, y_h)$  impinging upon the CCD will be registered. The optical field at the image plane located at a distance  $d$  from the CCD camera, is found by calculating the diffraction process of the plane reference wave when it illuminates the transmittance represented by  $I(x_h, y_h)$ . This diffraction process is described by the Kirchoff-Fresnel diffraction integral, which due to the geometrical parameters involved in the setup fits the requirements to consider the problem in the Fresnel-Fraunhofer approximation, so it can be written as

$$E(x_i, y_i, z) = \frac{iE_0}{\lambda z} e^{-\frac{i\pi}{\lambda z}(x_i^2 + y_i^2)} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(x_h, y_h) e^{-\frac{i\pi}{\lambda z}(x_h^2 + y_h^2)} e^{\frac{i2\pi}{\lambda z}(x_h x_i + y_h y_i)} dx_h dy_h \quad (1)$$

where  $E_0$  is the amplitude of the plane reference wave and  $\lambda$  the wavelength of the optical field. The distance  $z$  between the hologram and image planes and the coordinate systems are represented in Fig.1.

The problem of determining  $E(x_i, y_i, z)$  from Eq. (1) with a digital processor has been extensively discussed in the literature [8]. It has been shown that, with a finite size of hologram  $I(x_h, y_h)$ , the image reconstructed from it is characterized by readings of the optical field  $E(m, n, z)$ , which are linked to the hologram readings  $I(k, l)$  by a discrete Fresnel transformation:

$$E(m, n, z) = \frac{iE_0}{\lambda z} e^{-\frac{i\pi}{\lambda z} \left( \frac{m^2}{N_x^2 \Delta x^2} + \frac{n^2}{N_y^2 \Delta y^2} \right)} \sum_{k=0}^{N_x-1} \sum_{l=0}^{N_y-1} I(k, l) e^{-\frac{i\pi}{\lambda z} (k^2 \Delta x^2 + l^2 \Delta y^2)} e^{i2\pi \left( \frac{k m}{N_x} + \frac{l n}{N_y} \right)}. \quad (2)$$

In Eq. 2 we have assumed the hologram registered by a rectangular CCD having  $N_x \times N_y$  pixels with pixel dimensions  $\Delta x_h \times \Delta y_h$ ,  $m = 0, 1, \dots, N_x - 1$  and  $n = 0, 1, \dots, N_y - 1$  and the image pixel dimensions  $\Delta x_i \times \Delta y_i$  are related to the pixel CCD dimensions  $\Delta x_h \times \Delta y_h$  by  $\Delta x_i = (\lambda z) / (N_x \Delta x_h)$  and  $\Delta y_i = (\lambda z) / (N_y \Delta y_h)$  [8].

This equation is the discrete Fourier transformation of the function  $I(k, l) e^{-\frac{i\pi}{\lambda z} (k^2 \Delta x^2 + l^2 \Delta y^2)}$ , so for its calculation it is just necessary to multiply the hologram readings  $I(k, l)$  by the chirp function  $e^{-\frac{i\pi}{\lambda z} (k^2 \Delta x^2 + l^2 \Delta y^2)}$  and make use of the Fast Fourier Transformer (FFT) algorithm.

From Eq. 2 it is possible to evaluate the intensity and phase of the optical field by

$$I(m, n, z) = |E(m, n, z)|^2 = \Re [E(m, n, z)]^2 + \Im [E(m, n, z)]^2 \quad (3)$$

and

$$\phi(m, n, z) = \arctan \left( \frac{\Im [E(m, n, z)]}{\Re [E(m, n, z)]} \right) \quad (4)$$

respectively. In these equations  $\Re$  and  $\Im$  stand for the real and imaginary part of a complex optical field, respectively.

It is apparent from the former equations that the digital holography allows us to calculate of the intensity and the

phase of reconstructed holograms for a particular distance  $z$  from the hologram plane. This fact has made possible the development of new microscopic and imaging techniques widely used in biological sciences [9]. However, in optical holography this is not possible, and added to other characteristics of digital holography, make this subject becomes a very active field for research in optics.

