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รายงานการวิจัย

การศึกษาการบันทึกแบบดิจิตอลของออปติคอลซิกแนล: ตอนที่2 ใช้คอมเพรสโฮโลแกรม

Study of Digital Recording of Optical Signals:

Part II. Compressed Hologram

ได้รับทุนอุดหนุนการวิจัยจาก
มหาวิทยาลัยเทคโนโลยีสุรนารี

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Study of Digital Recording of Optical Signals: Part II. Compressed Hologram

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ผลงานวิจัยเป็นความรับผิดชอบของหัวหน้าโครงการวิจัยแต่เพียงผู้เดียว

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บทคัดย่อ

เพื่อที่จะแก้ปัญหาเรื่องการจัดเก็บข้อมูล และเป็นการปรับปรุงการตอบสนองทางเวลาของมาตรวิทยาทางฮอโลกราฟฟี จึงได้ทำการศึกษาการบีบอัด อิน-ไลน์ ฮอโลแกรมเชิงตัวเลขด้วยอัลกอริทึมแบบ lossy-JPEG โดยทำการศึกษาความคลาดเคลื่อนของการวัดระยะบันทึกฮอโลแกรม และภาพสร้างกลับของมัน ซึ่งได้จาก อิน-ไลน์ ฮอโลแกรมที่ถูกบีบอัดด้วยระดับการบีบอัดต่างๆ ข้อมูลที่ต้องการสามารถหาได้จากวิธีการสร้างกลับโดยใช้แอมพลิจูดเชิงซ้อน ผลที่ได้แสดงให้เห็นว่า ฮอโลแกรมสามารถถูกบีบอัดให้เล็กลงประมาณ 90 เท่า โดยไม่ทำให้เกิดการสูญเสียข้อมูลอย่างเด่นชัด

Abstract

In order to solve storage problem and improve time response of holographic metrology, compression of digital in-line holograms by using lossy-JPEG algorithm is studied. Error of measurement of recording distance and its corresponding reconstructed image obtained from compressed in-line holograms are quantitatively studied for given compression levels. Desired information is retrieved by using complex amplitude based numerical reconstruction method. The results show that the hologram could be compressed by about 90 times smaller without causing significant degradation.

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CHAPTER 1

INTRODUCTION

1.1 Background and Significance

In the past decades, applications of in-line holography to the study of dynamic micro-objects [1], fog and cloud droplets [2,3], aerosol [4], oceanic particles [5] have been reported. The technique provides a useful method for storing information, size and relative position, of a three-dimensional (3-D) distribution of objects in holographic plate. In in-line particle holography, opaque or semi-transparent particles are illuminated by a collimated coherent light. By recording an interference pattern produced between light waves diffracted from the particles and the light wave transmitted directly onto photosensitive media such as holographic film, a hologram of the particle is generated. In order to study the objects rigorously, the developed hologram is re-illuminated by the same coherent light. The stationary image of the object is reconstructed at the same distance as the recording distance. Since, in general, this distance is not known in advance, the image plane of best focus for each object must be investigated by scanning the overall depth along an optical axis with fine steps. Since the conventional reconstruction process is very tedious and time consuming, computer-based algorithm can be employed to perform automatic analysis and measurement.

Recently, with technological advancement of charge-coupled device (CCD) image sensors, it is now possible to record holograms by the CCD and extract its information digitally by using either numerical reconstruction [6-8] or signal processing approach [9,10]. This digital approach has advantages over the conventional holography in that it is free from wet chemical development and no optical reconstruction is needed. In the case of the numerical reconstruction method, the amplitude and the phase of particles can be obtained by solving the Fresnel diffraction integral of the digitized holograms at consecutive depth along the optical axis. From the numerical standpoint, the diffraction integral can be solved either by convolving the digitized holograms with the Fresnel diffraction kernel or by taking a discrete Fresnel transform.

