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# การถอดรหัสเชิงตัวเลขของอินไลน์ฮอโลแกรมเพื่อปรับปรุงคุณภาพของภาพที่ได้จากการบูรณะ

# Digital Decoding of In-Line Holograms for Improving Quality of Reconstructed Images


ผู้วิจัย

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ผู้วิจัยได้ทำการศึกษาคุณภาพของภาพซึ่งถูกสร้างกลับจาก อินไลน์ เฟรเนล ฮอโลแกรม ด้วยการกำจัดพื้นหลังโคฮีเรนท์ โดยคำนวณพื้นหลังจากค่าเฉลี่ยของความเข้มผลจากการจำลองสถานการณ์และการทดลองแสดงให้เห็นว่าการนำพื้นหลังออกจากฮอโลแกรมเชิงตัวเลขสามารถปรับปรุงคุณภาพของภาพสร้างกลับได้อย่างมีนัยสำคัญแม้ว่าจะยังคงมีภาพเสมือนอยู่

# Abstract

Quality of images reconstructed from in-line Fresnel holograms by eliminating the coherent background is quantitatively studied. The background is calculated by taking an average intensity of hologram. The simulation and the experimental results show that the background removal from digital holograms can improve significantly the quality of the reconstructed images, even though the virtual image is still intact.

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# Chapter 1
# Introduction

## 1.1 Background and Significance

One of useful methods for recording amplitude and phase of light wave is an in-line holography [1]. In the in-line holography, an interference pattern produced between light waves directly transmitted and diffracted from specimens being studied is recorded onto photosensitive media such as holographic film. After chemical development, a hologram of the objects is generated. In order to study the objects rigorously, the developed hologram is re-illuminated by the same laser light. The stationary image of the object is reconstructed at the same distance as the recording distance. However, since the resulting transmitted light carries both real and virtual images together with the direct beam on the same axis, an observer focusing on the real image always sees the reconstructed image is superimposed on the out-of-focus virtual image as well as a strong coherent background [2]. Note that the occurrence of the out-of-focus virtual image is known as the twin image problem. This unwanted image causes serious limitation of the in-line holography.

Although the twin-image problem can be optically solved by recording holograms with off-axis reference beam [3], the price paid for this method is that the optical setup becomes complicated. A unique situation exists in which in-line holograms can be used without inherent problems associated with the presence of the twin image. This situation arises when the objects to be studied are so small, so that the generated diffracted patterns can be considered to lie in the far field. For this reason, this method is known as the in-line Fraunhofer holography, while the conventional method is regarded as the in-line Fresnel holography. In the reconstruction of the in-line Fraunhofer hologram, at the real image plane, the virtual image appears to lie in a plane a long distance away. In this case, its optical field is spread over the whole image plane. Hence, it becomes weaker background. Since the successful generation of the Fraunhofer hologram of aerosol particles [4], studies of dynamic micro objects [5], aerosol [6], cloud droplets [7], oceanic particles [8], and bio-stabilized sediments [9] by using the in-line holography have been extensively reported.

On the other hand, the requirement that the particle field must lie in the far-field region can be regarded as a limitation of the in-line Fraunhofer holography [10]. Since the far field distanced is defined as the square of the object's maximum dimension divided by the illuminating wavelength, this requirement sets a recording distance of all objects must be at least one far-field long. As a consequence, the physical size of optical setup for implementing Fraunhofer holography becomes impractical. Thus, it is important to remove the far-field condition in recording the holograms.

With the advanced development of charge-coupled device (CCD) sensors, digital recording of holograms has been widely reported [11-14]. This has advantages over the conventional holography in that it is free from wet chemical development and no optical reconstruction is needed. In the digital holography, the stored information can be digitally retrieved by using either numerical reconstruction [11,12] or signal processing approach [13,14]. In the numerical reconstruction method, the amplitude and phase of the objects is obtained by solving a Fresnel diffraction integral of the digitized holograms at consecutive depth along the optical axis. When the real image of the objects is not of particular interest, the signal processing approach that employs wavelet transform can be used for extracting directly the spatial position and size of the objects from the holograms. Since this approach does not require the knowledge of the correct position of the in-focus plane, the processing time can be significantly reduced.

