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# White Light Digital Speckle Photography for Measuring Rigid Body Motion

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**Abstract** This paper presents a method for measuring rigid body motion by white light digital speckle photography. Instead of using laser beam to generate the Young's fringe pattern from a specklegram as conventional speckle photography, a digital Fourier transformation is employed yield the Young's fringe pattern from which rigid body motion can be computed by a new FFT phase shift method. Moreover, a new technique for improving the quality of the Young's fringe pattern is given. Theory together with experiment is demonstrated.
**Key words** white light digital speckle photography, rigid body motion, fringe patterm enhacement.

## 1. Introduction

Speckle photographic method has been widely used to measure deformation, displacement and shape of an object[1~2]。Its essential procedure includes speckle registrating, specklegram developing, and Young's fringe generating and analyzing. However, in conventional speckle photography, the above process involves film plate, chemicals and the interpretation of deformation, displacement and shape from the Young's fringe pattern is time consuming. With the development of computer and image processing board, several automated methods have been developed such as speckle correlation[3~4], automatically acquiring and deducing laser beam generated Young's fringe pattern[1~2], and computer aided speckle interferometry[5~8]. Computer aided speckle interferometry uses a video camera and computer image processing system to record speckle patterns before and after deformation to form a double exposure speckle pattern and to generate Young's fringe pattern by FFT. Since for nonconstant displacement, the whole speckle pattern must segmented into a series of small subimages, the Young's fringe patterns generated from these small subimages are relatively low quality. However, computer aided speckle photography is ready to obtain a relatively high quality Young's fringe pattern for rigid body motion. This paper presents a method which can generate high quality Young's fringe pattern by digital Fourier transformation without using laser beam from a computer procuced double exposure specklegram and the Young's fringe pattern can be automatically deducted by a new FFT phase shift method to measure rigig body motion[9]. The new FFT phase shift method can cancel the influence of the diffraction halo to the computed result. Moreover, a new technique for enhancing Young's fringe pattern is described.

## 2. Theory

Without lossing generity, we consider one demension problem and assume $I_1(x)$ and $I_1(x+d)$ as the intensity distributions of speckle patterns before and after a constant displacement $d$ . The two speckle patterns, which are digitized via a video camera into a computer image processing system and superimposed to form a double exposure specklegram, can be expressed as

$$I(x) = I_1(x) + I_1(x+d) \tag{1}$$

After applying digital Fourier transformation to Eq. (1), we obtain

$$I(u) = F[I(x)] = \int_{-\infty}^{\infty} [I_1(x) + I_1(x+d)]\exp(-i2\pi xu)dx = I_1(u) + I_1(u)\exp(i2\pi ud) \tag{2}$$

The intensity of Eq. (2) then is

$$\begin{aligned} I^2(u) &= [I_1(u) + I_1(u)\exp(i2\pi ud)][I_1(u) + I_1(u)\exp(i2\pi ud)]^* \\ &= 2I_1^2(u) + I_1^2(u)\exp(i2\pi ud) + I_1^2(u)\exp(-i2\pi ud) \end{aligned} \tag{3}$$

$$I^2(u) = 2I_1^2(u) + 2I_1^2(u)\cos 2\pi ud \tag{4}$$

where $I_1^2(u)$ is a both noise and halo term. Eq. (4) represents a Young's frings pattern. Before any quantitative analysis of the Young's fringe pattern, the noise term need to remove. Applying digital Fourier transformation to Eq. (3), we have

$$F = A + B + B^* \tag{5}$$

in which $A$, $B$ and $B^*$ are the Fourier spectra of $2I_1^2(u)$, $I_1^2(u)\exp(i2\pi ud)$ and $I_1^2(u)\exp(-i2\pi ud)$. Term $B$ includes

$$B = F[I_1^2(u)] * F[\exp(i2\pi ud)] = I_1^2(x) * \delta(x-d) \tag{6}$$

where $*$ denotes convolution. A digital filter can be easily designed to let $\delta$ function pass and filter out the noise term in $I_1^2(x)$ . Eq. (6) becomers

