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# Heterodyne Optical Interferometer using Dual Mode Phase Measurement

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## ABSTRACT

We present a new digital phase measuring method for heterodyne optical interferometry, which provides high measuring speed up to 6 m/s with a fine displacement resolution of 0.1 nanometer. The key idea is combining two distinctive digital phase measuring techniques with mutually complementary characteristics to each other ; one is counting 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 of beat frequency shifting, heterodyne phase detection, and low-pass filtering.

**Keywords** : interferometry , phase measuring, frequency counting, dual mode, heterodyne phase detection, beat frequency

## 1. Introduction

Positioning accuracy is required during the production of ULSI, magnetic disks, optical disks, and many measurement systems. There is also a requirement to reduce the positioning time in such processes and a measurement system is needed that can respond to the high speed movement. Since the accuracy and the measurement speed are mutually limit, it has been difficult to accomplish both.

Heterodyne optical interferometry provides high precision less than single wavelength of light in displacement measurement with good traceability of uncertainty to the international length standard. A remarkable recent industrial application of the interferometry is that many modern precision machines are increasingly adopting heterodyne laser interferometers as position feedback transducers to obtain a sub-micrometer resolution over a long travel. A good example is the lithography stepper that equips a set of heterodyne laser interferometers to support the projection of fine master patterns of integrated circuits onto wafers in stepping or step-and-scan mode [1]. The overall throughput of the lithography operation greatly depends upon the moving speed of machine components; thus the optical position transducers are required to provide a high value of the maximum measurable speed while maintaining a fine resolution. However the task is not easy to be accomplished since currently available phase measurement techniques for heterodyne interferometry tend to have a low resolution when measuring bandwidth is increased.

Although the intensive work has been done during last decades, quite a few noble techniques of phase measurement are available; they are the Doppler frequency counting with phase lock loop [2], Synchronous demodulation (phase sensitive detection)[3], Pulse width averaging[4], Vernier inspired scheme[5], Triangular wave generation[6], and Linear time-interpolation scheme[7]. For the accurate and the speedy measurement, we have developed a system that can measure the displacement of the object precisely and can respond to high speed movement. In this paper, we propose a new digital phase measuring concept based upon the hybrid concept of adopting two distinct techniques with mutually complementary 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 resolution. The two techniques are operated in switching mode in accordance with the object speed in a synchronized way. When the object moves much faster than a predefined threshold limit, a high bandwidth electronic counter with a relatively low displacement resolution can be used for the measurement. On the other hand, when the object moves slower than the threshold limit, a high resolution phase sensitive detection scheme meter can be used for the measurement for extremely fine resolution. This dual mode concept allows a low cost, but high performance phase measurement as demonstrated in detail through a series of relevant experiments.

## 2. Measuring Speed and Resolution

Fig. 1 illustrates the typical system configuration of heterodyne laser interferometers for displacement measurement. A stabilized He-Ne laser source generates two orthogonal beams of linear polarization with different frequencies, $f_1$ and $f_2$. Part of the source beam splits off in front of the interferometer and passes through an analyzer to produce the reference electrical signal of $f_1$-$f_2$ beating frequency. Major part of the source beam impinges on the polarizing beam splitter and splits into the reference and measurement arms in compliance with polarization. The reflecting beams get together in the beam splitter and pass through an analyzer to produce the measurement electrical signal. The frequency shift $\Delta f$ between the reference and measurement electrical signals is then obtained in accordance with the Doppler effect such as

$$\Delta f(t) = \frac{2nv(t)}{\lambda} \tag{1}$$

where n is the refractive index of the medium; λ the wavelength of light in vacuum; and v(t) the velocity of the moving object. Integrating the above equation about time gives

$$\varphi(t) = \frac{4\pi nL(t)}{\lambda} \tag{2}$$

where φ(t) denotes the phase shift between the reference and measurement signals, while L(t) is the displacement of the object to be finally determined.

