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위상보정을 이용한 백색광 위상 천이 간섭계에서의 반복능 향상에 관한 연구

Improvement of Measurement Repeatability for White Light Phase Shifting Interferometry by Phase Compensation

2016 년 2 월

서울대학교 대학원

기계항공공학부

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Abstract

In this thesis, the measurement repeatability of White Light Phase Shifting Interferometry (WLPSI) is improved using phase compensation algorithm. In WLPSI, phases which include height information of a target can be obtained by calculating intensities of captured images. The mechanical vibration of a stage, however, could affect each phase of an image. In consequence of the vibration, phase errors are implicated at each phase and these errors could bring out the unstable repeatability. In order to enhance the repeatability, a phase compensation method is introduced based on the phase variation theory.

At the ideal measurement, a set interval of PZT actuator is equal when scanning. Based on the theory, the phase variation is proportional to the scanning interval. Therefore, the phase compensation method can be applied using the relation between the phase variation and the interval.

In order to verify the performance of the suggested method, measurement of three types of micro patterns and Standard Step Height Sample with vibration is carried out. As a result, the repeatability of measurement is improved by applying proposed phase compensation method.

Keyword : White Light Phase Shifting Interferometry (WLPSI), Phase error, Phase compensation, Repeatability.

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I : Intensity of Interferogram

I_r : Intensity reflected from reference surface

I_t : Intensity reflected from measurement surface

A : Amplitude of intensity reflected from reference surface

B : Amplitude of intensity reflected from measurement surface

I_0 : Average Intensity

γ : Visibility function

$k = \frac{2\pi}{\lambda}$: Wave number

λ : Wave length of light source

l : Distance between beam splitter and reference surface

h : Measurement height of target

z : Distance between actuator and target

ϕ : Phase of interferogram

ϕ_{ref} : Reference phase

ϕ_{new} : Compensated phase

1. Introduction

1.1. Study Background

In high precision field, such as semiconductor and display manufacturing industries, a stable and a high production rate is strongly important. Among the manufacturing processes, the measurement is one of the critical steps to manage each process.

There are various measurement targets in the field. Since the unknown target is measured, the measurement repeatability has been considered as a key performance in metrology along with the accuracy. When the result of repeatability is high enough, the accuracy result will be reliable, and it maintains a stable process.

White Light Phase Shifting Interferometry (WLPSI) is widely used in manufacturing area due to its advantages, which can measure a small target with a fast speed and high resolution. In WLPSI, the calculation of a height is conducted by using the interferogram signal. During the height calculation process, getting an appropriate phase is a critical process for obtaining the precise height result. The mechanical vibration of a system, however, may affect the interferogram signal, therefore it may cause phase error.