### 3. Signal-to noise ratio increasing techniques

#### 3.1. In digital holography

The regular appearance of the digitally recorded and reconstructed holograms is shown in Fig. 2. There, a well defined real image of the scene is shown, where the elimination of the zero diffraction order has been reached successfully, but a strong speckle noise over the image is still apparent, thus its SNR is greatly decreased. Once identified that the cause of the reduction of SNR in digital holography is the speckle noise associated with the process, we will focus all our efforts to the reduction of it, so as to generate an increase in the SNR of the digitally reconstructed holograms.

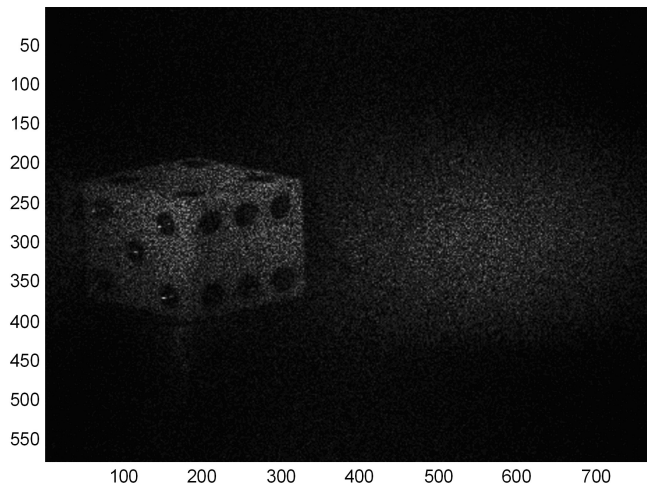


FIGURE 2. Digitally reconstructed hologram after effective reduction of zero diffraction order.

The presence of speckle noise in digital holography arises from the coherent recording [7], as in optical holography, and from the finite size of sampling devices, *i.e.*, the finite size of the pixels in the CCD camera [3,8]. Thus, its reduction

can be attempted by means of reducing it from the recording process itself; by improving the digital recording devices; and/or by means of digital processing of the reconstructed images. Below we shall present different methods of reducing the speckle noise, based on the digital processing of the reconstructed hologram itself.

The first approach to reducing the speckle noise is based on the idea of reducing the size of the reconstructed hologram as sketched in Fig. 3 [5]. From the original reconstructed

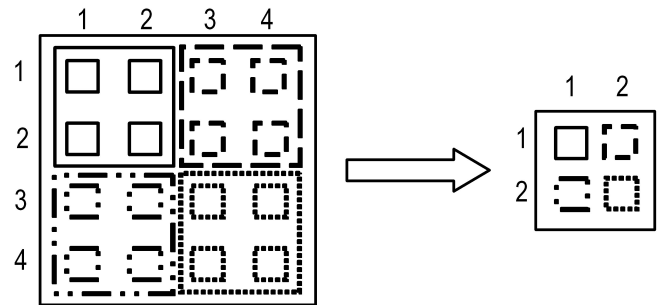


FIGURE 3. Illustration of the technique of reducing the reconstructed hologram size.