In order to perform faithful reconstruction, the interference fringe spacing must be resolved in the recording by the CCD sensor. This leads to the use of the CCD sensor with mega pixel resolution. As a consequence, the recorded digital hologram requires considerable storage capacity, because the resultant file size may exceed several megabytes. Furthermore in real-world situations, we may have to deal with optical testing in which a huge number of in-line digital holograms may have to be transferred from remote locations and/or hostile environment. This requires an interface system with high bandwidth and data transfer rate. To solve these problems, we envision a use of a lossy image compression such as a joint-photographic experts group (JPEG) [11] to reduce the file size of the digital holograms. The reason behind this is based on our previous study of compression of digital specklegrams which reveals that the specklegrams can be compressed into the JPEG format by manifolds without distorting significantly displacement information [12]. However, although the JPEG compression algorithm offers a practical solution for the storage problem and its format is widely supported by the CCD sensors and digital cameras, the compression achieved by discarding permanently image details.

Since the JPEG algorithm degrades the quality of the image being compressed, it is important to study quantitatively the effects of compression on information retrieved from the compressed in-line holograms. Our focus is on the resultant measurement of the recording distance and the reconstruction of the image by using the numerical method.

1.2 Objective:

1. To study quantitatively effects of compression on digital specklegrams
2. To determine the smallest compression that can be done without causing significant degradation of information content

1.3 Scope

In order to study the effects of compression on the desired information, the in-line holograms of an optical fiber with a radius *a* of 62.48μm were generated at the recording distance *z* of 9 and 34cm by using a laser light operating at a wavelength of 543.5nm. The optical fiber was oriented along the vertical direction and its interference pattern was captured by the Hamamatsu C5948 CCD camera with the resolution of 640 × 480 pixels in the area of 8.3 × 6.3 mm. The recorded holograms were saved in TIFF file format with the pixel depth of 24 bits. The size of each digital hologram was about 904 Kbytes. The compression of the digital specklegrams is done by using a lossy-JPEG algorithm, because it produces a higher compression ratio than the lossless compression. Error of measurement of recording distance and its corresponding reconstructed image obtained from compressed in-line holograms are quantitatively studied for given compression levels.

1.4 Expected Benefit

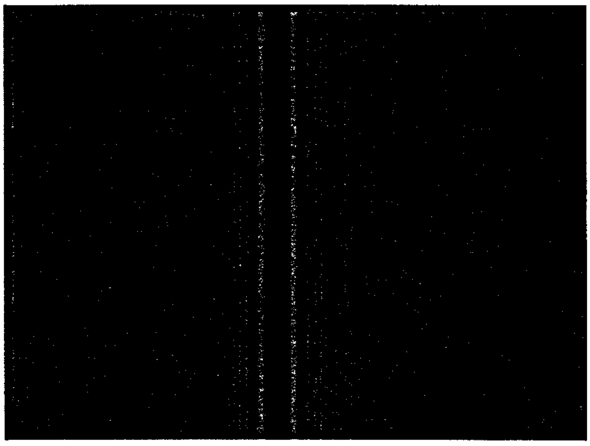
The result obtained from this research project will significantly reduce practical and technical problems of application of holographic metrology in industries.

Chapter 2

Method

Figures 2.1(a) and (b) show the in-line holograms of the optical fiber recorded at the distances z of 9cm and 34cm, respectively. The transmittance function of these holograms can be expressed as [1]

(a)



(b)

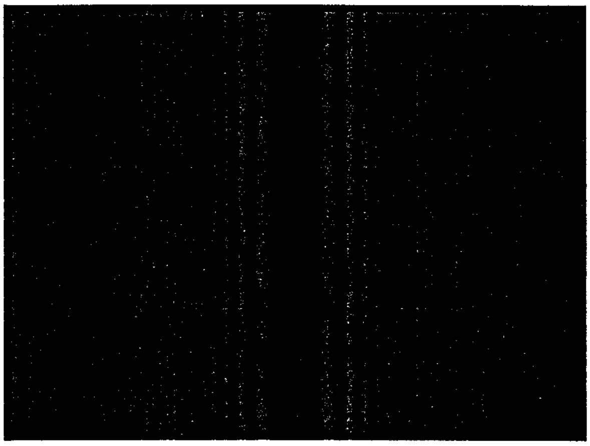


Fig. 2.1 In-line holograms of optical fiber recorded at distance (a) 9cm and (b) 34cm.