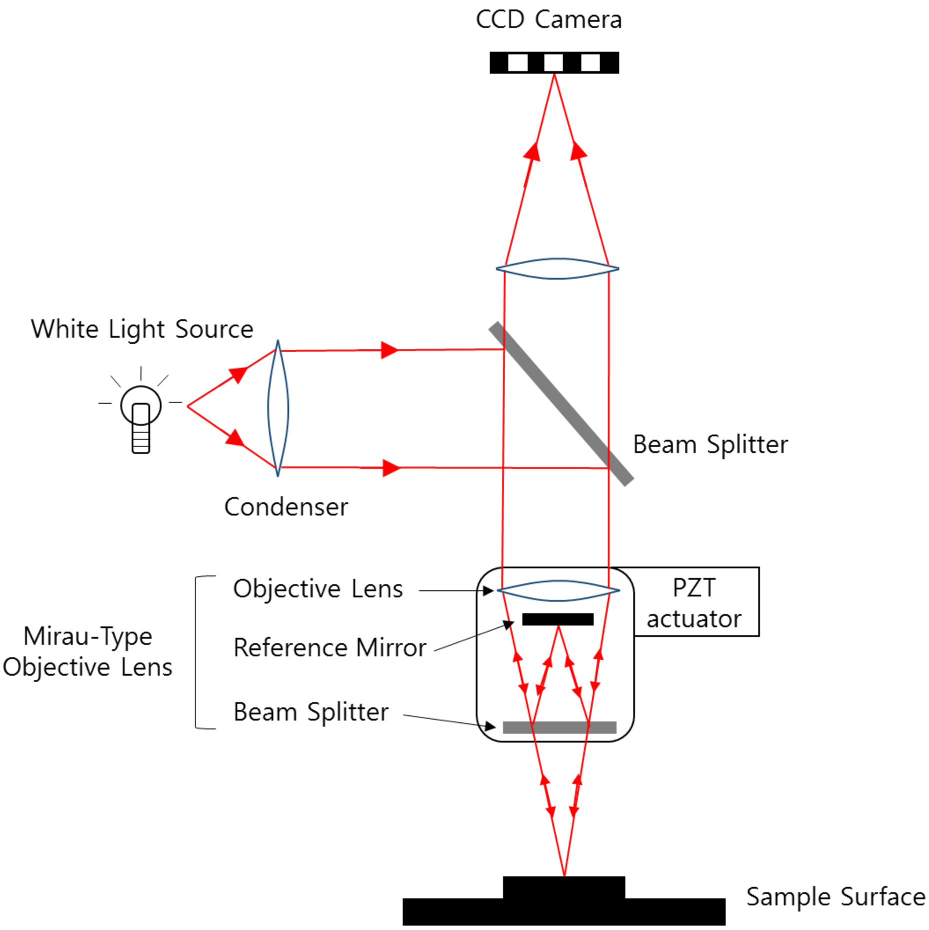


Figure 1 Configuration of WLPSI

1.2. Previous Research

In previous research, phase compensation methods were proposed. Ahn [15] suggested relative phase error concept and numerically applied that idea to compensate the phase error. This method only used the obtained interferogram image without any extra hardware. Another method was introduced by Kim [17]. Using two-cameras, phase mismatches can be found between the phase error from the main camera and that from the extra camera based on the theory of the relative phase error. Kim proposed two methods; one is Phase Ratio Matching (PRM) and the other one is Phase Error Offset Matching (PEOM) for phase compensation.

1.3. Purpose of Research

In WLPSI, the measurement repeatability is affected by phase error which is a consequence of an external factor, a mechanical vibration. When the amplitude of vibration produces by nano-scale movement, it is difficult to mechanically control the hardware. Therefore, compensation of phase error at the signal analysis process is necessary to enhance the repeatability.

In this thesis, phase compensation algorithm is suggested to improve measurement repeatability. This proposed algorithm compensates phases according to the theory of phase variation. The phase variation based on the theory is applied to the interferogram signal, and phase compensation is conducted. In order to verify the suggested method, two experiments are carried out. Firstly, three types of micro patterned samples are used for comparing the repeatability. Secondly, to see the robustness of a vibration, the measurement of Standard Step Height Sample induced by vibration is conducted, and the proposed algorithm is applied to the measurement data.

2. Interferometry

Interferometry uses the phenomenon of lights. In apparatus, the fringes are captured by a CCD camera while an actuator changes the OPD. Due to the fringe intensities containing phases, various studies were proceeded to calculate phases. Carre’ [20] firstly developed how to calculate the height from the phase. Since then, several methods have studied such as 3-Bucket, 4-Bucket, N-Bucket and so on.

Phase Shifting Interferometry (PSI) generally uses laser beam or white light with filter of short wavelength as a light source, so it creates a long coherence fringe. Using the fringe intensity, the phase which contains the height information can be calculated with high resolution. However, it has phase ambiguity due to the characteristic of the coherency, which means it is hard to measure if the measurement height is higher than 1/4 of a light source’ s wavelength. White Light Scanning Interferometry (WSI), developed to cover the weakness of PSI, has short coherence fringe since it uses a white light as a light source. White light fringe forms visibility function which maximum point indicates the height can be computed by fringe intensities. Although the measurement limit of a height was solved, it has low resolution compared to PSI, because the visibility function is less sensitive to the height direction.

WLPSI takes advantage of high resolution of PSI and possibility in various measuring heights of WSI.

2.1. Phase Shifting Interferometry

Phase Shifting Interferometry (PSI) generally uses a laser beam or white light with a filter of short wavelength as a light source, so it creates a long coherence fringe. Optical Path Difference (OPD) of a light source creates interferogram fringes when the single light is split into two rays and come across together where they reflected from the reference surface and the measurement surface. The optical path of a ray reflected from the measurement surface can be changed while an actuator moves to the optical direction. Using the fringes, the relative phase is calculated.
Two rays can be expressed by the wave equation of a light.

$$
\begin{aligned}
I_r &= Ae^{i(wt+2kl)} \\
I_t &= Be^{i(wt+2k(l+z-h))}
\end{aligned}
\tag{2.1}
$$

$$
\begin{aligned}
I &= \overline{|\, I_r + I_t \,|^2} \\
&= A^2 + B^2 + 2AB\cos(2k(h-z)) \\
&= I_o[1+\gamma\cos(2k(h-z))]
\end{aligned}
\tag{2.2}
$$

where $I_0 = A^2 + B^2$ and $\gamma = \dfrac{2AB}{A^2 + B^2}$

The distance between measurement surface and the actuator, referred to z , is changed when the PZT scanning is conducted. So the scanning variation Δz is expressed in $z = z_{ref} + \Delta z$. Therefore, the reference phase and the variation of phase can be expressed in $\phi_{ref} = 2k(h - z_{ref})$ and $\delta = 2k\Delta z$, respectively. The Equation (2.3) is finally organized as follows.

$$
I = I_0(1 + \gamma\cos(\phi_{ref} - \delta))
\tag{2.3}
$$

At the equation (2.3), the movement of the actuator changes the phase variation δ and the interferogram intensities, so the reference phase ϕ_{ref} can be obtained by calculating multiple intensities, therefore, h is finally obtained. When the actuator moves along the z-axis, the CCD camera captures interferogram images in equal interval. So I_i is can be expanded as below.

$$I_i = I_0 + I_0\gamma\cos(\phi_{ref})\cos(\delta_i) + I_0\gamma\sin(\phi_{ref})\sin(\delta_i)$$
$$where \quad \delta_i = \frac{2\pi}{N}(i-1), \quad (i = 1,2,\cdots,N) \tag{2.4}$$