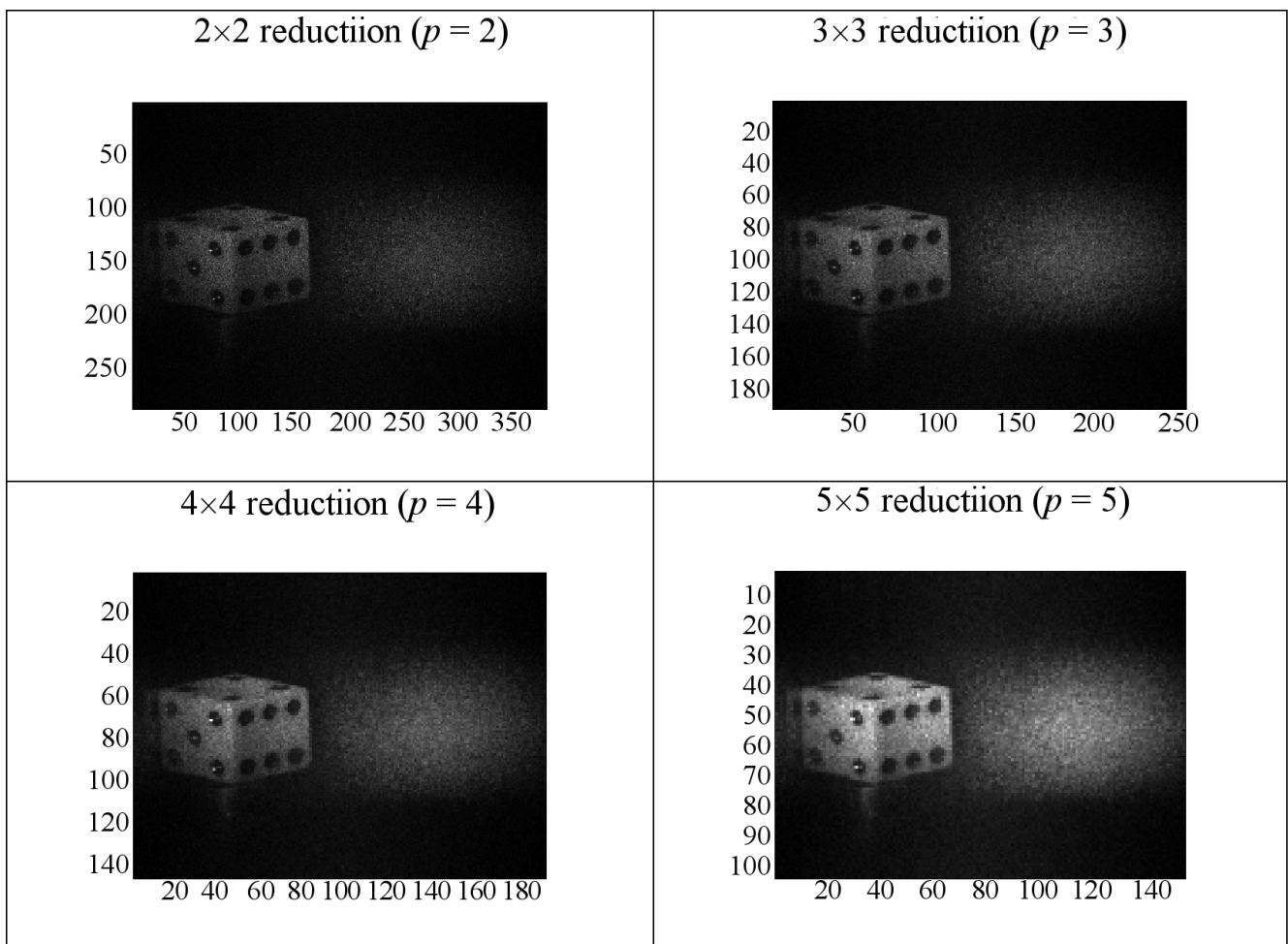


FIGURE 4. SNR increasing by the technique of resizing the original image shown in Fig.2.