In the past decades, several methods for improving quality of the reconstructed images have been reported. Rogers suggested a hologram subtraction technique which employs two in-line holograms [15]. The unwanted background is subtracted from the field reconstructed from the first hologram by using the second one which is recorded at twice distance of the first one. Besides generating noise to the resultant image, this approach requires perfect collimation setup and high environmental stability because the holograms must be recorded at different distances. A digital filtering and phase retrieval methods, which employ either complicated algorithm or iterative process, have also been used for solving the twin image problem [16-19]. Zhang et al. reported a successful elimination of the unwanted information by using a phase-shifting digital holography [20], while Lai et al. improved the algorithm later on [21]. Although this technique is attractive, it has several drawbacks. One of the main disadvantages is that an environmental stability of the recording setup is crucial, owing to the requirement for recording four in-line holograms with different phase-shifted reference waves. The other disadvantage is that the recording setup becomes complicated because in order to perform phase modulation, the reference wave must be separated from the object wave before the interference process. Finally, a control system and the cost of a phase modulator may restrict extensive applications of the method to real-world applications such as soft x-ray microscopy [15,22].

During reconstruction, the image degradation is caused by the interference between the coherent background and the diverging wave from the virtual image. The quality of the reconstructed images can be improved, provided one of the waves is eliminated. This leads to a straightforward implementation that is the elimination of the coherent background, because its value can be numerically calculated by taking average intensity of the recorded holograms. The elimination is then done by subtracting the calculated average intensity from the hologram. However, this simple subtraction method keeps the virtual and the real images overlap. Since the image degradation is partially suppressed, study of image quality reconstructed by the coherent background elimination is important. The second reason for this interest is that the background elimination method is applicable to the classical in-line setup which is simpler than the phase-shifting holography, owing to no use of mirrors and beam splitters. In this research project, our study is performed through computer simulation and experiment with a peak signal-to-noise ratio (PSNR) is employed as quantitative measures of image quality. Note that in the digital off-axis holography, the coherent background elimination has been used for solving a problem of recording large object [23]. This is because the maximum angle formed between the reference and the object waves is determined by the resolution of the CCD sensors. For a hologram of a large object, its reconstructed image will be easily overlapped by the coherent background.

## 1.2 Objectives

1. To develop a method for improving quality of images reconstructed from in-line holograms by suppressing coherent background.
2. To study quantitatively quality of images reconstructed image from in-line holograms by suppressing coherent background.

## 1.3 Scope

In this study, 1-D or 2-D object is used as a test specimen. The in-line holograms of this object will be simulated and experimentally generated at different recording distances. In the experiment, the CCD sensor is used to capture the interference pattern of the holograms. The elimination of the coherent background will be digitally performed.

## 1.4 Expected Benefit

The result obtained from this research project can improve accuracy of measurements of small particles and of monitoring industrial emission, air pollution or raindrop.

# Chapter 2
# In-Line Holography

When a unit-amplitude plane wave with wavelength $\lambda$ illuminates a small object with an amplitude transmittance function $o(\xi, \eta)$, the field distribution at the plane a distance $z$ away is given by [5]

$$\psi(x,y) = [1 - o(x,y)] \otimes h_z(x,y), \tag{2.1}$$

where $\otimes$ denotes convolution operation, while $h_z(x,y)$ is the Fresnel diffraction kernel for given distance $z$ [24]

$$h_z(x,y) = \frac{1}{j\lambda z}\exp\left[\frac{j\pi}{\lambda z}\left(x^2 + y^2\right)\right]. \tag{2.2}$$

By recording this field distribution $\psi(x,y)$, the amplitude transmittance of the hologram is proportional to the intensity distribution

$$I(x,y) = 1 + \left|o(x,y) \otimes h_z(x,y)\right|^2 - o(x,y) \otimes h_z(x,y) + o^*(x,y) \otimes h_z^*(x,y) \tag{2.3}$$

with $^*$ denotes the complex conjugate. The first and the second terms of Eq. (2.3) represent thc directly transmitted light and intermodulation term. The third term corresponds to the virtual image, while the last term is of particular interest since it can be used to generate real image of the object.