$$I(x) = 1 - \frac{4a}{\sqrt{\lambda z}} \cos\left(\frac{\pi x^2}{\lambda z} - \frac{\pi}{4} \right) \left[\frac{\sin\left(\frac{2\pi a x}{\lambda z} \right)}{\frac{2\pi a x}{\lambda z}} \right]^2 , \qquad (1)$$

which consists of a modulation of a chirp signal by a sinc function. In Eq. (1), the frequency of the chirp signal is equal to $x/\lambda z$, while the zero-crossing positions of the sinc function are determined by a factor $\lambda z/2a$. In comparison with Fig. 1(b), the hologram recorded at a short distance consists of the sinc function with a narrower spatial size and a rapid decrease of the fringe spacing. When the spatial position x increases, the spatial frequency of the chirp signal will eventually become higher than the sampling frequency of the CCD sensor. As the fringe spacing becomes finer, the fringes at the higher-order side lobes are under-sampled, aliasing error occurs in which the higher frequencies of the chirp signal are detected as lower frequencies [13]. As a consequence, the fringe shown in Fig. 2.1(a) is significant only around the main lobe of the sinc function, whereas at the higher-order side lobes they are hard to be observed. In contrast, it is obvious that the amplitude variation of the fringes up to the first-order of the side lobe can be observed from Fig. 2.1(b). Therefore, this implies that the hologram recorded at the distance z = 34 cm contains more high spatial- frequency components.

The in-line holograms were then compressed into the JPEG file format by using ACDsee software version 3.1 in which the compression quality is determined by a parameter called the quality factor (QF) whose value can be varied from 100 to 0. High value of the QF discards less information than that of the small value. Thus, the higher the value of the QF, the better the image quality and the bigger the file size of the compressed image. Figure 2.2 shows the compression ratio (CR) and the bit rate (BR) as a function of the QF of the holograms, respectively. The CR is defined as the ratio of the uncompressed file size to the compressed file size, while the BR is the average number of compressed bits/pixel [11]. By decreasing the QF, the average number of bits used to represent each pixel shown by the BR becomes lower. As a consequence, the value of the CR becomes higher.