$$b = h * \delta(x-d) \tag{7}$$

where $h$ represents approximately the halo. The inverse digital Fourier transformation is applied to Eq. (7), we obtain two pure Young's fringe patterns without speckles with one from imagenary part and the other real part as follows

$$I_i = H\sin(2\pi ud) \tag{8}$$

$$I_r = H\cos(2\pi ud) \tag{9}$$

Thus, the phase distribution and hence the displacement can be calculated by

$$2\pi ud = \arctan\frac{I_i}{I_r} = \arctan\frac{\sin(2\pi ud)}{\cos(2\pi ud)} \tag{10}$$

$$d = \frac{1}{2\pi u}\arctan\frac{I_i}{I_r} \tag{11}$$

We see that the halo is canceled.

## 3. Enhancement of Young's Fringe

There are two major factors which affect the quality of Young's fringe pattern. One is the diffraction halo and the other is speckles. The halo can be canceled during the phase calculation as mentioned in previous section. The intensity of a Young's fringe pattern can be expressed as

$$I = B\cos^2 x \tag{12}$$

in which $B$ is a speckle term with high frequency compared with the cosine term. The Young's fringe pattern is that a low frequency term, which represents the fringes, is modulated by a high frequency term, the speckle noise. The dark fringes have no speckles since the low frequency term is zero at these fringes' locations. However, the bright fringes have many dark speckles. If the number of bright speckles is increased, the quality of Young's fringe pattern will be improved. Eq. (12) can be simulated as

$$I_s = \cos^2 Ax\cos^2 x \tag{13}$$

In usual, a fringe has more than 6 speckles, which is the case chosen for simulation in the following and Eq. (13) becomes

$$I_{s6} = \cos^2 6x\cos^2 x \tag{14}$$

For enhancement of the Young's fringe represented by Eq. (14), a new equation is formed as

$$I_s = \cos^2\left[\frac{\pi}{2}k\cos^2 6x\cos^2 x + \frac{\pi}{2}\right],\ k \geqslant 1 \tag{15}$$

For comparison, Fig. 1 shows the curve of Eq. (14), (b) illustrates the curve for $k = 1$ of Eq. (15), and (c) demonstrates the curve for $k = 1.5$ of Eq. (15). We see that the contrast of the curve in (b) is increased. Both the number of bright speckles and contrast in (c) are increased and thus the quality of the Young's fringe pattern. For real process, the formula is

$$I_{sr} = \cos^2\left[k\frac{\pi}{2B}I + \frac{\pi}{2}\right] \tag{16}$$

where $I$ is the real Young's fringe pattern in Eq. (12). Fig. 2 show the experimental results in which the upper left is an original Young's fringe pattern, the upper right stands for $k = 1$, the lower left represents $k = 2$, and the lower right depicts $k = 3$

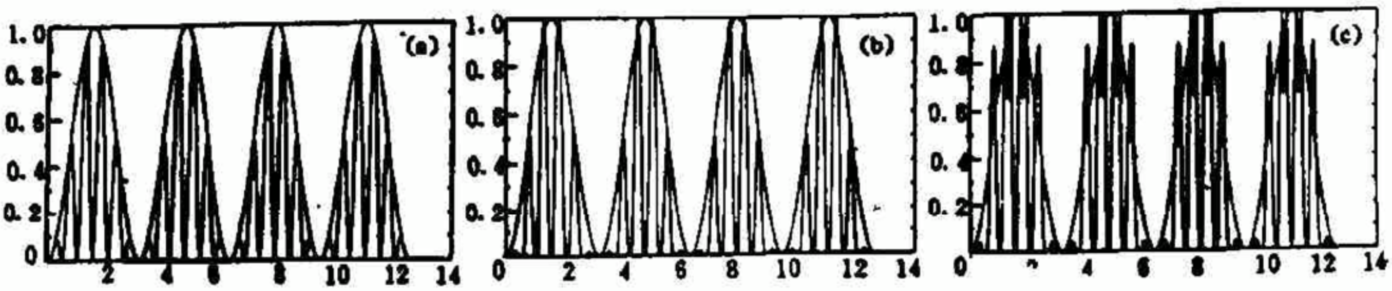


Fig. 1 Computer simulated results of Eq. (15), (a) is original of Eq. (14), (b) for $k = 1$, and (c) for $k = 1.5$