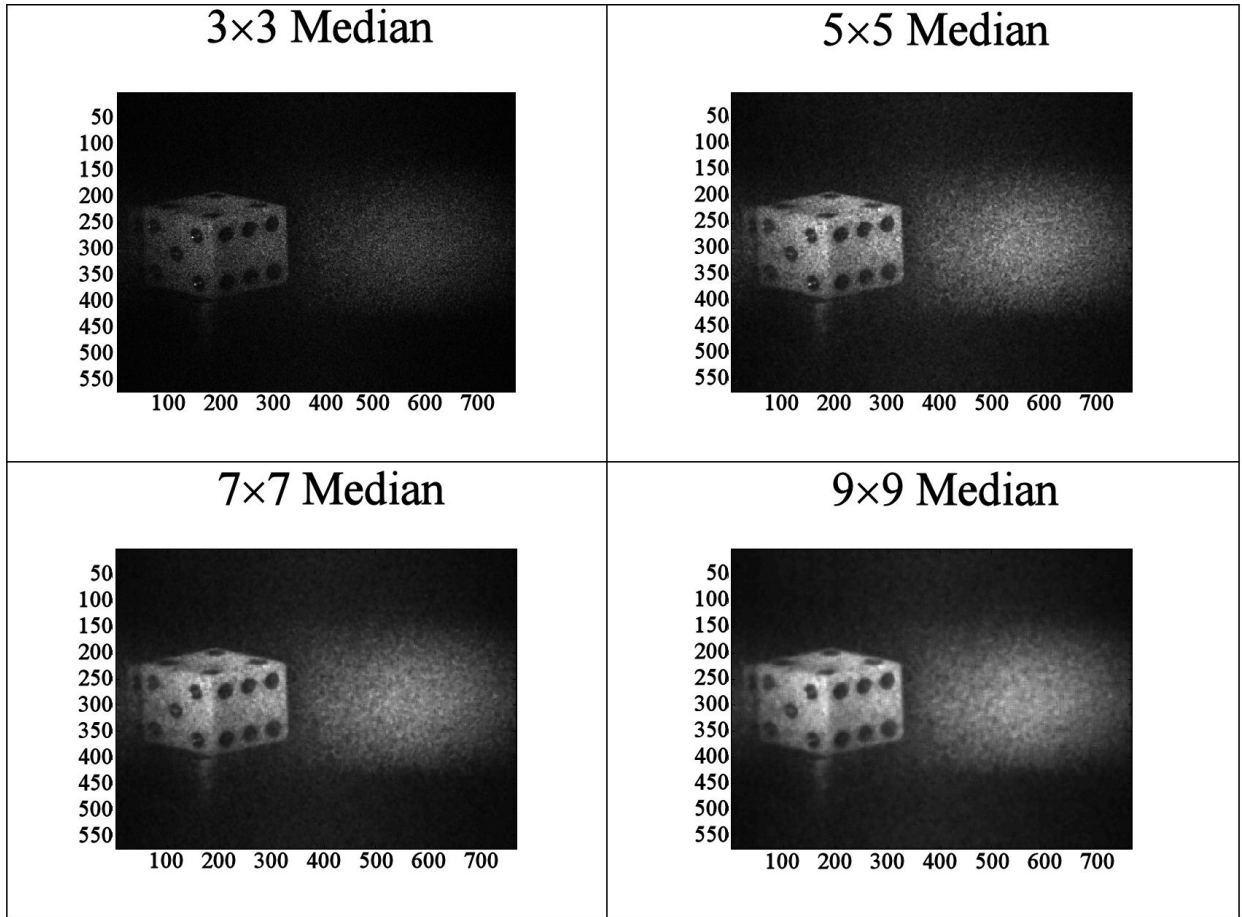


FIGURE 5. SNR increase by the technique of median filtering applied to the original image shown in Fig.2.

hologram  $I(m, n)$  a shortened version of it  $I'(m', n')$  is generated. Each pixel of  $I'(m', n')$  is the result of averaging square regions of side  $p$  in the image  $I(m, n)$ . Thus, if the pixel number of the image  $I(m, n)$  is  $N_x \times N_y$ , the pixel number of the reduced image  $I'(m', n')$  will be  $int(N_x/p) \times int(N_y/p)$ , with  $int$  standing for the integer part and  $p$  for the reduction order.

This reduction can be understood as a modified and localized low-pass filtering that generates a smaller output image in which all its entries are a smoothed versions of corresponding square regions of size  $p$ , i.e., each pixel of  $I'(m', n')$  is obtained from the weighted average of the local neighborhood of the pixel in the input  $I(m, n)$ :

$$I'(m', n') = \frac{1}{p^2} \sum_{i=1}^p \sum_{j=1}^p I[(p[m'-1]+i), (p[n'-1]+j)]$$

$$p = 1, 2, 3, 4 \dots$$

$$m' = 1, 2, \dots, int\left(\frac{N_x}{p}\right);$$

$$n' = 1, 2, \dots, int\left(\frac{N_y}{p}\right) \tag{5}$$

with  $int$  the integer part,  $N_x, N_y$  the pixel number of the CCD camera along each coordinate axis and  $p$  the reduction order.