In the optical reconstruction, the hologram is illuminated by the same collimated coherent light. When the reconstruction distance is exactly equal to the recording distance, the reconstructed field is

$$\psi(x,y) = 1 + \left|o(x,y) \otimes h_z(x,y)\right|^2 \otimes h_z(x,y) - o(x,y) \otimes h_{2z}(x,y) + o^*(x,y), \tag{2.4}$$

where the third term corresponds to the twin image and can be regarded as the field of the hologram of the same particle recorded at a distance $2z$, while the fourth term is the reconstructed image of the object. Due to a nature of a square law detector, the reconstructed image is proportional to the intensity $|o^*(x,y)|^2$.

The principal drawback that limits the application of the in-line holography is an undesirable defocused image together with the strong coherent background overlaid on the desired focused real image. This can be attributed to the lost of phase during the hologram recording. Therefore, in order to remove the Fraunhofer requirement for recording in-line holograms, the phase of the complex field distribution $\psi(x,y)$ must be determined by using phase retrieval algorithms [18,19]. However since the phase retrieval requires an iterative step, the drawback of this method is the considerable number of iteration and computation time is required.

In this project, an alternative method for improving quality of the reconstructed image will be investigated. This proposed method allows the in-line holograms to be recorded in the near-field region. The method is based on signal processing approach and can be digitally implemented. Rather than eliminating the twin image, the hologram is digitally modified by suppressing the undesired coherent background. According to Eq. (2.4), the strong coherent background corresponds to the first term can be digitally measured by taking an average intensity of the recorded holograms. After the background suppression, the image is reconstructed by convolving the resultant bipolar holograms with the Fresnel diffraction kernel $h_z(x,y)$.

# Chapter 3
# Materials and Methods

When the interference pattern between the wave field diffracted by the object with an amplitude transmittance $o(\xi,\eta)$ and the reference wave at a distance $z$ is recorded by using a CCD sensor, the resultant digitized hologram can be mathematically expressed as

$$I(k,l) = 1 + |o(k,l) \otimes h_z(k,l)|^2 - o(k,l) \otimes h_z(k,l) + o^*(k,l) \otimes h_z^*(k,l) \tag{3.1}$$

where $h_z(k,l)$ is the discrete impulse response of a free-space propagation To remove the coherent background, the average intensity of the hologram is determined by computing

$$I_{av} = \frac{1}{M \times N} \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} I(k,l), \tag{3.2}$$

where $M$ and $N$ are the number of pixels in the $x$ and the $y$ directions of the digital holograms, respectively. By subtracting this average intensity from the hologram $I(k,l)$, the coherent background of the hologram is eliminated as

$$\begin{aligned} I'(k,l) &= I(k,l) - I_{av}(k,l) \\ &= |o(k,l) \otimes h_z(k,l)|^2 - o(k,l) \otimes h_z(k,l) + o^*(k,l) \otimes h_z^*(k,l) \end{aligned} \tag{3.3}$$

To do numerical reconstruction, Eq. (3.3) is digitally convolved with the impulse response $h_z(k,l)$. As a result instead of intensity, the numerical computation gives the complex amplitude of the wave field $o^*(x,y)$ of the real image object. Finally, the quality of the reconstructed images are quantitatively measured by computing a PSNR defined as [25]

$$PSNR = 10\log_{10}\left\{ \frac{255^2}{\frac{1}{M \times N} \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} [o(k,l) - o'(k,l)]^2} \right\}, \tag{3.4}$$

where $o(k,l)$ and $o'(k,l)$ are the original and the reconstructed images, respectively. When the image reconstruction has a high fidelity, the PSNR gives a high value. In order to verify rigorously this method, the image quality of the background elimination method is compared with those of the phase-shifting holography.