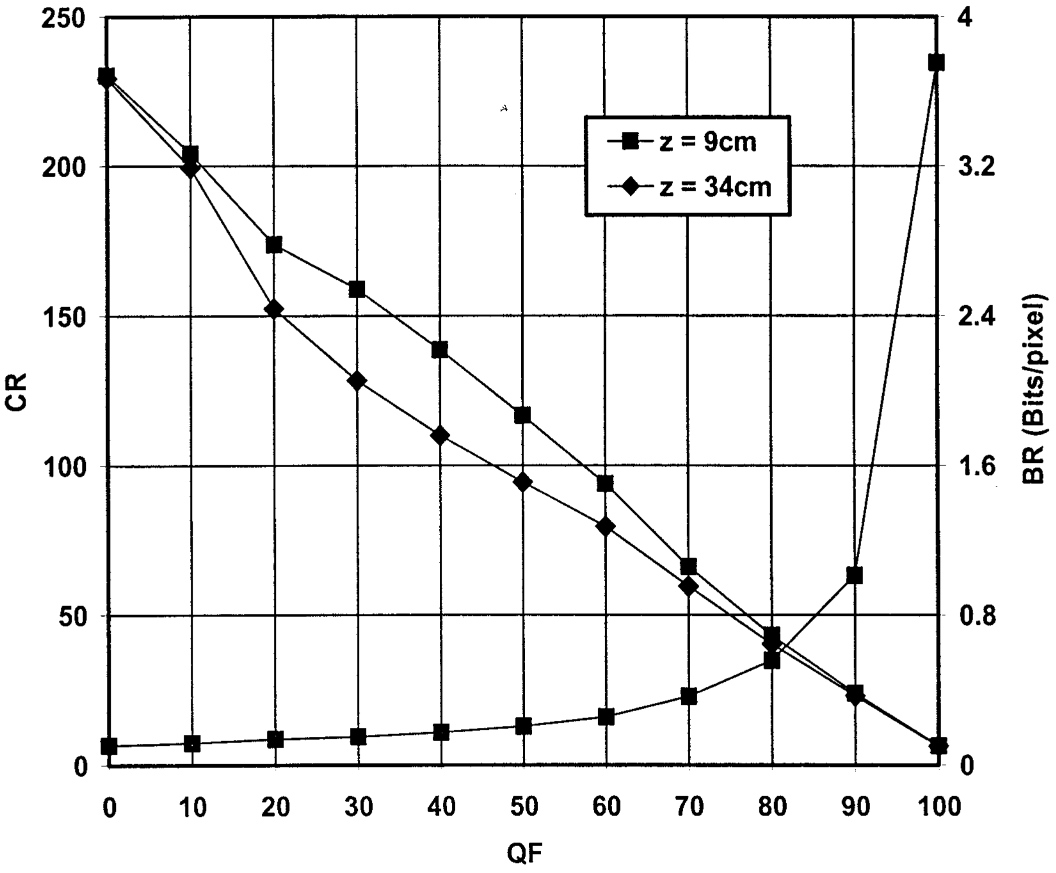


Fig. 2.2 CR and BR of the compressed in-line holograms as a function QF.

It is clear from Fig. 2.2 that the CR of the hologram recorded at the distance $z = 9$cm is higher than that of the hologram recorded at 34cm. This is due to the fact that the hologram recorded at a shorter distance contains less high spatial-frequency components. The quantization process done on the hologram recorded at a shorter distance yields more zeroes of the AC components of the spatial frequency. As a consequence, the run length coding and the Huffman coding can encode efficiently the redundant zeroes.

In this work, the lowest QF produced the compressed file of 4 Kbytes, while the highest QF gave about 141 Kbytes. The compressed holograms corresponding to Fig. 2.1(a) and (b) with the QF = 50 are shown in Figs. 2.3(a) and (b), respectively. It is obvious that it is hard to observe the effect of compression.

