REAL-TIME PERIODIC ERROR COMPENSATION WITH LOW/ZERO VELOCITY PARAMETER UPDATES

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INTRODUCTION
It has been shown recently that periodic errors caused by frequency leakage in displacement measuring heterodyne interferometers can be compensated in real time [1]. The approach is to acquire error parameters during target motion in 1 millisecond intervals and apply the current error parameters through digital compensation in the next millisecond, while again measuring the error parameters. In this way, the compensation is applied in a leap-frog manner with 1 millisecond latency. While compensation can be applied at any travel velocity, updating the error parameters currently requires that a minimum travel speed be met or exceeded. There are applications, however, where this minimum speed is seldom or never reached in operation. Therefore, the parameters cannot be updated even though they are continuously changing. An example of this situation is the x-axis interferometer on a stage moving mainly in the y-direction (such as the position feedback for a lithographic stepper machine used in semiconductor fabrication). Mirror imperfections cause beam shear in the x-axis interferometer, which alters its periodic error magnitude even though there is effectively no x-travel.

In this work, it is shown that by monitoring the interference signal strength, it is possible to update first order periodic error magnitude even at low/zero velocities because there is an inverse-proportional relationship between the two. A setup is presented where beam shear is intentionally modified to vary the intended interference signal magnitude, while maintaining the first order periodic error signal magnitude. The resulting variation in first order periodic error magnitude is identified from the position signal.

BACKGROUND
A schematic of a single pass heterodyne displacement measuring interferometer is provided in Fig. 1. The two light frequencies, f1 and f2, are collinear, but orthogonally polarized so that they can be separated at the polarizing beam splitter (PBS). Ideally, f1 travels only to the moving target and f2 only to the fixed target. However, due to physical imperfections, frequency leakage occurs. Specifically, f1 and f2 travel to the both the moving and fixed targets. In this case, rather than obtaining only the intended interference term (f1 to moving target and f2 to fixed), multiple interference terms appear in the frequency spectrum. These multiple “interferometers” yield the cyclical perturbations in the measurement signal referred to as periodic error. The frequency leakage is depicted in Fig. 1 using an asterisk to identify the unintended frequency in each path.

FIGURE 1. Schematic of single pass heterodyne interferometer with frequency leakage.

The individual terms that appear in the frequency spectrum for the fully leaking interferometer are: 1) f1-f2, intended signal; 2) f1*-f2 and f1-f2*, responsible for first order periodic error; 3) f1*-f2, responsible for second order periodic error; and 4) f1-f1* and f2-f2*, equivalent to homodyne interference signals (only problematic at high velocities and corresponding large Doppler shifts [2]).

Beam shear, or a change in overlap between the beams returning from the fixed and moving
targets, is introduced by a lateral (left/right) offset of the moving target. This is demonstrated in Fig. 2. In this case, the magnitude of the first order periodic error signals are unaffected because they exist in a single path; both f₁ and f₂ appear in the fixed path and both f₁ and f₂ appear in the moving path. However, the magnitudes of the remaining signals do vary with the change in beam overlap. For example, the magnitude of the intended interference signal between f₁ and f₂ varies with beam shear because the overlap between the two (nominally) Gaussian profile beams changes.

Periodic error magnitudes can be calculated using the magnitudes of the individual interference terms [3-4]. First order error depends on the ratio of the f₁*-f₂/f₁-f₂* signals, which appear at the beat frequency (i.e., the difference between the f₁ and f₂ frequencies), and the f₁-f₂ intended interference signal, which appears at the beat frequency shifted by the Doppler frequency (that varies with the target velocity). Because the magnitudes of the f₁*-f₂/f₁-f₂* signals are constant, but the intended interference signal magnitude is not, their ratio varies and first order periodic error magnitude changes with beam shear.

Second order error depends on the ratio of the f₁*-f₂* signal, which is also Doppler shifted from the beat frequency but in the opposite direction from the intended interference signal, and the f₁-f₂ intended interference signal. Because both signals are attenuated with beam shear, the ratio remains approximately constant and the magnitude of second order periodic error does not change with beam shear.

As noted, however, these error magnitude calculations require that the individual signals can be resolved in the frequency spectrum, which demands relatively high target velocities to achieve the necessary separation via the Doppler shift. In this work, it is shown that low velocity compensation for first order periodic error is possible due to the relationships just described.