Since the δ_i is a 2π periodic function, the equation (2.4) is a Fourier series. Therefore, it can be expressed as follows.

$$\begin{aligned} I_i &= I_0 + I_0\gamma\cos(\phi_{ref})\cos\left(\frac{2\pi}{N}(i-1)\right) + I_0\gamma\sin(\phi_{ref})\sin\left(\frac{2\pi}{N}(i-1)\right) \\ &= a_0 + a_1\cos\left(\frac{2\pi}{N}(i-1)\right) + b_1\sin\left(\frac{2\pi}{N}(i-1)\right) \end{aligned} \tag{2.5}$$

The coefficient of the equation (2.5) is shown as below.

$$\begin{aligned} a_0 &= \frac{1}{N}\sum_{i=1}^{N} I_i \\ a_1 &= \frac{2}{N}\sum_{i=1}^{N} I_i\cos\left(\frac{2\pi}{N}(i-1)\right) \\ b_1 &= \frac{2}{N}\sum_{i=1}^{N} I_i\sin\left(\frac{2\pi}{N}(i-1)\right) \end{aligned} \tag{2.6}$$

From the equation (2.6), the reference phase ϕ_{ref} is calculated.

$$\phi_{ref} = \tan^{-1}\left(\frac{b_1}{a_1}\right) = \tan^{-1}\left(\frac{I_0\gamma\sin(\phi_{ref})}{I_0\gamma\cos(\phi_{ref})}\right)$$

$$= \tan^{-1}\left(\frac{\sum_{i=1}^{N} I_i \sin\left(\frac{2\pi}{N}(i-1)\right)}{\sum_{i=1}^{N} I_i \cos\left(\frac{2\pi}{N}(i-1)\right)}\right) \qquad (2.7)$$

The equation (2.7) is a normal method, called N−bucket method, for calculating phases using intensities which are obtained by equal interval step. Among N−bucket methods, 3−bucket and 4−bucket methods have been widely used for simplifying the calculation.

$$3-bucket$$

$$\phi_{ref} = \tan^{-1}\left(\frac{\sqrt{3}(I_2 - I_3)}{2I_1 - I_2 - I_3}\right) \qquad (2.8)$$

$$where \quad \delta_i = \frac{2\pi}{3}, \quad (i = 1,2,3)$$

$$4-bucket$$

$$\phi_{ref} = \tan^{-1}\left(\frac{I_2 - I_4}{I_1 - I_3}\right) \qquad (2.9)$$

$$where \quad \delta_i = \frac{\pi}{2}, \quad (i = 1,2,3,4)$$

Both two bucket methods, however, are not considered of measurement errors. Therefore, the 5−bucket method which is insensitive to the minor phase errors was developed by Schwider et al [19].

$$5-bucket$$

$$\phi_{ref} = \tan^{-1}\left[\frac{2(I_4 - I_2)}{I_1 - 2I_3 + I_5}\right] \tag{2.10}$$