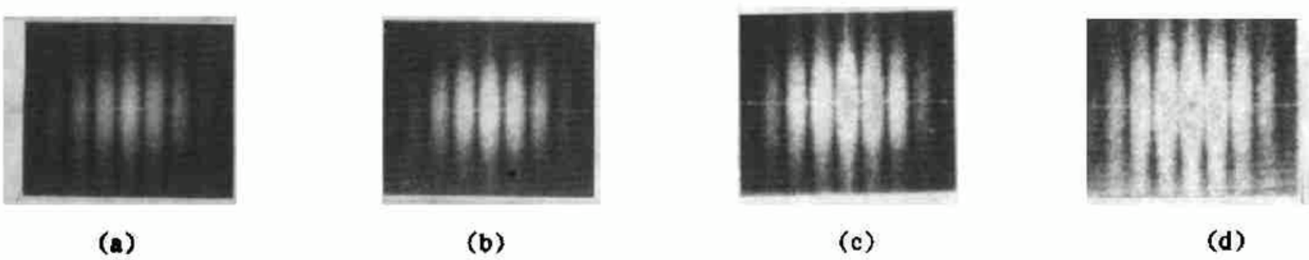


Fig. 2 Example of enhancement of Yong's fringe by Eq. (16), the Fig. (a) is original, the Fig. (b) represents $k = 1$, the Fig. (c) for $k = 2$, and the Fig. (d) for $k = 3$

## 4. Experimental Demonstration

The optical setup of this experiment is shown in Fig. 3. A rectangular plate is illuminated with a white light beam and imaged via a video camera connected with a image processing computer system. Two speckle patterns are digitized and stored in the computer before and after rigid body motion. The speckle patterns are superimposed to form a specklegram in the computer. Digital Fourier transformation is applied to the specklegram to generate Young's fringe pattern as illustrated in Fig. 4. Applying Eq. (16) to Fig. 4 gives a improved Young's fringe pattern as shown in Fig. 5. The digital Fourier transformation is again applied to the Young's fringe pattern as shown in Fig. 5 to obtain the spectra as shown in Fig. 6. Choose the one first order of diffraction and perform inverse digital Fourier transformation, we obtain the imagenary and real parts as shown in Fig7(a) and (b). With the fringe patterns in Fig. 7, we can calculate the phase distribution of the Young's fringe pattern as demonstrated in Fig. 8. From the phase map in Fig. (8), four Young's fringe patterns with 90 degree sequential phase shift can be reconstructed as shown in Fig. 9. Finally, the rigid body motion can be calculated from Eq. 11.

