DUAL-WAVELENGTH SIMULTANEOUS PHASE SHIFTING INTERFEROMETRY (SPSI) FOR ONE-SHOT MEASUREMENT

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Abstract:
In the article, a new two-frequency simultaneous phase shifting interferometric measurement method is developed for one-shot nano-scale microscopic surface profilometry with a measurable depth range up to tenth of micrometers. Limitations of measurement using phase shifting interferometry are a short measurement range due to the long coherence light source employed and undesired sensitivity to external environmental vibration. The developed method proposes a dual-frequency simultaneous phase shifting interferometric (SPSI) method in resolving the potential phase ambiguity encountered in two-step phase unwrapping. In the developed method, three phase-shifted interferograms are captured at one shot, so vibration effect and errors from the mechanical translation device can be minimized. To overcome the phase ambiguity problem, dual laser sources are employed to provide essential information in the two-step phase unwrapping process. It is worth noting that it implements two steps phase shifting with 0° and 180° phase shift and cosine phase wrapping. The proposed method is verified using an artificial interferograms that resembles the interferogram from a step height with 0.25 um height. The simulated result indicates that the method is feasible for achieving the expected measurement capability.

Keywords: Dual wavelength, Phase shifting interferometry, One-shot measurement, Automatic optical inspection (AOI)

1. INTRODUCTION
Phase-shifting interferometry (PSI) has become a useful tool for nano-meter measurement area for almost 30 years. The traditional PSI system like the Michelson interferometer usually has two prolong problems to be resolved, such as environmental vibration and phase ambiguity. Conventional PSI measurement needs at least three different phase-shifted images for object phase identification. Under this circumstance, unexpected environmental vibration easily affects the different phase shifted interferograms with a time-varying phase amount and can induce unacceptable measurement errors. To deal with this, Creath and Schmit [1] and Schmit et al. [2] have performed comprehensive analysis of the errors in PSI systems for different phase shifting algorithms. Wingerden et al. [3] also performed a study to make a linear approximation of the measurement errors by analyzing the effects of error sources in PSI measurement.

There are at least three methods that have been developed to reduce undesired vibration effects in PSI measurement. The first one is to implement PSI with more phase-shifting step such as four or five steps. The second way is by controlling the phase-shifting quantities and performing active feedback either by adjusting the laser frequency [4-8] or modifying the phase-shifter’s position [9-14]. Furthermore, the third way is to perform a one-shot measurement such as the implementation of the Fourier method that was introduced by Takeda [15] or performing a simultaneous phase shifting interferometry (SPSI) which was firstly introduced by Smythe and Moore [16] in 1984. The main principle of SPSI is that the phase-shifted interferograms are captured simultaneously so that random vibration affects all the phase-shifted interferograms at the same amount which can be cancelled each other while performing phase wrapping. The SPSI employs various kinds of optical configurations with optical beam-splitting components for generating multiple phase-shifted interferograms which are then captured by the CCD simultaneously [16-20].

In general, the developed SPI systems can be classified into two categories, one employs multiple CCDs [16-18] for capturing the interferograms while the other uses a single CCD [19-20]. The drawback of employing multiple CCDs in the system is that the calibration and alignment task of the CCDs is not simple and tiny misalignment can introduce unacceptable measurement errors. This drawback can be overcome by performing the SPSI using a single CCD.

Another important issue to be resolved is that the real height difference is not possible to be identified if the optical path difference (OPD) between two neighboring pixels is larger than a quarter of the wavelength. This phenomenon is known as the phase ambiguity problem. A common way to resolve this is by introducing one more light source to obtain a larger equivalent wavelength. In the PSI, an arctangent function is usually used for the phase calculation. The phase range of a tangent wrapped phase is from 0 to π and there is phase discontinuity when the phase value is π. This characteristic is used for performing the phase unwrapping process. However, when the phase value is approaching π, the phase calculation result is approaching...
infinity. Due to the limitation of hardware, the accuracy of phase calculation may be significantly reduced. Therefore, Zhu [21] proposed the arccosine phase unwrapping method and showed that it can produce a better calculation result in comparison with the arctangent phase wrapping method. But the drawback of this method is that the calculated phase value could lose its orientation, i.e. corresponding plus and minus phase values cannot be identified around 0 or \( \pi \).

In this paper, a method combining a dual laser SPSI system and cosine wrapping was developed to resolve the above issues. To deal with the phase ambiguity problem, two laser sources are employed to generate an equivalent wavelength for achieving a long measuring range. Another purpose of using multiple wavelengths in the method is that the ambiguity problem of the phase orientation in cosine phase unwrapping can be resolved. To attest the feasibility, theoretical simulation of the proposed method is performed. From the simulated results, the method is capable of performing one-shot interferometric measurement on common optical bench without vibration isolation.