$$where \quad \delta_i = (i-1)\frac{\pi}{2}, \quad (i = 1,2,3,4,5)$$

$$I_1 = I_0[1+\gamma\cos(\phi_{ref} - \pi)]$$

$$= I_0[1-\gamma\cos\phi_{ref}]$$

$$I_2 = I_0\left[1+\gamma\cos\left(\phi_{ref} - \frac{\pi}{2}\right)\right]$$

$$= I_0[1+\gamma\sin\phi_{ref}]$$

$$I_3 = I_0[1+\gamma\cos(\phi_{ref})]$$

$$= I_0[1+\gamma\cos\phi_{ref}]$$

$$I_4 = I_0\left[1+\gamma\cos\left(\phi_{ref} + \frac{\pi}{2}\right)\right]$$

$$= I_0[1-\gamma\sin\phi_{ref}]$$

$$I_5 = I_0[1+\gamma\cos(\phi_{ref} + \pi)]$$

$$= I_0[1-\gamma\cos\phi_{ref}]$$

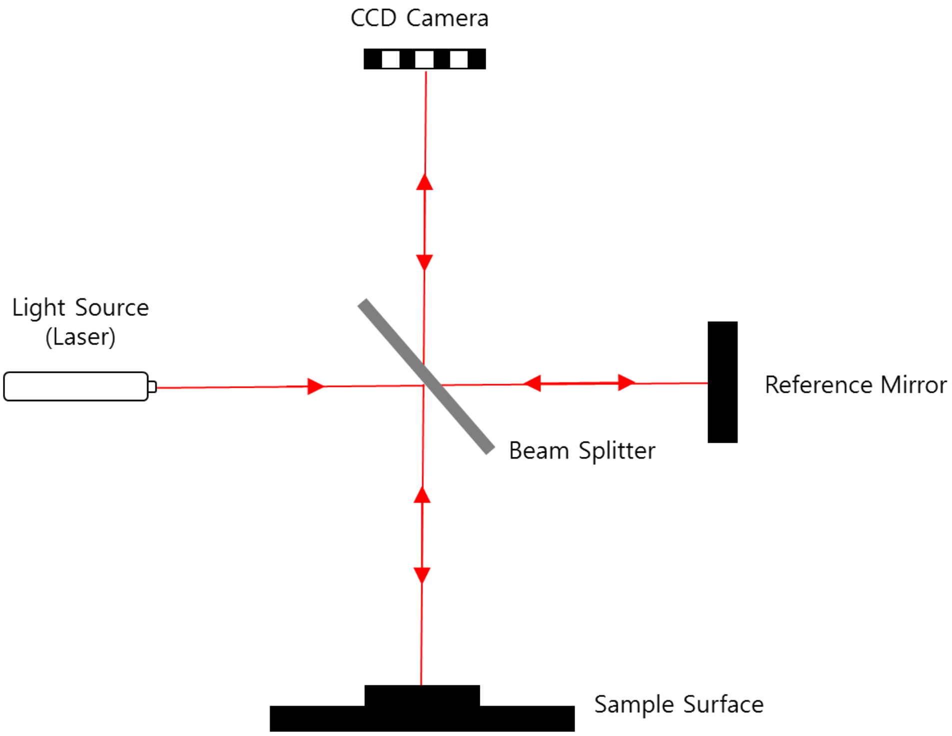


Figure 2 Michelson interferometry

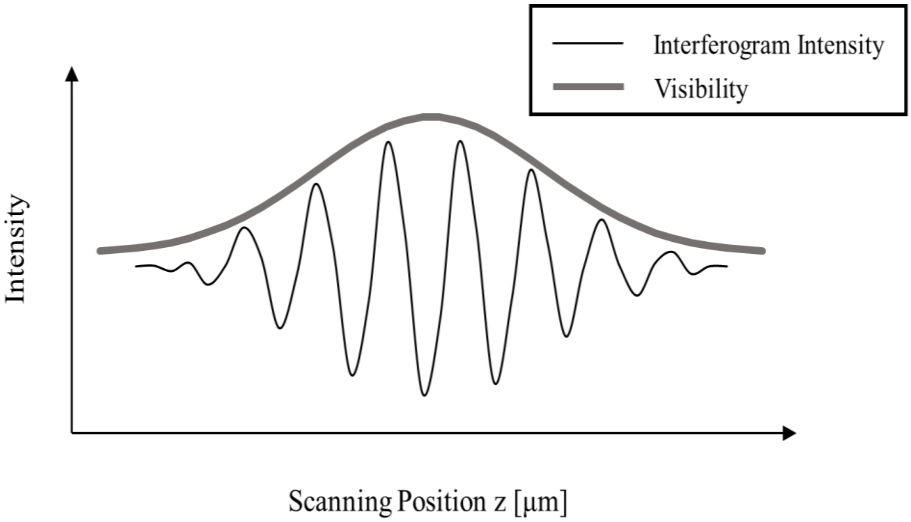


Figure 3 Interferogram and Visibility of WSI

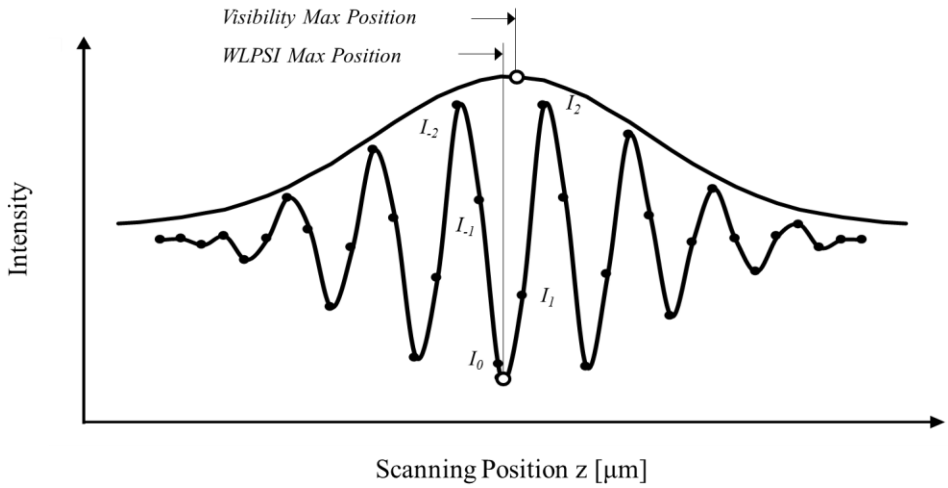


Figure 4 Interferogram Intensity of WLPSI

2.2. White-light Scanning Interferometry

White-light Scanning Interferometry (WSI) uses a white light source, which means the light source contains multiple monochromatic lights. Due to the overlapping interference of each wavelength, the coherence fringe of a white light is short. The interference equation at WSI can be expressed by an integral of the equation (2.2).

$$I = \int_{\lambda_{\min}}^{\lambda_{\max}} I_o[1+\gamma\cos(2k(h-z))] \; dk \tag{2.11}$$

At Figure 3, the visibility function is shown. In WSI, The maximum point of the visibility function is considered as the height position.

2.3. Principles of WLPSI

Fringe intensities of WLPSI are shown in Figure 4. As shown in Figure 4, the height calculation process is performed by two steps. Finding a visibility peak is the first step. Next step is getting a phase at the peak

2.3.1 Detection of Visibility Function

At WLPSI, detecting an envelope (or visibility function) is conducted. Since the phase at the peak point contains height information, the robustness of peak detecting is very important. Various researches have studied about detecting the envelope peak.