### 3.1 Computer Simulations

In order to study quality of the reconstructed images, the in-line Fresnel hologram of line objects having a diameter of 125 μm and different transmittances was simulated under an illumination of a coherent light operating at a wavelength of 632.8 nm. The size of a gray-level image file of the objects used to generate the hologram was 640 × 480 pixels. In this work, all convolution operations were performed by using a Fourier transform property that is the inverse Fourier transform of a product of spectra of two functions is equivalent to their convolution in the space domain.

### 3.2 Experimental Verifications

The feasibility of the coherent background elimination method was experimentally verified by generating optically the in-line holograms of an optical fiber with a diameter 124.96 μm. The collimated coherent beam was generated from a HeNe laser with a wavelength of 543.5 nm. The holograms were captured by using a CCD sensor Hamamatsu C5948 with a resolution of 640 × 480 pixels in an area of 8.3 × 6.3 mm. For synthesis of the phase-shifted holograms, a Mach-Zehnder interferometer setup was employed. The phase shift of the reference wave was introduced by a mirror mounted on a computer-controlled piezoelectric translator.

# Chapter 4
# Results and Discussions

## 4.1 Simulation Results

Figures 1(a) and (b) show the hologram $I(k,l)$ simulated at the recording distance $z = 21$ cm and its 1-D amplitude transmittance, respectively. The hologram consists of the vertical interference fringes. Besides the dc background signal, the transmittance consists of a chirp signal which is modulated by a sinc function. The frequency of the chirp signal is inversely proportional to the recording distance, while the sinc function corresponds to the diffraction of the line object. Figures 1(c) and (d) show the modified hologram $I'(k,l)$ and its 1-D amplitude transmittance [26]. It is obvious that the dc signal reduces to approximately zero.

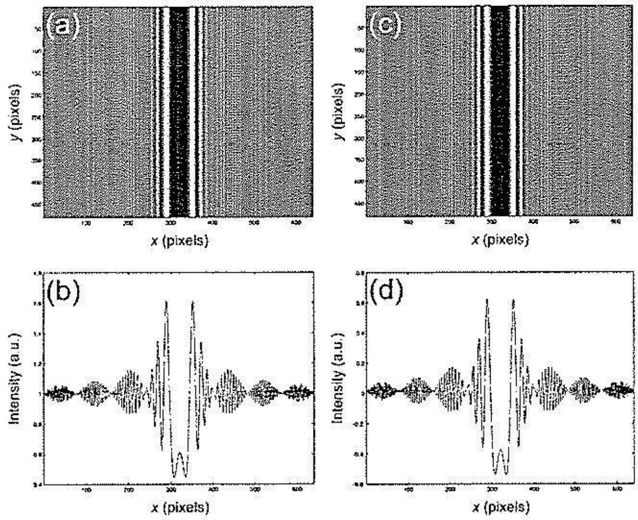


Figure 4.1 (a) In-line holograms of a line object and (b) its amplitude transmittance. (c) The background eliminated hologram and (d) its 1-D amplitude transmittance.

The image and its 1-D intensity distribution reconstructed by using the conventional method from the corresponding hologram of Fig. 4.1 are shown in Figs. 4.2(a) and (b), respectively. The real image of the line object which appears at the center of the figure is overlapped by the unwanted interference pattern. Note that the contrast of the image is reversed in order to compare with the original object distribution. Figures 4.2(c) and (d) are the results obtained by the phase-shifting method, while the results by the background elimination are shown in Figs. 4.2(e) and (f). In comparison with the phase shifting method which can eliminate totally the unwanted pattern, the elimination of the coherent background prevents the occurrence of the pattern. In the present of the virtual image which appears as the two side lobes in Fig. 4.2(f), the reconstructed image of the line object can be clearly distinguished. This is because the diffracted wave from the virtual image becomes a broad pattern with small amplitude.