Equation (1) tells that if the object moves at a speed of 1.0 m/s in air, the frequency shift is worked out to be $\Delta f(t) = 3.2$ MHz, assuming $n = 1.0$ and $\lambda = 0.63$ μm. In practice, the maximum amount of frequency shift is limited by the beating frequency of the laser source, which is usually in the typical range of 2 MHz in case of the Zeeman type , 20 MHz the acousto optic modulator (AOM) type , and 600 – 1000 MHz for the stabilized two-mode lasers [8]. Maximum measuring speed is also limited by the bandwidth of the phase meter. Practically for a lower bandwidth than variation of the beating frequency "phase unwrraping problem" meets. Another constraint on the maximum measurable speed is the angle resolution of the phase meter used for detection of the phase shift φ(t). If one wishes to measure the displacement L(t) with a resolution of 0.1 nm, equation (2) depicts that the phase shift φ(t) should be monitored with a angle resolution of 0.1°. In practice, the bandwidth of a phase meter is restricted so that the angle resolution is in inversely proportion with the frequency of the input signal.

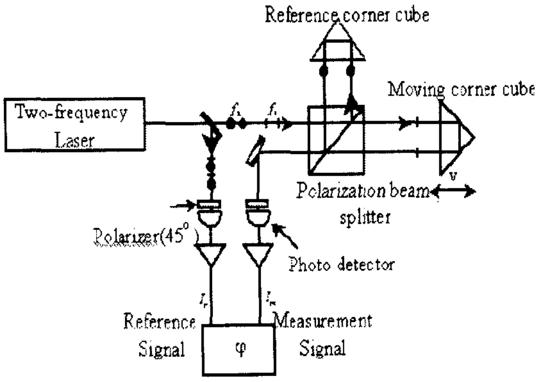
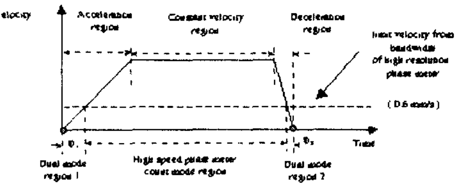


Fig. 1 Heterodyne interferometer

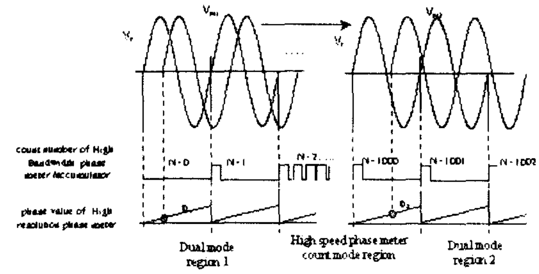
## 3. Dual Mode Phase Measurement

Fig. 2 (a) illustrates the position and velocity profiles of a motion control servo, which usually comprises three distinctive sequences of acceleration, constant velocity, and deceleration. For the motion controlling, the laser interferometer is needed to provide the accurate position. In this investigation the task of increasing the measuring speed while maintaining a fine resolution is accomplished by adopting a dual mode phase measuring scheme.