2. METHODOLOGY

The developed system is an interferometer which is a Michelson-like structure to grab four interferograms simultaneously. A glass plate is employed to generate an extra 180° phase shift. In order to deal with the phase ambiguity problem, two laser sources with 632nm (red laser) and 532nm (green laser) are employed in the system with an optical configuration shown in Figure 1.

The laser sources are combined by a cube beam splitter and the combined lights are expanded by a 4X beam expander. A neutral density (ND) filter is employed to control the intensity of the laser source and a linear polarizer is used to modulate the polarization of the light beams by adjusting the orientation of the polarizer.

In Figure 1, the light is initially split by the glass plate into two parts. The refracted light enters the glass plate toward a measured object and the reflected light is directed to the reference mirror. Apertures are used to block the unwanted light beam and pass the wanted light beam. The two beams reflected from the object and reference mirror are combined to form interference patterns on the CCD. The beam from the object is reflected by the glass plate and from the reference mirror is refracted into the glass plate. Therefore the former and the latter will have a 180° phase shift between them. By doing this, a set of interferograms with 180° phase shift can be obtained simultaneously.

Due to the different reflection and refraction efficiencies of the beams for travelling through the glass plate, a set of ND filters are employed to control the light intensities of the interferograms. A color CCD (charge couple device) camera is used to simultaneously capture two sets of interferograms generated by the red and green lasers independently. Figure 2(b) illustrates the locations of four interferograms captured by the camera. \( I_1 \) and \( I_4 \) have a 180° phase shift compared to \( I_2 \) and \( I_3 \). However, it is not easy to make all the four interferograms have clear interference fringes. Therefore, only three interferograms with clear interference fringes are used to calculate the phase.

The three interferograms formed by a laser can be expressed as:

\[
I_1 = I_{r1} + I_{o1} + 2\sqrt{I_{r1}I_{o1}} \cos(\phi + \alpha_1) \\
I_2 = I_{r2} + I_{o2} + 2\sqrt{I_{r2}I_{o2}} \cos(\phi + \alpha_2) \\
I_3 = I_{r3} + I_{o3} + 2\sqrt{I_{r3}I_{o3}} \cos(\phi + \alpha_3)
\]

where:

\( \phi \) is the phase difference between the object beam and the reference beam
\( \alpha_1, \alpha_2, \) and \( \alpha_3 \) are the phase shift quantity 180°, 180°, and 0°, respectively
\( I_{r1}, I_{r2}, \) and \( I_{r3} \) are the intensities of the reference beams for the three interferograms; and,
Since the reference and object beams of the interferograms depends on the light source, we could formulate coefficients that describe the ratios between the light that form the three interferograms as follows:

\[ C_1 = \frac{I_1}{I_2} \]
\[ C_3 = \frac{I_3}{I_2} \]
\[ C_{o1} = \frac{I_{o1}}{I_{o2}} \]
\[ C_{o3} = \frac{I_{o3}}{I_{o2}} \]

where \( C_1, C_3, C_{o1}, \) and \( C_{o3} \) are obtained by system calibration by blocking the reference and object beams, respectively. Then, substituting equation (4)-(7) into equations (1), (2) and (3), the following equations can be further obtained:

\[ I_1 = C_1 I_2 + C_{o1} I_{o2} - 2\sqrt{C_1 C_{o1}} I_2 I_{o2} \cos \phi \]
\[ I_2 = I_2 + I_{o2} - 2\sqrt{I_2 I_{o2}} \cos \phi \]
\[ I_3 = C_3 I_2 + C_{o3} I_{o2} + 2\sqrt{C_3 C_{o3}} I_2 I_{o2} \cos \phi \]

The following two variables are defined to simplify the equation:

\[ D_1 = \sqrt{C_1 C_{o1}} \quad \text{and} \quad D_3 = \sqrt{C_3 C_{o3}} \]

Substituting D1 and D2 to Eq. (8)-(10), Eq. (11) and (12) can be summarized as:

\[ (C_1 - D_1) I_2 + (C_{o1} - D_1) I_{o2} = I_1 - D_1 I_2 \]
\[ (C_3 + D_3) I_2 + (C_{o3} + D_3) I_{o2} = I_3 + D_3 I_2 \]

Eq. (11) and (12) are the simultaneous phase equation for solving \( I_2 \) and \( I_{o2} \). They can be resolved as follows:

\[ I_2 = \frac{I_1 - D_1 I_2 - C_{o1} - D_1}{C_1 - D_1} \]
\[ I_{o2} = \frac{I_3 - D_1 I_2 - C_{o3} - D_3}{C_3 + D_3} \]

Once \( I_2 \) and \( I_{o2} \) are determined, the phase can be further derived from Eq. (9) and expressed as:

\[ \phi = \cos^{-1}\left(\frac{I_2 + I_{o2} - I_1}{2\sqrt{I_2 I_{o2}}} \right) \]

\( \phi_R \) and \( \phi_G \) can be obtained by applying these steps for both red and green laser interferograms. To increase the measurement range, the two-frequency phase unwrapping step has to be performed.