Kino [4−5] suggested Fourier Transform method to extract envelope function [4] and Hibert Transform to eliminate the average intensity of the interferogram [5]. Groot [6] calculated phase and height using Frequency Domain Analysis. Larkin [9] assume the temporal phase−shifting algorithm around the envelope and extracted the modulation equation, $f(i)$ also referred to as five−sample−adaptive (FSA) nonlinear algorithm.

$$f(i) = (I_{i-1} - I_{i+1})^2 - (I_{i-2} - I_i)(I_i - I_{i+2}) \qquad (2.12)$$

The robust envelope function of the WLPSI can be simply calculated by using the equation (2.12).

2.3.2 Phase Calculation

Even though WLPSI includes PSI's advantage, it is difficult to apply PSI's phase calculation methods. While the envelope created by Optical Path Difference (OPD) of single wavelength remains constant in the PSI, the envelope of white light is changed throughout the wavelength.

To compensate the effect of the envelope, Larkin [9] suggested that envelope near the peak position is constant, and Sandoz [12] assumed that the envelope change is locally linear. The Other method is the elimination of the envelope affection. Kang [14] extracted an envelope using Hilbert transform and eliminated it from the fringe intensity. After these envelope assumptions were conducted, the phase was calculated.

2.3.3 Data Acquisition in the System

The schematic diagram of WLPSI system and ideal image acquisition process are shown in Figure 5. The objective is attached to the PZT actuator. When the objective moves downward, CCD camera captures interference images with a set interval. In an ideal situation, the interval of images should be equal.

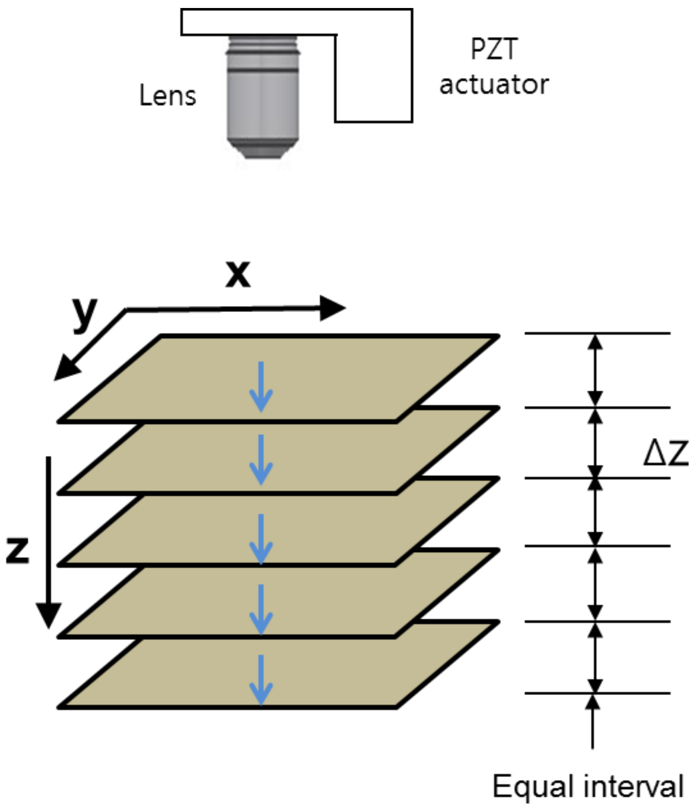


Figure 5 Image Acquisition Concept of WLPSI

3. Causes of Phase Error

There are several factors that cause phase error. Ahn [15] and Kim [17] listed causes of phase error, which are largely divided into two parts.

One is a mechanical factor that results an undesirable difference of relative distance. It includes an external stage vibration, a scanner movement error and a vibration of a scanner. Because of those errors, the distance between a beam splitter and a reference mirror or a measurement target is always changed. The other one is an electrical factor which includes noises of a camera, a lack of uniformity of a light source and an error of quantization. Those electrical errors are usually shaped of high frequencies, so they have a less affection compared to mechanical factors.

Among the mechanical errors, the external vibration of a stage is considered as the main cause of phase error. Above all, the low frequencies which are spread under the 20Hz are the critical range that affects the relative distance of the measurement. An isolation stage which is one of a configuration part of WLPSI system has a role of reducing the transition rate of a floor vibration. Despite of the function of the isolation stage, however, the affection of a nano-scale movement exists and it is difficult to control by the hardware.

The affection of phase vibration error ϕ_v can be expressed as follows.