In this article, we start from the simple concept that both goals can be accomplished if we measure phase using two different phase meters: one has high electronic bandwidth with low resolution and the other has high resolution but low electronic bandwidth. We call this concept "Dual mode phase measurement" scheme. The schematic diagram of this measurement concept is illustrated in Fig. 2 (b). Basically we assume that linear and angular displacement measurement starts at rest and velocity profile of the moving object is known as in cases of motion control. A typical motion of the moving object has three different regions of acceleration, constant velocity and deceleration. So, the measurement of the moving object can be done with three different regions of a dual mode, high-speed phase count mode and another dual mode, respectively. A limit velocity from bandwidth of the high resolution phase meter is used for the reference of the mode change. Under the reference velocity, the high-resolution phase meter and the high-speed phase counter can be used, simultaneously. We call this mode as a "dual mode". In case of over the reference velocity, the high-resolution phase meter can be used only and is called "high-speed phase count mode". A high-resolution and high-velocity measurement can be achieved by use of these methods. But for this concept, a major problem should be solved. Practically a phase of up/down counting point of the high-speed phase meter is not exactly the same with the unwrapped phase of the high resolution phase meter. That means we should know the exact phase of counting point. If not, an incorrect counting number and an incorrect displacement information are obtained. A correct phase of counting point can be obtained by simultaneous detection of starting time and stopping time displacement for several periods. The configuration of this measurement concept is illustrated in Fig. 3. For the high-resolution phase meter, the heterodyne detection scheme and "beat frequency shift" concept are used under the reference velocity of Fig. 2. A pair of signals divided by power splitters is routed to double balanced mixers, mixed with a local oscillator signal. Then two low beat frequency signals (equal to difference between signal frequency and local oscillator frequency; 1 ~ 5 kHz) can be generated by being low-pass filtered. By this "beat frequency shift" concept, measured phases on high beat frequency are shifted into on low difference frequency.[8] Next a normal phase meter with high resolution (say 0.01°) is added to measure phase between low pass filtered outputs. The other pair is routed to the high-bandwidth phase meter/accumulator for fringe counting with $\lambda/2$ resolution. The high-resolution phase meter and circuit of beat frequency shift are illustrated on



(a) Typical velocity profile for motion control



$$L = \frac{\lambda}{2} \times \left\{ N + \left( \frac{\varphi_2 - \varphi_1}{360} \right) \right\}$$

(b) Concept of dual phase measurement

Fig. 2 Scheme of dual phase measurement for real positioning

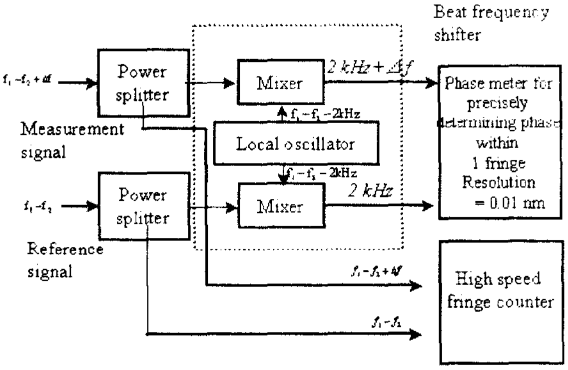


Fig. 3 Concept diagram of dual phase measuring method

Fig. 5 and Fig. 6. For the high-speed phase counter, the double balanced mixer, the circuit of Schmitt trigger and a up/down counter are used as shown on Fig. 7. Basically the measured velocity is limited by the beat frequency of the laser source. The source with a high beat frequency of 600 MHz and a high stabilization with $10^{-10}$ uncertainty is developed[9]. The measurable velocity is approximately over 15 m/sec with this source and the low pass filter, which has wide enough bandwidth of 100 MHz.

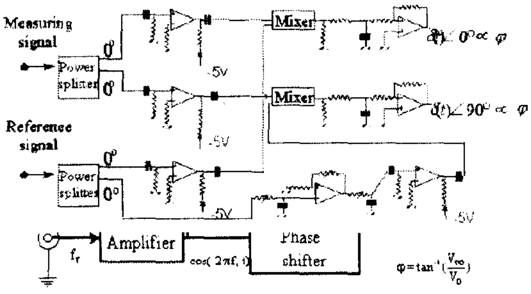


Fig. 4 Measuring method of phase difference using PSD

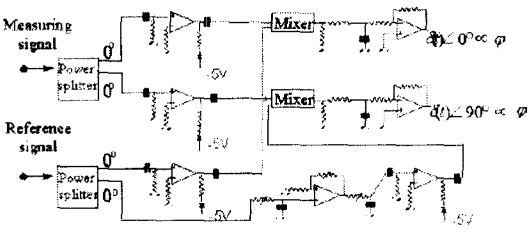


Fig. 5 Phase demodulator circuit diagram

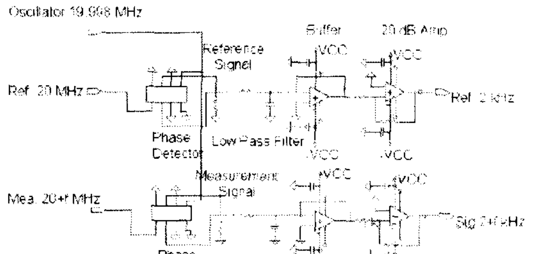


Fig. 6 Electronic circuit diagram for a beat frequency shifter

This phase meter generates an up/down pulse every phase increment/decrement of 180° and accumulator counts this pulse. The outputs from two phase-meters can be used to measure the total displacement of a moving object as follows:

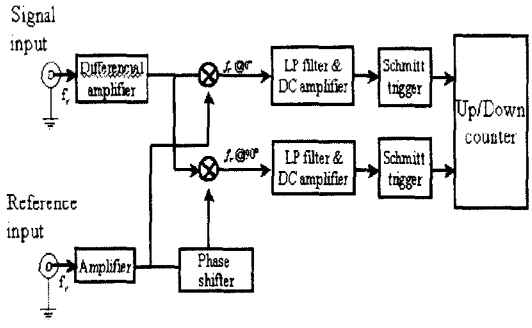


Fig. 7 Diagram of a high frequency counter for unwrapping

$$L = \frac{\lambda}{2} \times \{N + (\frac{\varphi_2 - \varphi_1}{360^{\circ}})\} \qquad (3)$$

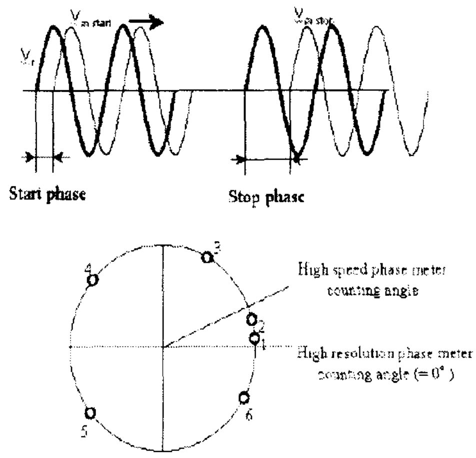
where, L is the displacement of mirror, N is number of counts at the accumulator, and $\varphi_1$, $\varphi_2$ is the initial and final phase value at the high resolution phase meter, respectively.

For implementation of the dual phase measurement scheme, we choose the commercial heterodyne laser source, which has the difference frequency of 20 MHz corresponding to the approximately 6 m/s velocity. We design the beat frequency shifter, which converts 20 MHz beat signal to 2 kHz for higher resolution and better uncertainty. The beat frequency shifter consists of phase sensitive detectors (Mini-Circuits, model MPD-1), 50 kHz bandwidth RC low pass filters, 30 dB amplifiers, and 19.998 MHz oscillator. We design the phase meter with "heterodyne detection scheme", PSD, and low-pass filter circuit with 0.01° resolution and 50 kHz bandwidth. To calibrate the designed system, we use the typical phase meter (Krohn-Hite Co., model 6620) for reference high-resolution measurement with 0.01° resolution and 10 Hz ~ 10 MHz input signal frequency range of 0.5 Hz bandwidth. This phase meter has the best performance when the frequency of input signals is in the range of 1 kHz ~ 5 kHz. The other phase meter and the high-speed phase meter are used for the heterodyne detection scheme, as illustrated in Fig. 7.

The high-resolution phase meter can detect the correct phase with 2 kHz bandwidth and the moving velocity of 0 to 0.6mm/sec, which is observed at both early region of acceleration and final region of deceleration. Simultaneously, the high-speed phase meter should detect the same movement and the position of counter pulse can be obtained by direct comparison of the phase of high-resolution phase meter for these regions. Fig. 8 shows the relation between the pulse counting angle of high speed phasemeter and the wrapped phase of the high-resolution phase meter in dual mode phase measurement scheme. For example, the phase at a start point of measurement signal $V_{m\,start}$ is $\varphi_1$ and the phase at a stop point of measurement signal $V_{m\,stop}$ is $\varphi_2$ about reference signal $V_r$ , $\varphi_3$ is the pulse counting angle of high speed phasemeter and $\varphi_0$ is the wrapped phase of the high-resolution phase meter. The counting number is $N_{count}$ and the real count number used in displacement calculation is $N_{real}$. Then, the relation and the count number are as follows;

