Development of a novel interferometric displacement measurement instrument with the folded resonant cavity

Yung-Cheng Wang, Lih Horng Shyu, and Chung-Ping Chang

Abstract—Precision measurement technology is one of the critical points of the development of precision mechanical industry. Because of the rapid development of the precision mechanical industry, the requirements of the measurement parameters are enhanced. The conventional measurement technologies cannot meet these requirements. For this reason, interferometric technology is used in the precision mechanical industry wildly. But the conventional interferometric technology cannot demonstrate its characteristics of high precision under the ordinary environment. Therefore, the interferometer cannot yield expected results in the application of precision mechanical industry.

In view of this situation, for the measuring condition of the precision mechanical industry under the fluctuating environments, a Fabry-Perot interferometer with the variable optical structures has been proposed. One of the structures is plane-mirror Fabry-Perot interferometer system utilized in small range, high precision and fine mechanical tolerance. Another structure is folded Fabry-Perot interferometer system which can be performed in large range and mechanical tolerance. By the development of the common path interferometer, the novel arrangement of the optical structure and the optimization of the signal processing model, the measuring range and the resolution of the proposed interferometer can be enhanced. With the aid of this interferometric technology, applications of the common path interferometer for precision mechanical industry can be promoted.

The results and verifications reveal that the interferometric system will be available for precision mechanical industry. From the experimental results, the measuring range is larger than 300 mm, precision about \( \pm 0.65 \mu m \) \((\pm 3\sigma)\).

I. INTRODUCTION

Interferometric displacement measurement technology is essential and critical for the development of precision machine industry. For current high precision length measurements, e.g., displacement measurement, precision positioning and calibration of machines, interferometers are indispensable for performing such measurement applications [1]. In length measurement in precision machine industry, the non-common path laser interferometer reveals the excellent performance of the large measuring range and high accuracy. Especially, the interferometer with the stabilized He-Ne laser source (frequency stability of \( 10^{-9} \)) has the measuring range of several tens of meters.

However, the stability of the general laser interferometer is sensitive to environmental disturbance and mechanical vibration. In some situations in mechanical industry, the interferometer cannot realize the proper accuracy, even the sub-micrometer order. Therefore, the key point of an interferometric measurement system for precision industry is not only involved with the resolution and measuring range, but also the resistance of the environment disturbance and mechanical tolerance.

Because the structure of the common path interferometer is much more stable than that of general interferometers [2-5], this kind interferometer has been expected for overcoming the limitation of the environment and mechanical problem in precision mechanical industry.

II. MEASUREMENT PRINCIPLE

A. Modified Interferometer

The main objective of this research is to develop an interferometer system for precision mechanical industry. For different measurement situations, there are two types with alternative measurement mirrors employed in this system, including the planar mirror and the corner cube reflector. The alternative criterion is dependent on the measurement ranges and the measurement mirror switching is convenient and rapid. Therefore, the measurement system can be feasible for the large range displacement measurement with the corner cube reflector. And planar mirror is for the small displacement measurement.

The optical structure shown in Fig. 1 indicates that the two types of the measurement mirrors are selectable for the different measurement objective. Laser light source passes through the BS into the optical cavity. The one eighth waveplate in the cavity is employed to form the orthogonal phase shift between interference signals. And the polarization axis of the waveplate must be the same as that of PBS. By this arrangement, the orthogonal signal can be acquired by two photodiodes (PDs) and then transmitted to the signal processing module. By this way, a flexible interferometer system can be established.
B. Simulation and Analysis

The corresponding equation of the modified folded Fabry-Perot interferometer can be derived as follows. The amplitude of the firstly reflected beam is expressed as $A_{N1}$ (Eq. 1) and that of the whole interference beam is denoted with $A_{N}$ (Eq. 2), where $A_{0}$ is the amplitude of Laser source, R and T are the reflectance and transmittance of the coated mirror, $T'$ is the resultant transmittance of the optical cavity [6, 7], and N is the number order of the backward reflected light beam.

$$A_{N1} = \frac{1}{2\sqrt{2}} A_{0} \times \sqrt{R}$$  \hspace{1cm} (1)

$$A_{N} = \frac{1}{2\sqrt{2}} A_{0} \times \sqrt{R^{N-2}} \times T \times T^{(N-1)} \ldots (N \neq 1)$$  \hspace{1cm} (2)

The corresponding electric field function of the interference beam can be described as Eq. 3 and Eq. 4, where $\delta$ is the phase difference of the optical path. When the planar mirror serves as the measurement mirror, $\delta$ is $4\pi d/\lambda$. If CCR is employed as the measurement mirror, $\delta$ becomes $8\pi d/\lambda$.

$$E_{N1} = A_{N1} \times e^{i[\omega t + kx + (N-1)\delta + \frac{\pi}{4}]}$$  \hspace{1cm} (3)

$$E_{N} = A_{N} \times e^{i[\omega t + kx + (N-1)\delta + \frac{\pi}{4}]}$$  \hspace{1cm} (4)

By Eq. 5 and 6 the intensity distribution of s-type and p-type can be denoted with Eq. 7 and Eq. 8. And Fig. 2 is the simulations of interferometric intensity.

$$I_s = E_s \times E_s^*$$  \hspace{1cm} (5)

$$I_p = E_p \times E_p^*$$  \hspace{1cm} (6)

