

A Phase Shifting Shadow Moiré Method Using Two Frame Images of Varying Light

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Abstract—In order to measure the surface of object's 3D contour, we proposed a phase shifting shadow moiré technique based on varying light position. The method can remove the mechanical motion in the process of measurement, and sample the fringe pattern of phase shifting quickly. However, when we sample the sequence of phase shifting with the method of varying light, because of the light position changed, the background and amplitude of fringe pattern will be modulated, so the classical method of phase shifting can't be used for picking up measurement phase, so as to solve this problem, A new shadow moiré method based on the spiral phase transform (SPT) is proposed in the process of demodulating phase, this method need to use two frame images of varying light position, and calculate phase shifting in sequence, estimate the height of measurement, finally, a new iterative algorithm of adaptation is designed to pick up measurement phase. The experimental results show the effective of this method.

Keywords-Component; Measurement; Two Frames Tuning Phase Shift; Shadow Moiré; Spiral Phase Transform; Iterative Algorithm

I. INTRODUCTION

The structure of shadow moiré technology is simple , and its price is cheap .it is suitable for measurement in industry. For example, we can develop a portable measurement machine with shadow moiré technology to detect flatness of CNC workbench. However, in order to realize this measurement device, we need to improve the structure and demodulation of traditional shadow moiré for meeting the demand of collecting data skimpily and demodulation accuracy higher. Usually , the method of phase shifting can be used to demodulate measurement phase of shadow moiré view .But this method is sensitive to the mistake of phase shifting, and the error will be introduced to measurement system of phase shifting shadow moiré which is elaborated in reference[1] .In order to improve the accuracy of phase shifting shadow moiré we proposed a method of iteration phase shifting based on least

squares ,which can reduce the measurement error coming from the unevenness of phase shifting ,and extend the apply area of phase shifting shadow moiré However, this method will produce mechanical movement with phase shifting, and limit the measurement speed. The technology of phase shifting with varying light position can solve this problem. this method can remove the process of phase shifting with using different light source, but because the position of the light is different, it will make the background and amplitude of fringe pattern to modulate ,and can't promise the formula of light intensity to have a constant background and amplitude , namely ,the method of varying light shadow moiré can't meet the standard phase shifting algorithm's demand, which ask the formula of light intensity in fringe pattern to have a constant background and amplitudes. So, the classic phase shifting algorithm can't search the right measurement phase, and the more frames used, the more error will be produced.

2001, a method of shadow moiré based on Fourier transform is used to measure D contour, it introduces carrier frequency into shadow moiré measurement with tilted grating, and use Fourier to rebuild D surface profile only by one fringe pattern. However, the method can't complete D measurement automatically and it is effetely easily by natural spectrum aliasing of Fourier transform.

In order to estimate the orthogonal signal of fringe pattern exactly, 2001, a method of spiral phase transform (SPT) is proposed, it can gain orthogonal signal of fringe pattern easily. But the method needs to estimate the direction of fringe pattern while using it.2011, Vargas proposed a new method to estimate the direction of fringe pattern based on regularization Optical flow algorithm, which supply a new road for SPT applying. However, Due to use two frame fringe patterns, it is sensitive for noisy, and need to improve measurement accuracy, others, the method is affected by the Fourier transform above, and can't remove the background light of fringe pattern effectively. So how to apply it in actual measurement need to research further. We propose a phase shifting shadow moiré technique using two frame images

based on two-dimensional empirical mode decomposition, because the background amplitude of varying light source shadow moiré technique can't use classic phase shifting algorithm.

This method introduce phase shifting into measuring filed quickly by varying light position, and regularized the fringe pattern with two dimensional empirical mode decomposition, then estimate the measurement phase with two frame phase shifting algorithm, Finally, we proposed a iterated algorithm to correct measurement phase. Simulation and experiment can prove the method effective.