The results obtained by applying the above technique to the image shown in Fig. 2, are illustrated in Fig 4. It is apparent from the scales on the images the reduction applied to each one, as well the effectiveness of this idea. It is true that the greater the  $p$  reduction order the smaller the speckle noise, for  $p= 5$ , for instance, but still the detriment of the image itself does not compensate for the decrease in speckle noise obtained. That means that the selection of the correct reduction order  $p$  will depend upon the specific application, the size of the original image, and the speckle noise initially present in the reconstructed image. This reasoning leads us to state that the election of the best reduction order  $p$  for a particular experiment will be handled by a rule of thumb based on the rigorous knowledge of the needs of a particular application.

An alternative approach to the reduction of speckle noise in reconstructed holograms, is carried out by using a conventional median kernel filter for image processing [5,10-12]. Taking advantage of its fundamental characteristic of eliminating the impulsive noise while preserving spatial resolu-

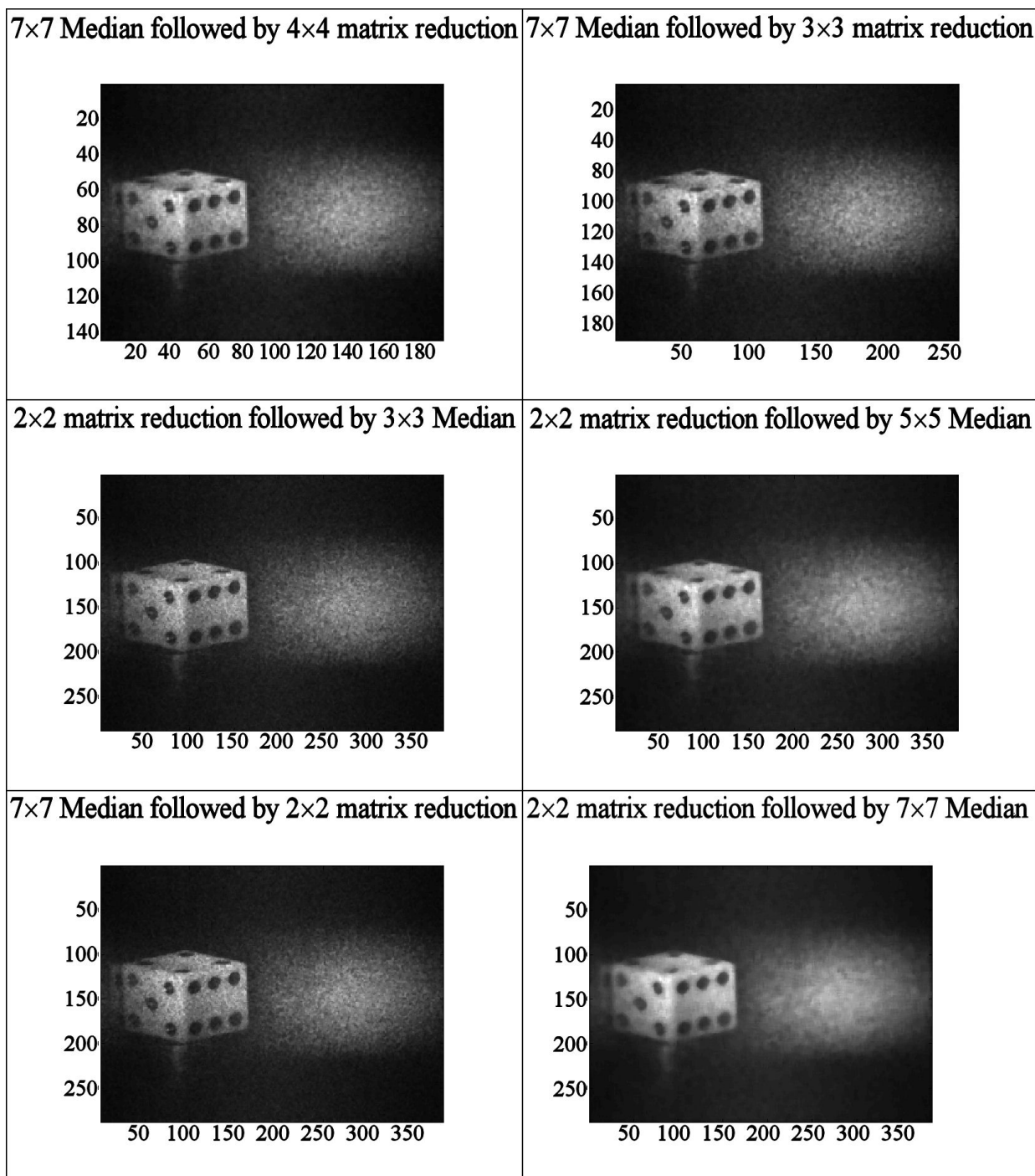


FIGURE 6. SNR increase by merged application of median filtering and matrix reduction of the original image shown in Fig.2.

tion, we applied this convolution filter to the image shown in Fig. 2. Here, we have considered the speckle noise similar to a binary or impulsive noise, so that it is possible to apply this type of filter to the reconstructed holograms and the results are shown in Fig 5.

Apparently, the best compromise between maintaining of spatial frequencies and reducing speckle noise reduction in our input image (Fig. 2) is achieved by means of 7×7 median filtering. For the others cases, either the speckle noise

is still so important or the blurring up of the image begins to be very noticeable. Considering that it is a digital image processing technique, it is very difficult to state which one is the best median filter order to be applied to digital holography. This decision must be made by the user; here we simply show the median filtering approach as a feasible method for reducing speckle noise in digital holography.

An attractive means of reducing speckle noise in digitally reconstructed holograms can be achieved by combining the

former approaches, *i.e.*, by applying the matrix reduction and the median filtering. In addition, simultaneously, by considering the non-linearity of the median filter, the sequence in which these two techniques are applied over the input image will also be important. The results of applying this compared approach to Fig. 2 are shown in Fig 6.