$$I = I_0(1 + \gamma \cos(\phi_{ref} - \delta + \phi_v)) \tag{2.13}$$

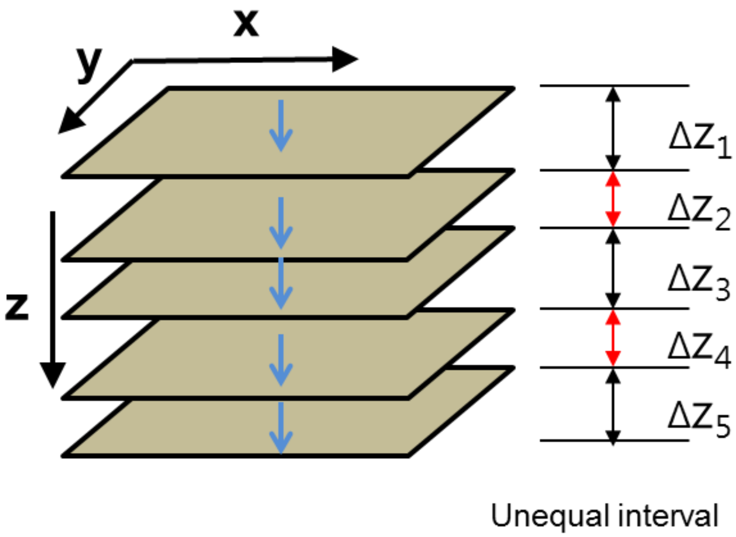


Figure 6 Abnormal Image Acquisitions Due to Vibration

4. Phase Compensation

In real measurement condition, it is difficult to figure out how the factors generate the error. Only the interferogram signal is the criterion of a judgment whether the interferogram signal is captured in same interval or not. In this section, phase variation of an ideal state is introduced. Based on the theory, the phase compensation method is applied to the distorted signal which contains phase error.

4.1. Principle

As the scan interval is equal, the variation of phase among images should be constant. In equations,

$$\begin{aligned} I_i &= I_o[1+\gamma\cos(2k(h-z_i))] \\ &= I_o[1+\gamma\cos(\phi_i)] \end{aligned} \tag{4.1}$$

At (i) th phase,

$$\phi_i = 2k(h - z_i) \text{ when } z_i = z_{ref} \tag{4.2}$$

At (i+1) th phase,

$$\phi_{i+1} = 2k(h - z_{i+1}) \text{ when } z_{i+1} = z_{ref} + \Delta z \tag{4.3}$$

When subtract two phases,

$$\phi_i - \phi_{i+1} = 2k(-z_i + z_{i+1}) \quad \Leftrightarrow \Delta\phi = 2k(\Delta z) \tag{4.4}$$

For White-light, the phase variation is also proportional to the scanner movement.

$$\Delta\phi = 2(\Delta z)\int_{\lambda_{low}}^{\lambda_{high}} k \cdot dk \qquad (4.5)$$

4.2. Process of Phase Compensation

In real measurement states, phases might include phase errors. Therefore, the phase variation can be rewritten as

$$\Delta\phi_{real,i} = 2k(\Delta z) + (\phi_{v,i+1} - \phi_{v,i}) \qquad (4.6)$$

At the equation (4.6), each phase has a different vibration experience when the measurement is conducted. In other words, there are many different phase variances in one interferogram signal.

Phase compensation is a process that sets various phase variations into a represented phase variation value.

Phases can be calculated by using 5−bucket method, and then the phase variation is obtained as follows.

$$\Delta\phi_i = \begin{Bmatrix} \phi_{i+1} - \phi_i & , \phi_{i+1} > \phi_i \\ \phi_{i+1} - \phi_i + 2\pi & , \phi_{i+1} < \phi_i \end{Bmatrix} \qquad (4.7)$$

Then, the new phase is obtained as below.

$$\phi_{new,i} = \overline{\Delta\phi} \times i + b_i \qquad (4.8)$$

And the minimum error function is derived as follows.

$$\sum E_i^{\ 2} = \sum (\phi_i - (\overline{\Delta\phi} \times i + b_i))^2 \qquad (4.9)$$

The values that minimized the error function are the coefficients of the new phase equation.

4.3. Compensate Distorted Signal

In Figure 7, the phase distribution of distorted interferogram signal is compensated by using the proposed phase compensation method.

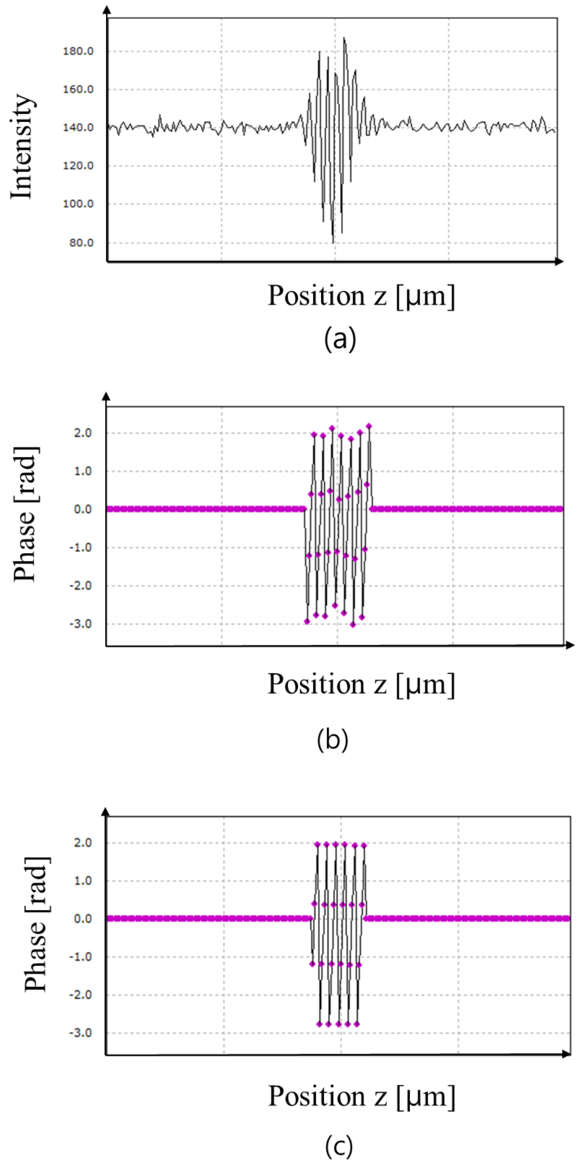


Figure 7 (a) Distorted Interferogram
(b) Phase Distribution of Distorted Interferogram
(c) Phase Distribution after Compensation