For s-type (PD1) intensity,

$$I_s = \frac{1}{8} A_{0}^2 \times \frac{R(1+R) T^2 - 2 R(1+R) \cos(\delta + \frac{\pi}{4})}{1+(R(1+R) T^2 - 2 R(1+R) \cos(\delta + \frac{\pi}{4}))}$$  \hspace{1cm} (7)

For p-type (PD2) intensity:

$$I_p = \frac{1}{8} A_{0}^2 \times \frac{R(1+R) T^2 - 2 R(1+R) \cos(\delta - \frac{\pi}{4})}{1+(R(1+R) T^2 - 2 R(1+R) \cos(\delta - \frac{\pi}{4}))}$$  \hspace{1cm} (8)

C. Signal Processing

Generally, the commercial signal processing modules of the homodyne interferometer are designed for orthogonal sinusoidal signals. Due to the signal of the Fig. 1, the signal of Fabry-Perot interferometer is not a sinusoidal signal. Hence the Lissajou figure is not perfectly circular. It means that each equal interval of phase angle in the Lissajou figure signifies different displacement quantity. Hence, the interpolation error cannot be neglected, if the commercial signal processing modules is used. This error will also increase in accompanying with the higher finesse of the interference signals. For reducing the error, an appropriate model of the signal processing must be developed.

By the theoretical simulation, the interpolation errors of interference signals with different finesses can be estimated (Fig. 3) with the sinusoidal signal processing module. The results indicate that over a displacement period the maximal
Interpolation error is about 9.6 nm for the finesse of 2.4. That will be reduced to 8.7 nm for the finesse of 2.2. Although the discrepancy is not appreciable, it has distinctly shown that the sinusoidal signal processing model is more suitable for the interference signals with lower fineses.

![Interpolation errors of interference signals with different finesse](image)

For the displacement in the range of hundred millimeters, the interpolation error of few nanometers is mostly tolerable. But for the applications in the small measurement range of millimeters or micrometers, e.g., high precision positioning or vibration measurements, this interpolation error is inacceptable. Thus especially for the type I with the planar mirror, a proper interpolation model for signal processing is urgently required.

Here according to the Eq. 7 and Eq. 8 and the simulation results shown in Fig. 2, the lookup table (LUT) can be established and determined for interpolation model of the multi-interference displacement measurement system. By the Fig. 4, the interpolation table can be accomplished as table 1. In this investigation, the resolution of the LUT table is about 0.1 nm. This model will be able to minimize the interpolation errors for both types of measurement mirrors.

![Lissajou figure of the interference signals](image)

### III. DESIGN OF THE INTERFEROMETER SYSTEM

#### A. Interferometer System

In the precision mechanical industry, the basic requirement for displacement measurements are the measuring range of few hundred millimeters and resolution of sub-micrometer scale. The design of the interferometer system has to fit this requirement. The complete measurement system has two chief modules, including sensor head and Laser and signal processing module (Fig. 5). In sensor head, the components of a folded Fabry-Perot interferometer are integrated on the common base. Laser and signal processing module consists of Laser light source and signal processing unit.

![Scheme of interferometric system](image)

#### B. System Verification

The verification of the measuring range is based on a precision linear stage. The measuring range is compared by the positioning of the linear stage. For the type I interferometer, the measuring range is 200 mm. The range of the type II interferometer is 500 mm. In each experiment, there are 7 measurement positions which repeat from the zero position to the maximum measuring range. Table 2 shows the comparison experimental results with the linear stage. Fig. 6 and 7 are the amplitude of the two interferometer systems during this testing. According to these results, the measuring ranges of two interferometric systems of 200 mm and 500 mm can be verified.

<table>
<thead>
<tr>
<th>phase angle (rad)</th>
<th>displacement (nm)</th>
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<tbody>
<tr>
<td>phase angle &lt; 0.000309</td>
<td>0</td>
</tr>
<tr>
<td>0.000309 ≤ phase angle &lt; 0.002409</td>
<td>0.1</td>
</tr>
<tr>
<td>0.002409 ≤ phase angle &lt; 0.004509</td>
<td>0.2</td>
</tr>
<tr>
<td>0.004509 ≤ phase angle &lt; 0.006607</td>
<td>0.3</td>
</tr>
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</table>

![Table 1 Table of LUT method](image)


<table>
<thead>
<tr>
<th>Type I</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td>stage</td>
<td>FPI</td>
</tr>
<tr>
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<td>-0.607</td>
</tr>
<tr>
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<td>199991.434</td>
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<tr>
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<tr>
<td>200000</td>
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</tr>
<tr>
<td>0</td>
<td>0.057</td>
</tr>
</tbody>
</table>

IV. EXPERIMENT RESULTS

A. Comparison Experiment Result

The experimental results (Fig. 9 and Table 3) showed that the maximum deviation is about 0.7822 μm and the maximum standard deviation is about 0.2162 μm in the whole range.

In the measuring range of 300 mm, there is a significant deviation in the first measuring interval. There exists a repeated systematic error and needs to be investigated in the future. In preliminary estimating, the deviation source might be the tilt angle or the straightness error of the linear stage.

V. CONCLUSION

A flexible and self-developed multi-interferometric system with difference measurement mirrors has been proposed. Its involving measurement features have been verified.
experimentally. In this interferometric system, there are the structures of common optical path, the single pass or double pass interferometric model, which can be simply realized according to different measurement purposes.

According to the results of the displacement measurements with the type II, the maximum deviation between two interferometric systems is 0.7822 µm and the maximum standard deviation is about 0.2162 µm in the measuring range of 300 mm..

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REFERENCES