In case of $\varphi_1 < \varphi_3 < \varphi_2$ then $N_{real} = N_{count} - 1$
for counter clock wise direction

In case of $\varphi_1 < \varphi_0 < \varphi_2$ then $N_{real} = N_{count} + 1$
for counter clock wise direction



| Start phase | Stop phase | High speed counting point | High resolution counting point | Real moving phase | Count Number | Real phase count number |
|---|---|---|---|---|---|---|
| 1 | 2 | No | No | $\varphi_2 - \varphi_1$ | N | N |
| 1 | 3 | Yes | No | $\varphi_3 - \varphi_1$ | N+1 | N |
| 1 | 4 | Yes | No | $\varphi_4 - \varphi_1$ | N+1 | N |
| 2 | 6 | Yes | No | $\varphi_6 - \varphi_2$ | N+1 | N |
| 2 | 1 | Yes | Yes | $\varphi_1 - \varphi_2 + 360°$ | N+1 | N+1 |
| 6 | 1 | No | Yes | $\varphi_1 - \varphi_6 + 360°$ | N | N+1 |
| 6 | 3 | Yes | Yes | $\varphi_3 - \varphi_6 + 360°$ | N+1 | N+1 |

Fig. 8 Correct phase counting method in dual phase measurement scheme

So, the relation should be known at a acceleration region and a deceleration region by simultaneous phase measurement. Also, data with enough periods and statistics are needed for correct estimation.

## 4. Experimental Results

Fig. 9 shows the configuration for performance test of the electronics of the phase meter with dual mode measurement. Two phase-locked function generators based on the static test which corresponds to interferometric measurements with the reflector at rest are used to generate constant phase difference. Each phase value is measured by the phase meter with "dual mode phase measurement" and read with digital voltmeter and transferred to PC via GPIB line and the phase difference between the two signals is calculated by PC. Then, the output of a function generator is adjusted into known value by software, which results in the change of the phase difference of the two function generators and the phase difference is also measured by the same procedure. So we can calculate the change of the phase difference which is resulted from adjusted value by software. By comparing the two value, one is the change of phase difference at the phase meter and the other is the adjusted phase value by software, the performance of the phase meter can be tested. By the same procedure, the performance of the conventional phase meter[4] can be tested.

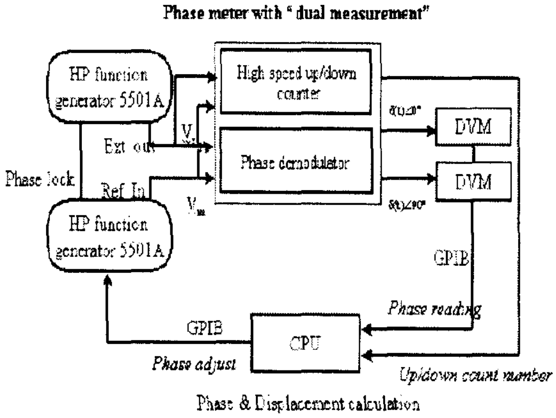
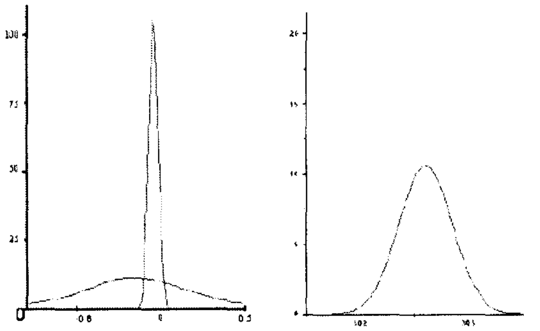


Fig. 9 Block diagram of phase demodulator static test

Also, we test the resolution and uncertainty of the designed phase meter. The accuracy of the phase measurement from the function generator, HP 5501A , is 0.05°, so that the input phase can be adjusted with step 0.1° which results in output change of 3 mV at the DVM. The circuit noise level is 0.3 mV, so that the resolution of the phase meter is 0.01°. And output variation is 0.1° with a same input phase during 6 hours, and uncertainty of the phase meter is 0.1°.