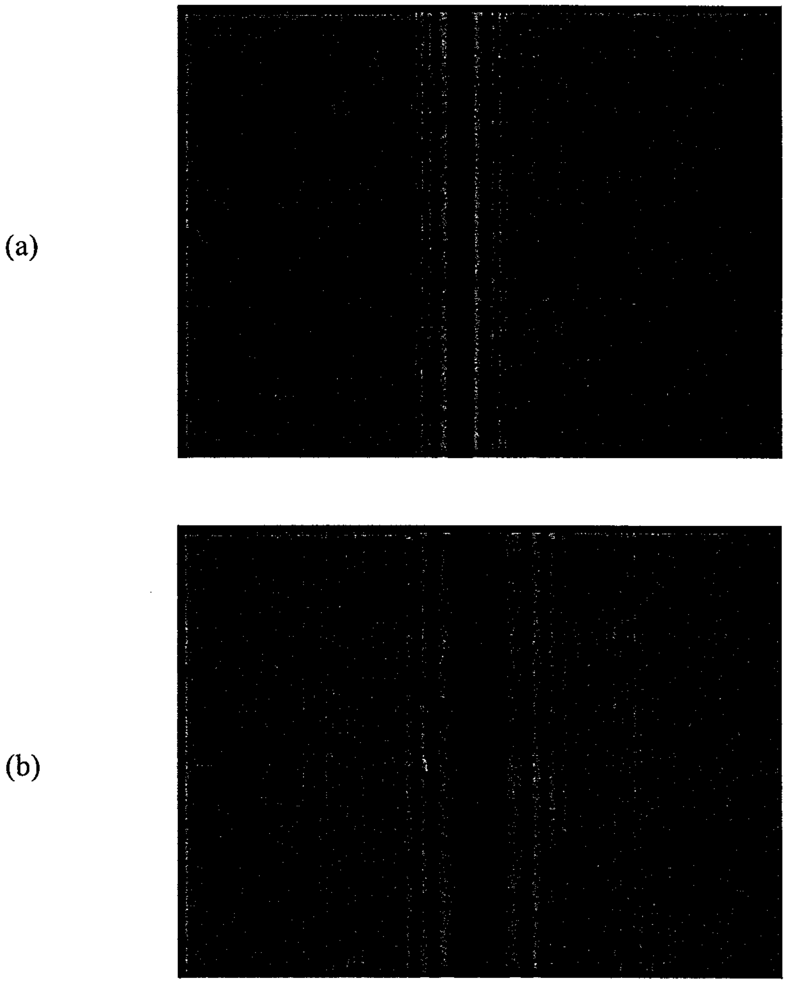


Fig. 2.3 Compressed holograms recorded at distance (a) 9cm and (b) 34cm with QF = 50.

Chapter 3

Analysis

The compressed holograms were numerically reconstructed by convolving their transmittance function with the Fresnel diffraction kernel $h_z(x,y)$. All computations were conducted by using the Matlab 6.1. In order to find the correct recording distance, the variance of the imaginary part of the complex amplitude $\phi(x,y)$ is investigated at consecutive depth z along the optical axis. When the variance is minimum, the reconstruction distance z employed in the Fresnel diffraction kernel $h_z(x,y)$ is exactly the same as the recording distance. In fact, this approach is equivalent to searching the in-focus image plane of particles reconstructed from the hologram.