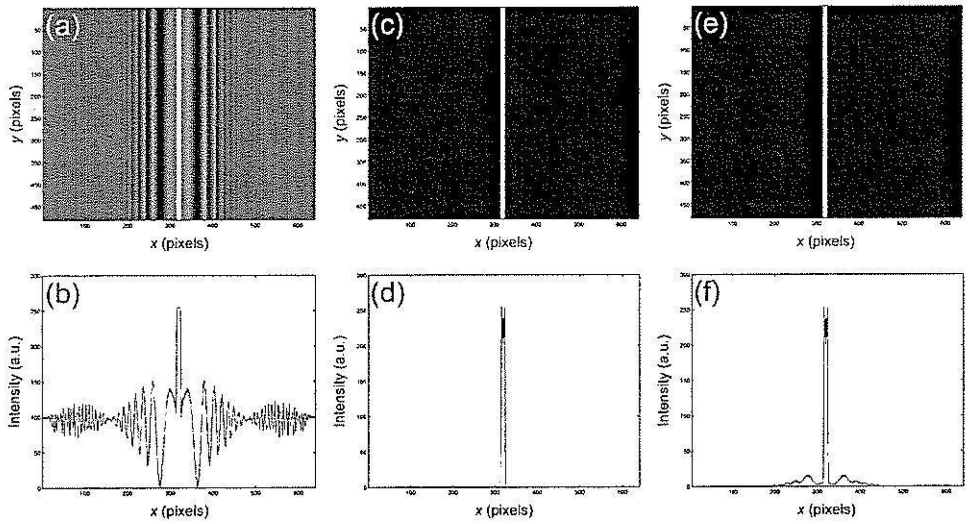


Figure 4.2 The image and its intensity profile reconstructed from the corresponding hologram by using the conventional method (a) and (b), respectively. (c) The reconstructed image by using the phase shifting method and (d) its intensity profile. (e) The reconstructed image by using the background elimination method and (f) its intensity profile.

After the image reconstruction, the image quality was quantitatively measured by using the PSNR given by Eq. (3.4). Figure 4.3 shows the PSNRs of the reconstructed images as a function of the recording distance $z$ for different object transmittance [27]. The circle, the square and the triangle symbols represent the numerical reconstructions accomplished by using the coherent background elimination, the phase shifting and the conventional methods, respectively. The solid and the dot lines correspond to the semi-transparent object with transmittance 0.9 and the opaque object, respectively. Regardless of the reconstruction methods, it can be seen from the figure that, first the PSNRs of the real image of the semi-transparent object is about two times higher than those of the opaque object. This is mainly caused by its edge ringing has smaller amplitude than the opaque object does. As a result, the degree of similarity to the original object image is higher. Second, when the recording distance is lower than 9 cm, the holograms are under sampled. As a spatial aliasing occurs during the reconstruction, the PSNRs decrease. By comparison, the conventional method gives the lowest image quality. Furthermore, owing to the unwanted interference background, when the object is semi transparent the PSNR of the images reconstructed by using the coherent background elimination and the phase shifting methods are almost the same. In the case of the opaque object, the PSNR of the background elimination method is slightly lower than that of the phase shifting method, due to significant distortion by the second term of Eq. (2.4).