We test the performance of the designed phase meter by comparing with those of conventional phase meter. Fig. 10(a) is the tested result. The input phase is adjusted with step 0.5° and detected output change of the designed phase meter is directly compared with that of conventional phase meter. Mean value of the conventional phase meter from high beating frequency of interferometer is –0.157° and standard deviation value is 0.283°. Mean value of the designed phase meter from shifted low beating frequency of interferometer is –0.045° and standard deviation value is 0.027°. This result means the designed phase meter is better than conventional phase meter for the measurement the phase of interferometer. The correct phase of counter pulse of constructed circuit is obtained as mean 302.6 nm and standard deviation 0.25 nm during 360 periods as following results of Fig. 10(b).



**a) Phase error between input and output of two phase meters (nm)**

**(b) difference between up/down counting phase and phase meter (°)**

Fig.10 Evaluation result

(a) phase detection error between conventional method and "phase dual measurement"

(b) difference between up/down counting reference phase and high resolution phase meter

In dynamic test, the tested reflector is moving. Fig. 11 is an experimental configuration for the dynamic test of the designed phase meter in long moving range. The set-up consists of two reflectors attached to each side of a moving table and the displacement module of commercial laser interferometer system for reference and tested dual mode phase measurement system with laser source. Displacement of the moving table is measured with one reflector, the commercial displacement measurement module, and the same displacement with the other sided reflector and the designed phase meter, simultaneously. Moving speed is 15 mm/sec in the design of the bandwidth 50 kHz . Two outputs are compared directly. Fig. 12 shows; the difference mean value of two phase demodulators with the same movement is –41.83 nm and standard deviation is 34.52 nm. It is a large error for two laser interferometer systems at a long distance apart. Air fluctuation and the temperature gradient can be a source of different displacement data. (For example, if the variation of the refractive index of air is $10^{-6}$ and distance is 1 m, then difference is 1μm and distance is about 2 m in our set-up.) The imperfect straightness of the moving guide and the imperfect simultaneous sampling are other sources of difference. By this test, possibility of "dual mode phase measurement "scheme can be proved.