II. FUNDAMENTAL PRINCIPLES

A. Varying light shadow moiré technology

An experimental structure of the varying light shadow moiré is shown as Figure 1. It contains three parts, (1) two lights which have random distance (2) one CCD camera. (3) Roach grating on the measurement surface, which is expressed by $z(x, y)$. In Figure 1, the light 1 and light 2 irradiate grating surface one by one, and we can camera two interference patterns about phase shifting shadow moiré whose intensity distribution can be described as [2, 4]

$$I_k(x, y) = A_k(x, y) + B_k(x, y) \cos[\varphi_k(x, y)] \quad k = 0, 1 \quad (1)$$

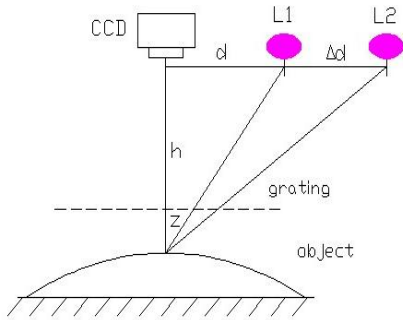


Figure 1. Block diagram of shadow moiré

In the formula above, $A_k(x, y)$ is background, $B_k(x, y)$ is modulation term, $\varphi_k(x, y)$ and is measurement phase. If the optical centre of camera and the centre of two light sources are on the surface in same height as grating, then the phase $\varphi_k(x, y)$ is shown as,

$$\varphi_k(x, y) = \frac{z\pi d_k z(x, y)}{p(h+z)} \quad (2)$$

As formula shown, p is grating space, h is the distance between light and grating surface, d_k is the horizontal space between CCD and the Kth light.

So, the phase shifting introduced into the shadow moiré view by varying the light position can be described as follows:

$$\sigma(x, y) = \frac{2\pi\Delta d z(x, y)}{p(h+z(x, y))} \quad (3)$$

In this formula, Δd means light space. It is Obviously, phase shifting is unknown and can't be estimated directly, Furthermore, because we alter the position of light when introduced phase shifting with the method above, the same pixel of fringe pattern sequence have a variable background and amplitude. so the classic phase shifting technology is false in varying light source shadow moiré and it can't used to measure phase demodulating directly

B. Fringe pattern regularization

Traditional phase shifting technology can demodulate phase using fringe pattern with more frames. And it isn't sensitive to noisy because of homogenization. But the method of the frame phase shifting need to take denoise into account, so as to ensure demodulation reliability while measuring phase.

Recently, the reference 10 proposed a method about fast bi-dimensional empirical mode decomposition, it can decompose fringe pattern into different mode component, and the first mode component is the part of high frequency in fringe pattern, namely, noise, the residual amount is the background of fringe pattern. So, after the fringe pattern is decomposed by empirical mode, remove the first mode component and residual amount, then rebuild fringe pattern, it will be regularized.

C. Estimate the phase pattern

We can get a result form the process of fringe pattern regularization above

$$I_k = b_k \cos \varphi_k \quad k = 0, 1 \quad (4)$$

In order to describe clearly, we will remove spatial coordinates (x, y) in the process of derivation, and can obtain quadrature signal with applying SPT in formula (4) as follows.

$$\tilde{I}_k = b_k \sin(\varphi_k) = -i \exp(-i\eta) SPT\{\tilde{I}_k(x, y)\} \quad (5)$$

In the formula (5), η is directional diagram of fringe pattern, it is can be estimate like as reference [7]. And the phase shifting can be solved by the formula (6), in which the phase shifting is introduced into the shadow moiré measurement view by varying the light

$$\delta(x, y) = a \tan\left(\frac{\tilde{I}_0 \tilde{I}_1 - \tilde{I}_0 \tilde{I}_1}{\tilde{I}_0 \tilde{I}_1 + \tilde{I}_0 \tilde{I}_1}\right) \quad (6)$$

Then we can obtain the phase diagram use two frame algorithm

$$\varphi = \arctan\left[\cot(\delta) - \frac{\tilde{I}_1}{\sin(\delta) * \tilde{I}_0}\right] \quad (7)$$

Finally, we can estimate the height of measurement by formula (8),

$$\tilde{z} = \frac{p h \phi}{2\pi d - p \phi} \quad (8)$$

D. Iteration and update

Obviously, when we use SPT in the process of picking up phase, the harmonic error will be introduced. In order to improve measurement accuracy, we proposed an iterative algorithm of adaptation for phase shifting, and regard height \tilde{z} as initial value, so the phase shift can be updated by the formula(9).

$$\delta(x, y) = \frac{2\pi \Delta d z(x, y)}{p(h + z(x, y))} \quad (9)$$

Put the updated phase shifting into formula [7], we can gain a new height, and this procedure can be repeated until the height is convergence in a preestablished accuracy range. And the convergence rule can be described as formula (10).

$$\max(|z^q - z^{q-1}|) < \varepsilon \quad (10)$$

In this formula, q —iteration times

ε —Accuracy preestablished

When the convergence conditions are satisfied, we can get the exact solution of measurement height.