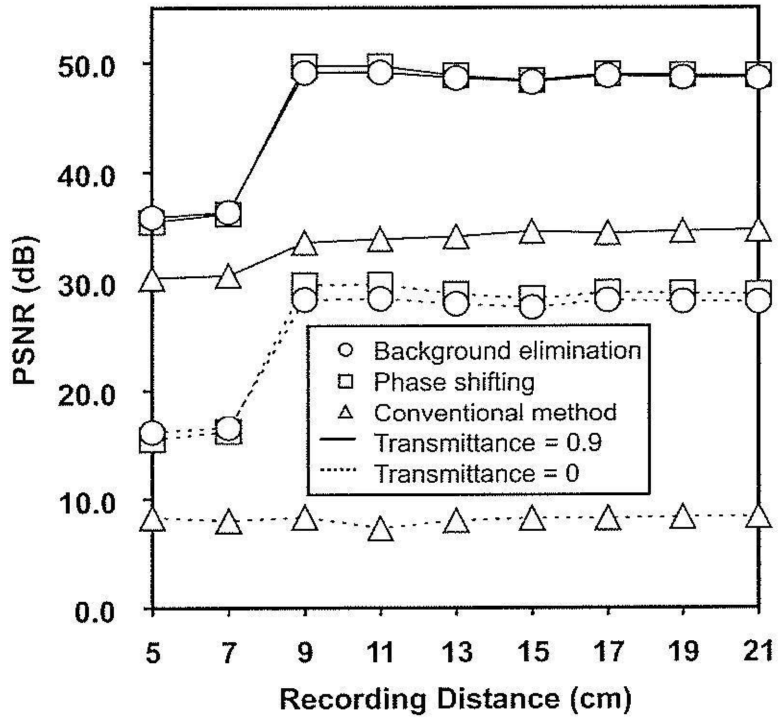


Figure 4.3 The PSNR of images reconstructed from the holograms of line object for different transmittance as a function of the recording distance $z$.

## 4.2 Experimental Results

Figures 4.4(a) and (b) show the hologram recorded at the recording distance $z = 11$ cm and its cross-sectional scan, respectively. The reconstructed image and its 1-D intensity profile obtained by the conventional method are depicted in Figs. 4.4(c) and (d). It is obvious that the object image is heavily degraded by the unwanted signals. Figures 4.4(e) and (f) are the results obtained by the phase shifting method, while the ones by the background elimination method are shown in Figs. 4.4(g) and (h). Since the hologram is corrupted by speckle noise, the reconstructed image appears to be noisy as well. The phase shifting method can improve significantly the reconstructed image. Almost all of the unwanted signals are removed, except two side lobes next to the object signal. This may be caused by instability of the recording environment and a non-liner movement of the transducer produced a phase-shift error. In comparison with the phase shifting method, the elimination of the coherent background can produce comparable results in that the object signal can be resolved and the unwanted signals are reduced.

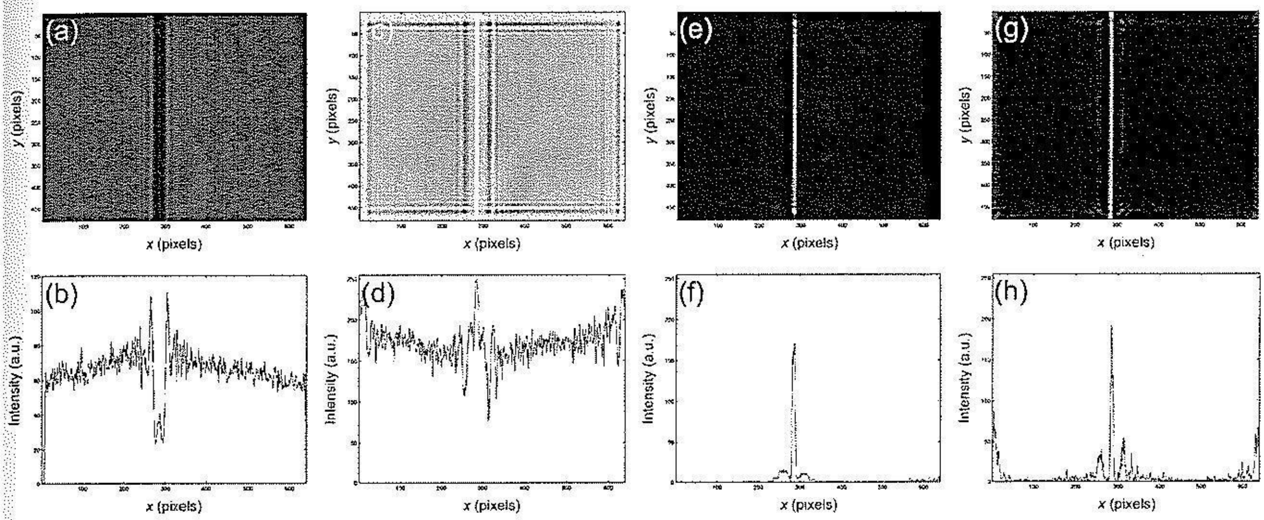


Figure 4.4 (a) The in-line holograms of an optical fiber recorded at the recording distance z = 11 cm and (b) its 1-D transmittance. (c) The reconstructed image by using the conventional method and (d) its intensity profile. (e) The reconstructed image by using the phase shifting method and (f) its intensity profile. (g) The reconstructed image by using the background elimination method and (h) its intensity profile.