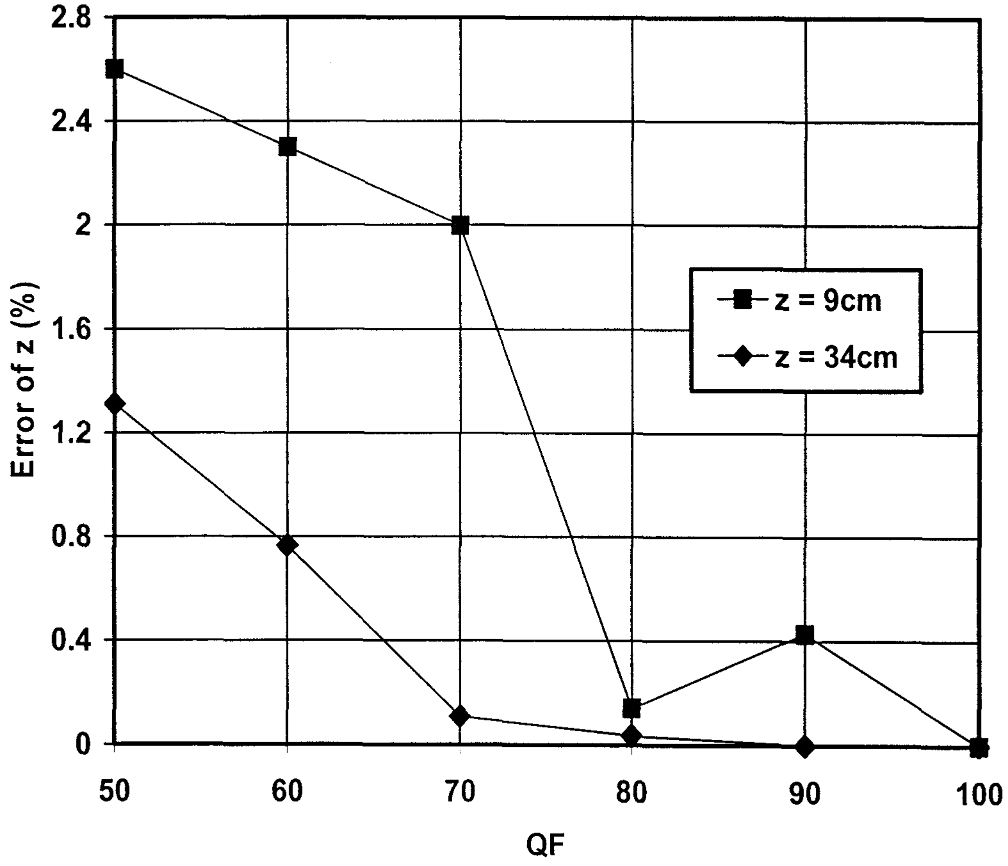
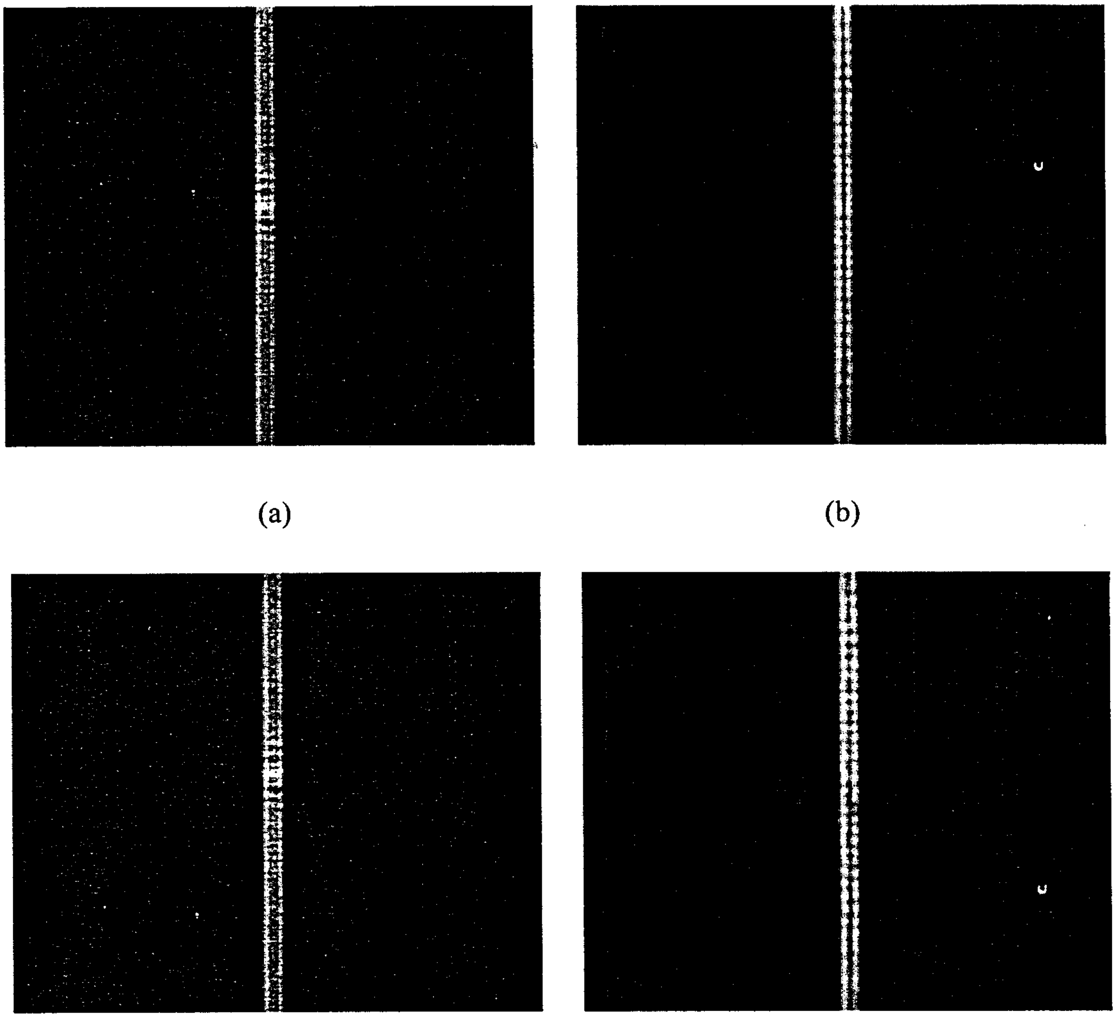