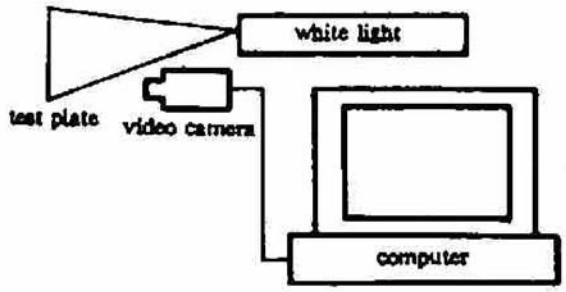


Fig. 3 The optical setup of white light digital speckle photography

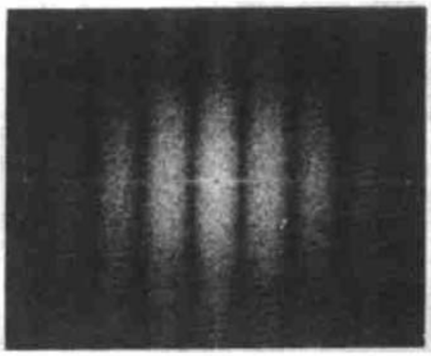

Fig. 4 The computer generated Young's fringe

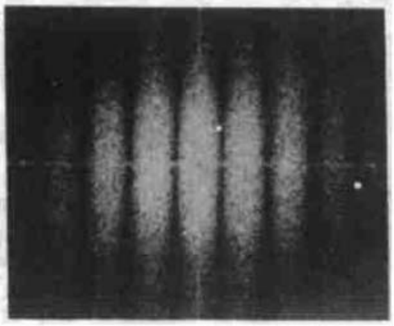

Fig. 5 The enhancement computer generated Youung's fringe

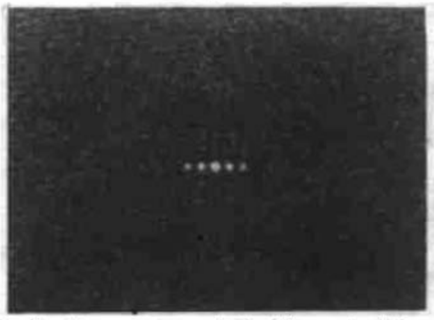

Fig. 6 The fourier spectra of the Young's fringe in Fig. 5

Fig. 7 The cosine and sine fringe patterns generated from the spectra in Fig. 6

## 5. Conclusion and Discussion

A white light digital speckle photographic procedure for measuring rigid body motion has been developed. The Fourier transformation is applied to the whole double exposure speckle pattern to generate relatively high quality Young's fringe pattern. A new enhancement technique is employed to further improve the Young's fringe pattern. The phase of the Young's fringe pattern is automatically

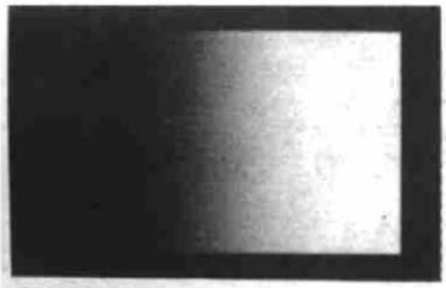

Fig. 8 The unwrapped phase map calculated from frings patterns in Fig. 7

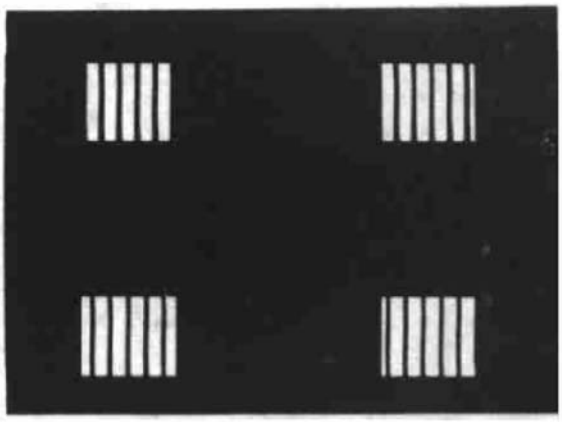

Fig. 9 The four Young's fringe patterns with 90 degress sequential phase shift reconstructed from the phase map in Fig. 8

deducted by a new FFT phase shift technique which can deliver high quality result and cancel the influence of diffraction halo. The white light is used to illuminate the test object. Thus, it has high potentical to become a pratical means in product environments to measure rigid body motion or velocity if a high speed camera is used.

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# 测量物体位移的数字白光散斑照相术

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**摘　要**　给出了一个测量物体刚体位移的数字白光散斑照相术。数字傅里叶变换从双曝光数字白光散斑图用来产生杨氏条纹。该杨氏条纹能够用数字傅里叶变换结合条纹重构进行自动分析。此外，给出一种条纹质量增强的方法。

**关键词**　数字白光散斑照相术，　刚体位移，　条纹增强。

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