III. NUMERICAL SIMULATIONS

In fact, the accuracy of object surface is difficult to get, this paper use the computer to simulate the surface tested in order to proving the method above is right. the height of simulation surface can be described as formula, $z(x, y) = xy \exp(-x^2 - y^2) mm$, and the parameter of measurement system in simulation are $p = 0.05 mm$, $d = 100 mm$, $\Delta d = 1 mm$, the formula of light intensity for fringe pattern is $I'_i = \cos(\phi + i\delta)$, in which, $0 \leq x \leq 2.25, 0 \leq y \leq 2.25$. the total pixel of x and y direction in image is 256 .so changing i value can get a series of phase shifting interference pattern simulated. Figure 2(a) is simulation surface, Figure 2(b) is simulation interference pattern.

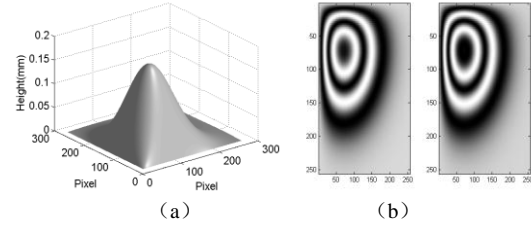


Figure 2. Simulation data: (a)simulation surface; (b) simulation interference pattern

In order to prove the method is accurate, we define the error function is $e(x, y) = abs(z(x, y) - h(x, y))$, in which $h(x, y)$ is the height of demodulation, $abs()$ is absolute value function. In Figure3, it is a result of demodulation which is iterated eight times with Vargas' method and Iterative algorithm we proposed Respectively .and the result indicate the proposed method can reduce error effectively

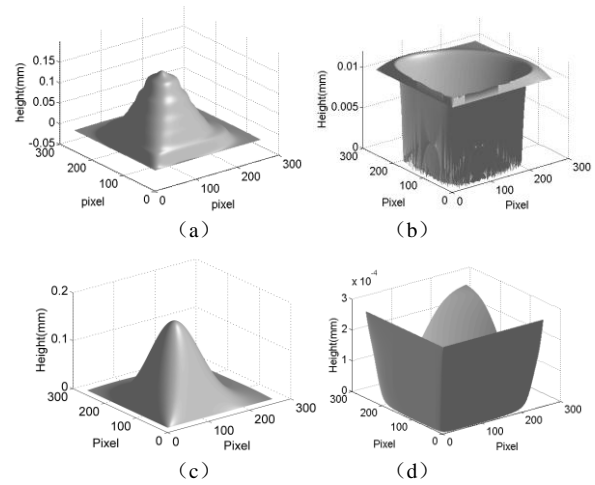


Figure 3. Simulation results: (a) the reconstructed surface by Vargas' method; (b) the residual error by Vargas' method; (c) the reconstructed surface by the proposed method; (d)the residual error by the proposed method;

In Figure.4, It shows a relationship between the STD errors of the proposed method and the iterations. And it indicate that we need iterated ten times to convergence by the proposed method

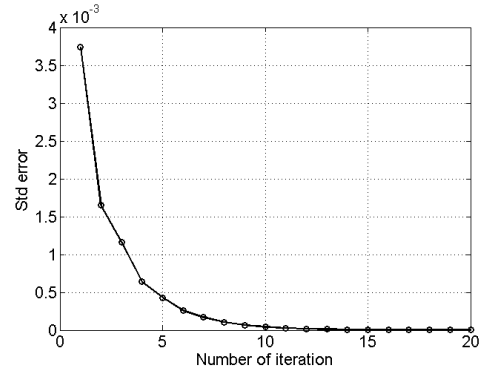


Figure 4. The STD errors of the proposed method vs. iterations.