One problem that is faced by cosine phase unwrapping is that it can lead to two ambiguous phase results (\( \cos \theta \) and \( \cos(-\theta) \)). To overcome this problem, the phases of two neighboring pixels are used to judge whether the calculated phase value is correct or not. The phase relation between the phase difference of two neighboring pixels and the wavelength is formulated as follows:

\[ \Delta \phi_R \times \lambda_R = \Delta \phi_G \times \lambda_G \]

where \( \Delta \phi_R \) and \( \Delta \phi_G \) are the phase difference of the neighboring two pixels of red laser and green laser for the same measured pixel; and \( \lambda_R \) and \( \lambda_G \) are the wavelength of the lasers.

Assuming that the phase of the first pixel are \( \phi_{R(0,0)} \) and \( \phi_{G(0,0)} \) and the phase of the second pixel are \( \phi_{R(0,1)} \) and \( \phi_{G(0,1)} \), Eq. (16) can be transformed into Eq. (17):

\[ (\pm \phi_{R(0,1)} \pm \phi_{R(0,0)}) \times \lambda_R = (\pm \phi_{G(0,1)} \pm \phi_{G(0,0)}) \times \lambda_G \]

The sign in front of the phase values indicates that there are 16 possible combinations in its phase computation. By evaluating these conditions, the sign of the phase can be obtained satisfactorily. Once the phase values \( \phi_{R(0,1)} \) and \( \phi_{G(0,1)} \) are obtained, the calculation of the next two pixels \( \phi_{R(0,2)} \) and \( \phi_{G(0,2)} \) can be further simplified as:

\[ (\phi_{R(0,2)} \pm \phi_{R(0,1)}) \times \lambda_R = (\phi_{G(0,2)} \pm \phi_{G(0,1)}) \times \lambda_G \]

In general, the calculation of the following next pixels can follow the above equation. However, when the phase values of \( \phi_{R(0,0)} \) and \( \phi_{R(0,1)} \) go through a phase discontinuous point around 180° or -180°, the above judgment equation could fail. To handle this situation, the equation can be further transformed into:

\[ (\phi_{R(0,1)} \pm \phi_{R(0,0)} + 2n\pi) \times \lambda_R = (\phi_{G(0,1)} \pm \phi_{G(0,0)} + 2m\pi) \times \lambda_G \]

where \( n \) and \( m \) are integer values as the order of the phase which can be directly converted into the height of the object.

By applying this evaluation rules for determining the phase difference, the unwrapped phase can be accurately obtained for 3-D surface profilometry.

### 3. SIMULATION AND VERIFICATION OF THE METHOD

Simulation is performed to test the feasibility of the developed method. Two sets of interferograms are generated using a red and a green laser. A surface with a standard step height of 0.25 μm is employed as a test surface. Figure 3 (a) shows the generated interferograms obtained with the red laser with a wavelength of 632.8 nm and Figure 3 (b) from the green laser of a wavelength of 532 nm, respectively.
Simulated SPSI interferograms are generated from a surface step height of 0.5 µm by using a laser light with a wavelength: (a) 632.8 nm; and, (b) 532 nm wavelength, respectively.

Then, the developed cosine phase wrapping algorithm is applied to the generated interferograms for obtaining two phase maps, shown in Figure 4. The result clearly indicates that the phase wrapping result doesn’t have an undesired phase discontinuity around π or −π, like the one obtained from the tangent based phase wrapping.

Wrapped phase maps obtained from the simulated SPSI interferograms: (a) by the red laser; and, (b) by the green laser.

Furthermore, by applying the developed method for solving phase ambiguity and also performing the phase unwrapping, the surface of the step height can be reconstructed as shown in Figure 5. This result shows that the method can be successfully applied to perform cosine based phase wrapping for a dual wavelength SPSI system.

Reconstructed 3-D surface map of the step height

From our simulated results, it is also found that the cosine wrapping and unwrapping still has its limits in the dual-wavelength SPSI. The result of phase wrapping could be unstable if there are unavoidable image noises in the detected interferograms and Eq. (19) may be still difficult in judging the phase correctly. More sophisticated algorithms in noise filtering and phase judgment are required for further development to ensure its robust implementation of the developed methodology.

4. CONCLUSIONS
The developed dual-frequency simultaneous phase shifting interferometry system was developed to overcome vibration effect and achieve a high measuring depth range. The method was developed to overcome the ambiguity problem that exists in cosine phase unwrapping. The developed method employing the phase difference between two neighboring points on the surface is further verified using a simulated interferograms from a step height with 0.5 um height. The result from the simulation shows that the method is capable of performing the two step phase-shifting using cosine phase wrapping and capable of overcoming the ambiguity with phase wrapping process. More sophisticated algorithms in noise filtering and phase judgment are proved to be essential in developing its robust implementation.

REFERENCES