**EXPERIMENTAL SETUP**

In order to enable variable beam shear in a single pass heterodyne interferometer, a dedicated setup was developed; see Fig. 3. In this setup, a two-frequency laser head directs the 1.5 mm diameter, collinear light beams first through a non-polarizing beam splitter (NPBS), where the reference signal for phase measurement is obtained. The beams then pass through an adjustable half wave plate (HWP) which enables the linear polarization vectors to be rotated and changes the amount of frequency leakage in the PBS. Next, the two frequencies are nominally separated at the PBS and travel to the fixed and moving targets; the moving retroreflector (RR) is mounted on an air bearing stage. The beams are recombined in the PBS, turned 90 deg by a prism and pass through an adjustable linear polarizer (LP), which enables the interference signal magnitudes to be modified. This provides the measurement signal for the phase measuring electronics (312.5 kHz sampling frequency, 0.3 nm resolution).

![FIGURE 2. Beam shear caused by lateral motion of the moving target.](image)

![FIGURE 3. Schematic of experimental setup to enable adjustable beam shear.](image)
cross slide position for a particular beam offset, collecting the position data using the phase measuring electronics, and then analyzing the data to determine the first and second order periodic error magnitudes. The periodic error magnitudes were identified by: 1) separating the position data into multiple sections; 2) subtracting a least squares polynomial fit to remove the macroscale motion and isolate periodic error; 3) calculating the discrete Fourier transform of the residual time-domain data; 4) identifying the first and second order periodic error magnitudes based on the Doppler shift (commanded velocity); and 5) averaging the results from the individual sections.

EXPERIMENTAL RESULTS

Figure 4 demonstrates the variation in signal magnitudes with changes in the moving RR offset (beam shear). The data was collected using a spectrum analyzer and the velocity was 5000 mm/min to produce sufficient frequency separation. It is seen that the intended interference signal (left) magnitude varies significantly with offset. It is maximum when the beams from the fixed and moving RRs are ideally overlapped (zero offset) and reduces with the moving RR lateral offset in either direction (±1 mm in the plot). The situation is similar with the second order error signal (right) magnitude. However, the magnitude of the first order error signal (middle), which appears at the 3.6 MHz beat frequency, does not change with offset as discussed previously.

Figure 5 shows the variation in first and second order periodic error magnitudes with offset. These magnitudes were determined from position data (obtained using the phase measuring electronics) with 3 deg HWP and LP misalignments and a velocity of 100 mm/min. Figure 6 shows the results for 5 deg HWP and LP misalignments. In both cases, the expected variation in first order periodic error magnitude with offset is observed. Additionally, the second order error magnitude is approximately constant, as discussed.

FIGURE 4. Variation in signal magnitudes with changes in the moving RR offset (beam shear).

FIGURE 5. Variation in periodic error magnitudes versus moving RR offset with 3 deg HWP and LP misalignments and a velocity of 100 mm/min.

FIGURE 6. Variation in periodic error magnitudes versus moving RR offset with 5 deg HWP and LP misalignments and a velocity of 100 mm/min.

In order to demonstrate the inverse-proportional relationship between the intended interference signal and first order periodic error magnitudes,
the following procedure was completed. First, the magnitudes of the interference signals were measured at offsets from \(+1\) to \(-1\) mm using a spectrum analyzer. A velocity of 5000 mm/min was used to provide adequate frequency separation and a misalignment angle of 10 deg was selected for both the HWP and LP to yield large periodic error magnitudes. Second, the first order periodic error magnitude was calculated using the spectrum analyzer data for each offset. The procedure described in Ref. [4] was applied. Third, a scaling factor, \(S_{Fi}\), was defined at each offset \(i\) which depended on the ratio of the intended interference signal magnitude, \(IIS_i\) (in dBm), at that offset to the intended interference signal magnitude at zero offset, \(IIS_0\). See Eq. 1, where the power relationships are required to convert from dBm to linear magnitude units. Fourth, the offset-dependent scaling factor was multiplied by the first order periodic error values. The results are displayed in Fig. 7.

\[
S_{Fi} = \frac{IIS_i}{10} \left(\frac{10^{20}}{IIS_0}\right)
\]  

(1)

In Fig. 7 it is seen that the first order periodic error (circles) again follows the parabolic trend observed in the position data analyses from Figs. 5 and 6. The errors are large due to the significant misalignments in the HWP and LP angles. Once the scale factor from Eq. 1 is applied at each offset, however, the scaled first order periodic error (crosses) is approximately constant with offset. This clearly identifies the inverse-proportional relationship between the intended interference signal and first order error magnitudes. Further, it shows that, provided the first order error signal magnitude can be identified (by a high velocity test), monitoring the interference signal magnitude enables the first order periodic error to be compensated, even for low/zero velocity motions.

CONCLUSIONS

In this paper, the variation in first order periodic error magnitude with beam shear was demonstrated. It was shown that by varying the overlap between the beams from the moving and fixed targets, the first order error varied parabolically and the second order error was constant. The outcome is that by first measuring the first order periodic error signal magnitude and then monitoring changes in the interference signal strength, it is possible to update first order periodic error magnitude even at low/zero velocities.

REFERENCES