Fig. 3.1 Error of measurement of recording distance z as a function of QF for compressed holograms with different recording distance.


(a) (b)

(c) (d)

Fig. 3.2 Reconstructed images from the original holograms with recording distance (a) 9cm and (b) 34cm, and from compressed holograms with $Q = 50$ recorded at (c) 9cm and (d) 34cm.

The error of measurement of the recording distance from the compressed holograms was calculated by comparing its measured distance with the resultant value obtained from the corresponding original hologram. Figure 3.1 shows the error of measurement of the distance z as a function of the QF for the holograms recorded at two different distances. In general, the error of measurement of the recording distance increases as the QF decreases, because more image information is discarded from the compressed holograms. However in the case of the compressed hologram recorded at the distance z = 9cm, the error and its rate of change are higher than that of the holograms recorded at 34cm. As discussed before, the hologram recorded at shorter distance can be efficiently compressed than the holograms recorded at longer distance. This implies that for the same value of the QF, more fine detail of the fringes is discarded from the hologram recorded at shorter distance. Since the degradation of the fringes is more significant, the error of measurement of the recording distance increases.

Figures 3.2(a) and (b) illustrates the images of the fiber reconstructed from the original holograms recorded at the distance z = 9cm and 34cm, respectively. Whereas the reconstructed images from the corresponding compressed holograms with the QF = 50 are illustrated in Figs. 3.2(c) and (d). In comparison with Fig. 3.2(a), the reconstructed image from the original holograms recorded at the distance z = 34cm shows better quality. This may be caused by the aliasing error occurred in the hologram recorded at the short distance. Although the file size of the compressed holograms has been reduced by about 90 times with its BR of about 0.2 bits/pixel, the numerical reconstruction can produce the image of the optical fiber with the quality as high as the reconstructed images of the original holograms. It can be observed that the image degradations occurred for the holograms recorded at the short distance is higher than that of the longer distance, however they are also not severe.

In order to quantify the effect of compression, the mean square error (MSE) defined as [14]

$$MSE = \frac{1}{M \times N} \sum_{m=1}^{M} \sum_{n=1}^{N} [f(m,n) - f'(m,n)]^2 \qquad (2)$$

was computed for each reconstructed image from the compressed holograms. Here $f(m,n)$ and $f'(m,n)$ stand for the original and its compressed image files, respectively. The MSE which has been widely used for objective image evaluation measures the difference between the original and the compressed versions. A large MSE means that the degree of difference between the original image and its compressed versions is high. Figure 3.3 shows the variation of the MSE as a function of the QF for the compressed holograms recorded at two different distances. It is clear that the MSE and its rate of change are small for the compressed hologram recorded at the distance z = 34cm than that of the shorter distance of 9cm. Thus the image of the optical fiber can be faithfully reconstructed from the compressed hologram recorded at longer distance. This is in a good agreement with the error of measurement of the recording distance shown in Fig. 3.1 in that the higher the error of measurement, the larger the MSE. This is caused by the reconstruction process which used the measured distance z. When the error of the measured distance was high, the image could not be correctly reconstructed.