5. Experiments and Evaluation

5.1. Experiments

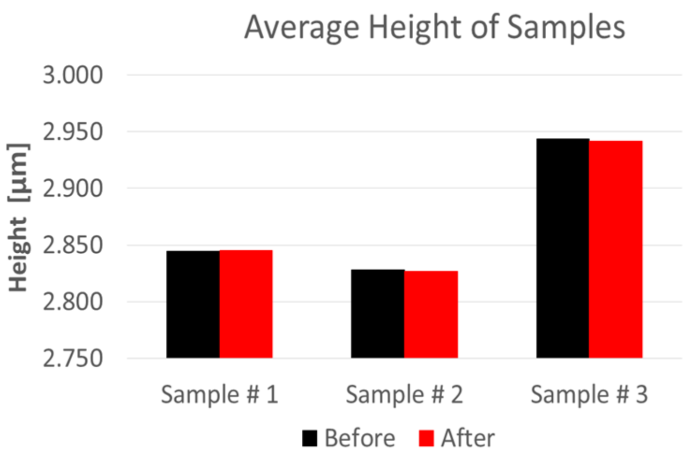
In order to verify the suggested phase compensation algorithm, two types of experiments are conducted. Firstly, three different types of micro patterned samples are tested, and both the height average and the repeatability are compared to the conventional method. Secondly, in order to see the robustness at stage vibration, the z−axis vibration was induced on Standard Step Height Sample. The frequency range is spread from 2Hz to 20Hz with 50nm amplitude. Both experiments samples are measured 20 times to see the height repeatability.

5.1.1 Micro Patterned Sample

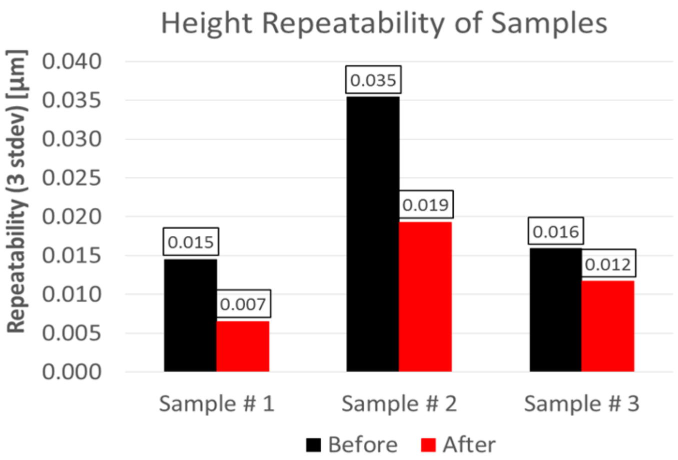
The proposed algorithm can be applied to various types of samples. Therefore, three types of samples are tested. As shown in Figure 8, the repeatability of the suggested results is improved while the average heights are the same. Table 1 shows the percentage of repeatability improvement of each sample.

5.1.2 Standard Step Height Sample with vibrations

The z−axis vibration on the measurement is considered as the main cause of phase error. Therefore, in order to see the robustness of the suggested algorithm at stage vibration, the z−axis vibration was induced using the piezoelectric exciter system. The repeatability distribution graph is displayed in Figure 9. After applying the phase compensation method, repeatability results at all frequencies become more stable than that of conventional method.



(a)

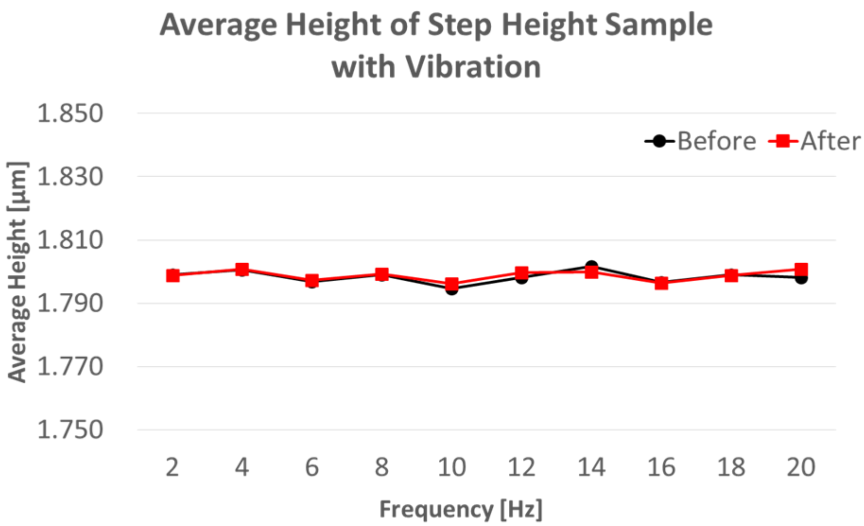


(b)