Figure 4.5 shows the PSNRs of the reconstructed images of the fiber as a function of the recording distance $z$. In calculating PSNR, the reconstructed images produced by the three methods were saved as gray-scale image files. They were compared to an ideal image of a line object with the same dimension. Owing to the speckle noise in the generated holograms, PSNRs of the three methods are generally lower than those of the resultant reconstructions shown in Fig. 4.3. The PSNR of the conventional method gives the lowest value, whereas the phase shifting method is the highest that is about 23 dB. On the other hand, the background elimination method has greater PSNR compared with the conventional reconstruction. Its average value is merely 2 dB smaller than that of the phase shifting method. Therefore, despite its simple setup and the presence of the virtual image, this experimental result verifies the advantage of the background elimination method for improving the quality of the reconstructed image over the other methods.

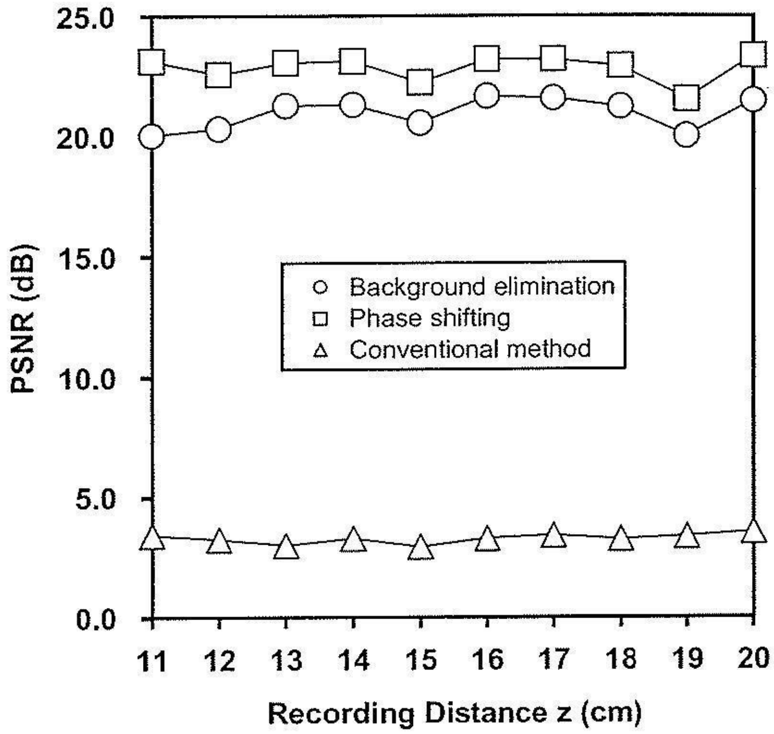


Figure 4.5 The PSNR of images reconstructed from the holograms of the optical fiber as a function of the recording distance $z$.

# Chapter 5

# Conclusions

We have studied quantitatively quality of images reconstructed from the in-line Fresnel holograms by eliminating the coherent background. The simulation and the experimental results show that the background removal can improve significantly the quality of the reconstructed images, even though the virtual image is still intact. For the semi-transparent object, the quality of the images reconstructed by using the proposed method is high as the ones obtained by the phase shifting method. This method has several advantages over the others in that first, it is simple and is not iterative. Second, it is low cost because it can be applied to in-line holograms produced by the classical recording setup without the use additional mirrors, beam splitters, or phase modulators. Finally, since only single hologram is used in the reconstruction, the requirement for the environmental stability is relaxed. For these reasons, this method is useful for soft x-ray microscopy.

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