IV. EXPERIMENTAL RESULTS

In order to prove it is right of the proposed method, we measure the object surface with the experimental structure above actually .the experimental parameter are define as: $p = 0.05mm$, $d = 100mm$, $h = 160mm$, $\Delta d = 2mm$. the experimental object is a little smooth spherical surface. we can control the light is on and off ordinal, and get fringe pattern of two frame phase shifting with camera, as we known, the fringe pattern have much noisy in actually, in order to improve signal - to - noise ratio (SNR) of fringe pattern, before demodulation of height ,we filter the fringe pattern with the method of reference [11] proposed ,and get two new fringe pattern, like as Figure 5

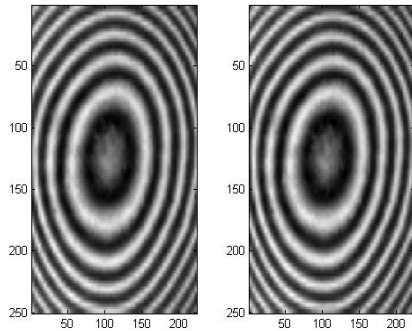


Figure 5. Measurement fringe pattern

In order to prove the performance of the proposed method, we measure the sample with the method of reference [11] proposed. And the measurement result is shown in Figure 6.

Compared the proposed method with regularization to Varga's, the latter is affected by noisy seriously more than the former. in summary ,the proposed method- A phase shifting shadow moiré method using two frame images of varying light ,Provide a new method to measure D surface profile quickly in the field of moderate accuracy

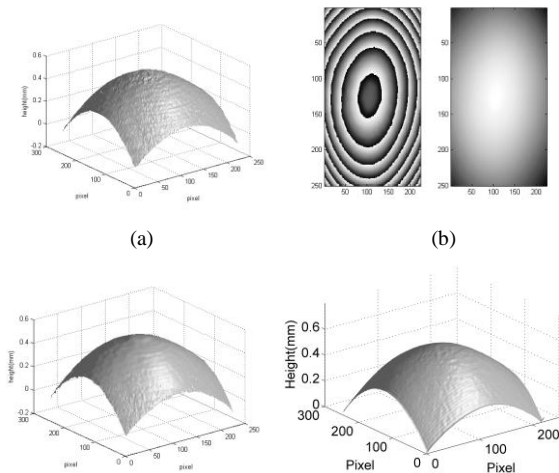


Figure 6. The measurement result : (a)the reconstructed surface by Vargas' method; (b)wrapped phase and unwrapped phase; (c)the proposed method; (d)the references[11] 's method.

In order to quantized prove the performance of the proposed method, we refer to the result using the method of references [11-13], and calculated error of measurement result with proposed method by formula (11)

$$e = abs(h_1 - h_2) \tag{11}$$

In which, h_1 is the height distribution of tested surface with the method of reference [11]. h_2 is the height distribution of tested surface with proposed method. And the result is shown as Figure [7].it proves that the error is less than $30 \times 10^{-3} mm$ with the proposed method. Due to the shadow moiré measurement system have more error sources, such as the error of measurement equipment parameter, non sinusoidal distribution of light field. And so on. In order to improve the accuracy of measurement we need to research the proposed method further more.

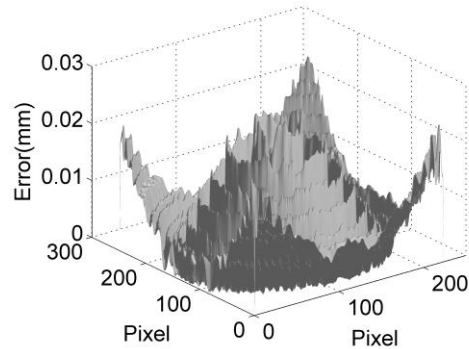


Figure 7. Residual errors of the proposed method

V. CONCLUSION

The paper proposed a phase shifting shadow moiré method using two frame images of varying light .this method use two dimensional empirical mode decomposition to regularized the fringe pattern ,and introduce phase shifting into measurement view by using the fringe pattern to calculate the position of varying light source, then, use two frames phase shifting technology to estimate the measurement height .due to the harmonic error in SPT, we proposed a iteration technology to improve the measurement accuracy .Because it is lack of mechanical motion, the process of measurement is quickly and satisfied with the rapid measurement. Finally, the method is proved to be right with experiment and the experiment result yet prove the proposed method can measure quickly.

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