From the images shown above, it is possible to state that better results in speckle noise reduction are achieved by merging the two formerly treated techniques than by their independent application. It is also apparent from these images that the results obtained are strongly dependent on the application sequence, as it was expected. However, it is difficult to establish a fully proved recipe that guarantees success in the speckle noise reduction process, this task, in concordance with the ideas of digital image processing, is addressed by rules of thumb.

Albeit it is impossible to establishing a well defined recipe to reduce the speckle noise, it can be pointed out that it has been possible to carry out all the above procedures due to the digital manipulation of the holographic process. This situation shows the huge versatility that the digital component has added to the optical world and how it has propelled the field of the digital optics.

#### 4. Conclusion

The existence of the speckle noise is sizeable drawback in digital holography since it substantially reduces its SNR. This fact has made the digital holography impractical for its use in

many optical applications as for instance 3-D object recognition, microstructure testing, digital holographic microscopy, etc., because it reduces the performance system's. Then, with the idea of overcome this drawback and by taking advantage of the digital component of digital holography, in this work we have presented different digital processing techniques focused on the idea of reducing the speckle noise in digitally reconstructed holograms and consequently increasing the SNR.

All approaches shown in this work are based on the idea of doing digital image processing over reconstructed images with low SNR. It is apparent from the results that processed images with a greater SNR than the directly reconstructed, are obtained with the application of the procedures here proposed. However, alternative approximations to the problem for removing speckle noise (principal responsible of digital reconstructed holograms with low SNR) in digital holography must be addressed, but more oriented toward attempting to reduce the speckle noise from the digital recording and reconstruction process, for instance by modifying the coherence of illumination in the recording process and by using CCD cameras with more appropriate characteristics.

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