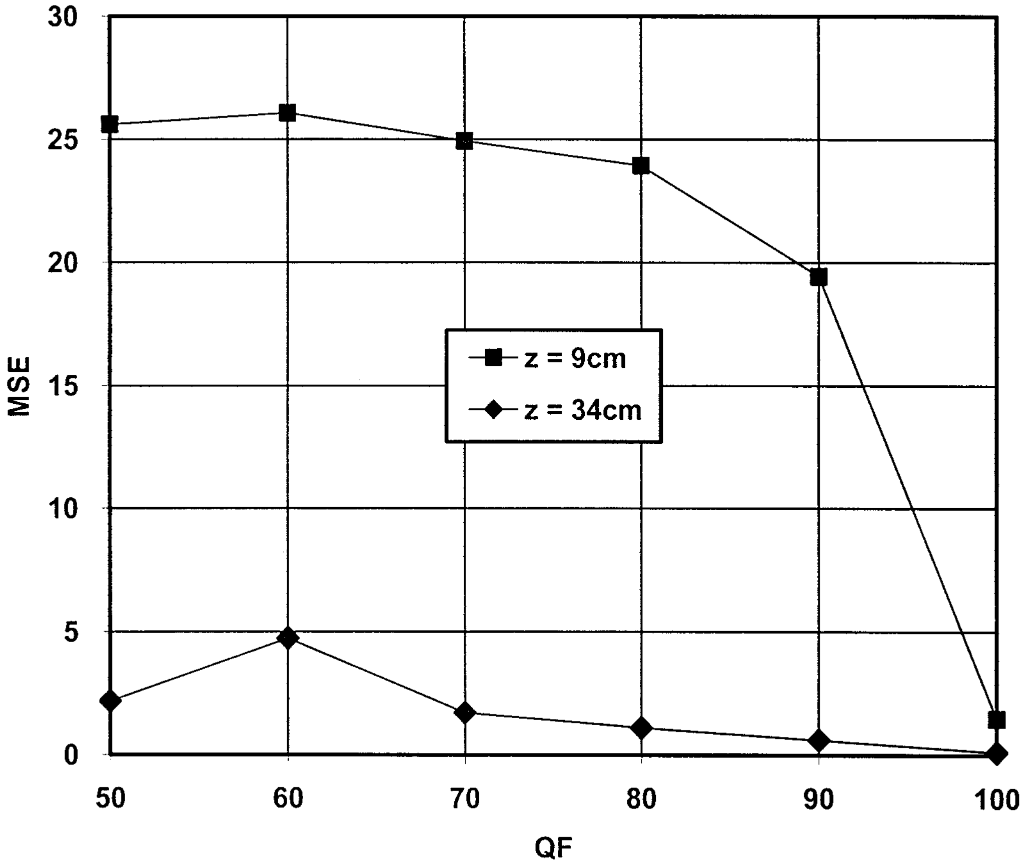


Fig. 3.3 MSE as a function of QF for compressed holograms with different distance z.

In summary, the error of measurement of the recording distance and the MSE of the reconstructed image are higher for the compressed holograms recorded at the shorter distance than that of the longer distance. This is caused by the fact that the interference pattern at short distance contains narrow fringe spacing. Since the resolution of the CCD sensor is limited, the digital holograms are under sampled. Aliasing error occurs. Therefore, the effect of compression on the retrieved information is more significant for holograms recorded at the shorter distance than that of the longer distance.

Chapter 4

CONCLUSIONS

Quality of information retrieved from the JPEG-compressed in-line holograms has been objectively evaluated. The results show that the error of measurement of recording distance is as small as 1% and the image of the fiber can be faithfully reconstructed from the compressed in-line holograms even the file size of the compressed holograms has been reduced by about 90 times with its BR of about 0.2 bits/pixel. This can be achieved provided the resolution of the CCD sensor is enough to sample the interference fringes so that the aliasing error does not occur. Therefore, high JPEG compression can be employed for solving storage and data transfer problems.

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