Dual Mode Phase Measurement of Heterodyne Optical Interferometry
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Abstract

We present a new digital phase measuring scheme for optical heterodyne interferometry, which provides high measurable velocity up to 6 m/s with a fine displacement resolution of 0.1 nanometer. The main idea is combining two distinctive digital phase measuring techniques with complementing characteristics to each other; one is the Doppler shift frequency counting with 20 MHz beat frequency for high velocity measurement and the other is the synchronous phase demodulation with 2.0 kHz beat frequency for extremely fine displacement resolution. The two techniques are operated in switching mode in accordance with the object speed in a synchronized way. Experimental results prove that the proposed dual mode phase measuring scheme is realized with a set of relatively simple electronic circuits for beat frequency shifting, heterodyne phase detection, and low-pass filtering.

Keywords: Optical heterodyne interferometry; dual mode phase measurement; displacement measurement; beat frequency shifting; Doppler shift.

1. Introduction

Nowadays high performance precision machines are increasingly adopting heterodyne laser interferometers as position feedback transducers to attain sub-micrometer resolutions over a long travel of machine axis movement. However, the task of achieving high velocity measurement together with sub-micrometer resolutions is not easy because currently available phase measurement techniques for optical heterodyne interferometry suffer degeneration in measuring resolution when the bandwidth of phase detection is increased. Many techniques demand a tradeoff between the maximum measurable velocity and the displacement resolution, because the two performance criteria conflict with each other to be attained simultaneously due to limitations of individual measuring principles. To cope with the problem, in this investigation, we propose a new digital phase measuring scheme based on the hybrid concept of adopting two distinct techniques with complementing characteristics to each other; one is the Doppler shift frequency counting with high velocity measurement capabilities and the other is the synchronous phase demodulation advantageous for extremely fine resolutions. The two techniques are concurrently operated in accordance with a switching strategy regarding the object velocity to be measured. This dual mode concept allows a low cost, but high performance phase measurement as will be demonstrated in detail through a series of relevant experiments.

2. Measurable Velocity and Displacement Resolution

If a laser source of 600 MHz beat frequency is used, the maximum measurable velocity
reaches above 200 m/s. However, increasing beat frequency for high velocity measurement deteriorates the measuring resolution in return. The reason is that the bandwidth of phase detection is usually fixed in the absolute time scale in most phase measuring techniques.

3. Dual Mode Phase Measurement

The concept of dual mode phase measurement proposed in this investigation is to combine two different but complementing phase measurement techniques. One is the high Doppler shift frequency counting with 20 MHz beat frequency technique that performs high speed measurement up to 6.7 m/s. The other is the high resolution displacement measurement of synchronous phase demodulation with 2.0 kHz beat frequency that is aimed for an extremely fine resolution of 0.1 nanometer within the speed limit of 0.67 mm/s. When the object speed is low at the onset of acceleration and also in the final positioning of deceleration, both the techniques are operated in the “high resolution phase mode.” In this mode, the total displacement \( L \) is measured as

\[
L = \frac{\lambda}{2} \times \{N + \left( \frac{\phi_2 - \phi_1}{360^\circ} \right) \}
\]

(1)

where \( N \) is the total number of frequency count of Doppler shift, and \( \phi_1 \) are \( \phi_2 \) are the initial and final phase values respectively measured by the high resolution phase measurement of synchronous demodulation.

Realizing the dual mode phase measurement proposed so far requires identifying by experiment the exact phase value of the phase meter right at the precise instance when actual up/down counting of the frequency counter takes place.

4. Experimental Results

Firstly, the measurement resolution and stability of the high resolution phase meter were examined in comparison with commercially available high performance function generators whose phase accuracy had been guaranteed as 0.05° through external standardized calibration procedures. Considering that the overall noise level of the circuits was measured 0.3 mV, it is concluded that the resolution of the phase meter is in the level of 0.01°. In addition, as for the long term stability of the circuits, it was found that the output of the phase meter fluctuates only within the limit of 0.1° over a period of 6 hours.

Secondly, the whole electrical circuits for both the phase meter and frequency counter were evaluated as an assembly. For this, the function generators were used in the same way as previously to generate the reference and measurement signals. In addition, for accurate digital determination of the displacement following Equation (1), the analog output of the volt meters were connected to an IBM PC via GPIB interface. Repeated measurements were taken to reveal that the mean deviation of phase readings from the assembly is –0.045° with 0.027° standard deviation. For comparison, the beat frequency shifter in the phase meter was
deactivated and then measurements were taken again with the original 20 MHz beat frequency. 
This comparison confirms that the beat frequency shift from 20 MHz to 2.0kHz improves 
measuring accuracy by a factor of 4.
Thirdly and finally, actual displacement measurements were performed after integrating 
the developed circuits with necessary optics for heterodyne interferometry. For evaluation of 
test results, a capacitive displacement sensor was installed after calibration as the reference in 
computing measurement errors of the laser interferometer.

5. Conclusions
We have proposed and tested a new dual mode phase measurement method for optical 
heterodyne interferometers, which is specially devised to provide advantages in measuring 
resolution and speed at the same time. This new method is realized with relatively simple 
electronic circuits of beat frequency shift, high resolution phase detection, and high 
bandwidth frequency counting. Repeated experimental results show that measurement 
resolution is improved by a factor of 10, while measurement repeatability is enhanced from 
1.47 ± 0.083 nm to 0.34 ± 0.061 nm in terms of standard deviation.

Reference
[1] F.C. Demarest , “High-resolution, high speed, low data age uncertainty, heterodyne 
interferometer displacement transducer for microactuator control”, Rev. Sci. Instrum. 63 
**Figure 1**
Electronic configuration of the dual mode phase measuring method.

**Figure 2**
Evaluation result:
(a) Phase detection variation (nm) between conventional method and "dual mode phase measurement"
(b) Variation (*) of the phase value at the up/down counting point.

**Figure 3**
Results of the dynamic test.