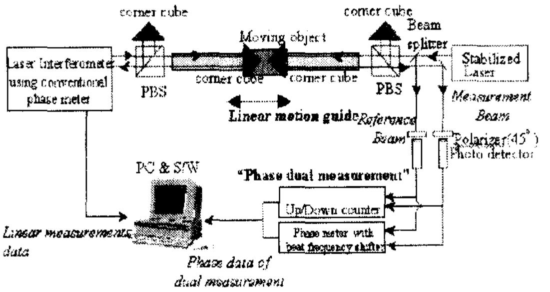


Fig. 11 Test set up concept diagram with "phase dual measurement

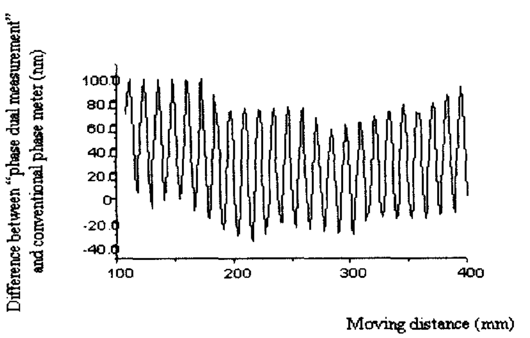


Fig. 12 Result with "phase dual measurement" and conventional phase meter

Fig. 13 is another experimental configuration for the dynamic test of the phase meter in short moving range. The set-up consists of a capacitance gap sensor attached to a moving table manufactured as the double parallel spring flexure. Tested "dual mode phase measurement" system with laser source and the conventional phase meter[14] of laser interferometer system are used. Displacement of the moving table is measured with the capacitance gap sensor and the designed phase meter and the conventional phase meter measure that displacement, simultaneously. Moving speed is 100 nm/sec. Two outputs of two phase demodulators are compared, directly. Displacement signal of the capacitance gap sensor is used as a displacement reference.(resolution; 0.1nm, linearity; 0.01%). In the results represented in Fig. 14, mean value is 3.25 ~ 4.47 nm, standard deviation is 4.98 ~ 8.21 nm with the commercial phase meter. Mean value is 0.97 ~ 1.38 nm, standard deviation is 1.17 ~ 2.48 nm with the designed phase meter. This result means the designed "dual mode phase measurement" scheme is better than that of commercial phase meter to measure the phase of interferometer.

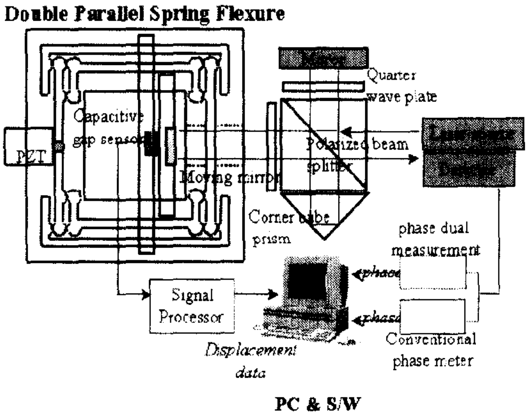


Fig. 13 Test set-up with "phase dual measurement" for dynamic testv

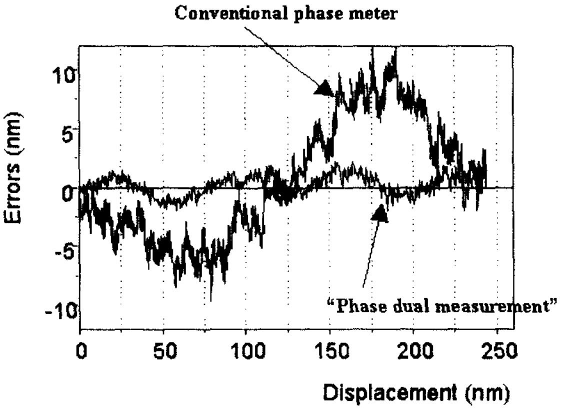


Fig. 14 Result of dynamic test with "phase dual measurement"

## 5. Conclusion

We have developed a new laser interferometer system that can precisely measure the position of an object and responds to high speed change in its position.

We proposed the "dual mode phase measurement" scheme of the high-speed and high-resolution phase meter for the laser interferometry system and made it with a set of relatively simple electronic circuits of beat frequency shifting, heterodyne phase detection, and low-pass filtering. The importance of the relation between the position of counting pulse and the phase of the high-resolution phase meter in proposed scheme is shown and used in high speed phase counter. Also, usefulness of that scheme is proved by direct comparison with results of the designed phase meter and the conventional one by the static and two dynamic tests. In the static test, two function generators with adjustable locked phases and tested phase meters are used and the designed phase meter allows the 90 % decreased standard deviation value than that of the conventional phase meter. The possibility of the proposed scheme is proved with the dynamic test used two laser interferometer systems with a long moving range of 400 mm and possible sources of the error is estimated. In another dynamic test, two outputs of two phase demodulators are compared directly and the results show the designed phase meter has the standard deviation of 1.17 ~ 2.48 nm but 4.98 ~ 8.21 nm with the commercial phase meter. So it can be used practically for more high speedy and accurate measurement of displacement.

The designed target specification of high speed over 6 m/sec and the accuracy under 0.1 nm can be achieved with the proposed "dual mode phase measurement" scheme.

## Acknowledgement

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