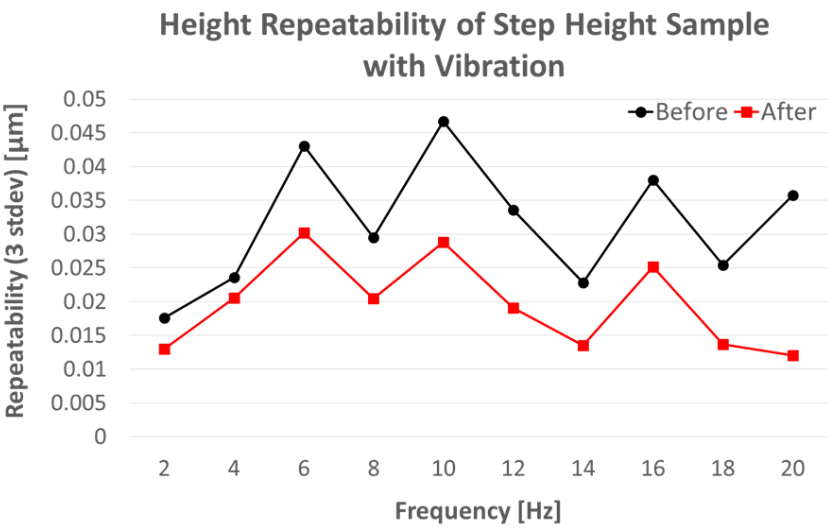
Figure 8 Results of Micro Pattern Samples after Compensation
(a) Average Height and (b) Height Repeatability

	Before	After	% of (1 - After/Before)
Sample # 1	0.015	0.007	55.2
Sample # 2	0.035	0.019	45.5
Sample # 3	0.016	0.012	26.4

Table 1 Improvement rate of Repeatability of Micro Patterned Samples



(a)



(b)

Figure 9 Results of Standard Step Height Sample with Vibration
(a) Average Height and (b) Height Repeatability

6. Conclusion

In this thesis, a phase compensation method in WLPSI is suggested. In the real measurement process, the external mechanical vibration mainly affects the phase value. The phase with errors brings out bad repeatability in measurement. To revise the phase error, phase compensation method is proposed.

The proposed phase compensation method is based on the theory that the phase variation of each state should be constant when the scanner movement is equal. In external error condition, however, each phase variation has different value due to vibration. The process of converting unequal phase variations into one represented phase variation is suggested to compensate the phases.

Various samples were used for verifying the algorithm. As a result, the height repeatability is improved about 40 percent of the conventional result at different types of pattern samples. Furthermore, the experiment result of Standard Step Height Sample with vibration support that the algorithm has robustness in z-axis vibration.

This suggested algorithm has an advantage that it can improve the repeatability without any extra hardware. Furthermore, it is compatible to various samples whenever the sample creates the interferogram signal.

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초 록

위상보정을 이용한 백색광 위상 천이 간섭계에서의 반복능 향상에 관한 연구

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본 논문은 위상보정을 이용한 백색광 위상 천이 간섭계의 반복능 향상에 관한 연구이다. 백색광 위상 천이 간섭계에서, 측정 대상의 높이 정보를 가지고 있는 위상은 얻어진 간섭 이미지의 광강도를 계산하여 얻을 수 있다. 그러나 기계적인 진동이 측정 스테이지에 가해지는 경우에, 미세한 진동이 위상계산에 영향을 주게 된다. 이러한 진동의 영향으로 위상오차가 발생할 수 있으며, 이는 불안정한 측정 반복능의 결과를 가져온다. 측정 반복능을 향상시키기 위해, 이론적인 위상변화를 기본으로 하는 위상 보정 방법을 제안하였다.

이상적인 측정환경에서는 PZT 구동기가 스캔을 할 때, 일정한 간격으로 간섭 이미지가 얻어진다. 이 때 이론적으로 식을 구하면, 위상의 변화는 PZT 스캔 간격에 비례하는 값을 가진다. 따라서 위상변화와 스캔 간격의 관계식을 이용하면 대표적인 위상변화 값을 구할 수 있다. 실제로 위상오차를 포함하는 간섭신호의 위상을 5-Bucket으로 구한 후, 대표 위상변화 값을 적용하여 위상 보정을 진행하였다.

제안된 알고리즘을 검증하기 위해, 세가지 종류의 마이크로 패턴 샘플과 진동을 가한 표준 단차 시편을 20회 반복측정 하였고, 기존 방법과 결과를 비교 하였다. 결과적으로, 제안된 위상보정 알고리즘을 적용하였을 때 측정 반복능이 향상된 것을 확인 할 수 있었다. 또한

진동을 가한 표준 단차 시편 실험을 통해서 제안된 알고리즘이 진동에도 효과가 있는 것을 확인 할 수 있었다.

주요어 : 백색광 위상 천이 간섭계, 위상 오차, 위상 보정, 반복능.
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