

EXPERIMENTAL EVALUATION OF PHASE DIGITIZING NONLINEARITY CORRECTION IN HETERODYNE INTERFEROMETRY

Vasishta Ganguly¹, Tony L. Schmitz¹, Daniel White², and Janet Yun²

¹Department of Mechanical Engineering and Engineering Science
University of North Carolina at Charlotte
Charlotte, NC, USA

²Agilent Technologies Inc.
Santa Clara, CA, USA

INTRODUCTION

Frequency leakage in polarization-dependent heterodyne interferometers results in nonlinearity, or periodic error, in the phase digitized result. Phase digitizing is the process of converting the interferometer signal, obtained from the interference of the reference and measurement beams, into a digital representation of phase. In a previous approach [1-5], the periodic error is removed in a two-step process including phase digitizing, and second, first order periodic error (i.e., a cyclic error with one cycle per wavelength of optical path change) removal from phase digitized data. The second step is repeated for second order periodic error (with two cycles per wavelength of optical path change). This paper describes experimental results for a method where the first order periodic error is removed in the phase digitizing process in a single step. The accuracy of this measurement is not sensitive to target velocity, provided a minimum velocity threshold is at least temporarily exceeded. Because the latency requirement is much reduced from the two-step process, the achievable accuracy in measurement and compensation is improved.

PERIODIC ERRORS IN HETERODYNE INTERFEROMETRY

Figure 1 shows a schematic representation of a heterodyne setup for a single-pass configuration. In the ideal case, the two collinear, orthogonally-polarized laser frequencies (f_1 and f_2) are perfectly split at the polarizing beam splitter and are directed into the measurement and reference arms of the interferometer. The measurement arm contains the moving retroreflector mounted on the stage whose displacement is to be measured, while the reference arm retroreflector is stationary. Motion of the moving retroreflector causes the measurement arm frequency to be Doppler shifted by f_d . The two frequencies from the

measurement and reference arms then pass through a mixing linear polarizer (to cause interference) and are collected by the photodetector, which carries the interference signal to the phase measuring electronics. This Doppler-shifted measurement arm frequency is compared to a reference interference signal in the phase measuring electronics and is used to determine the displacement information. However, due to non-ideal performance, leakage of each frequency into both the measurement and reference arms can occur. This frequency leakage gives rise to nonlinearity in the displacement signal. This nonlinearity is often referred to as periodic error, which is non-cumulative in nature and repeats with integer wavelength changes in the optical path.

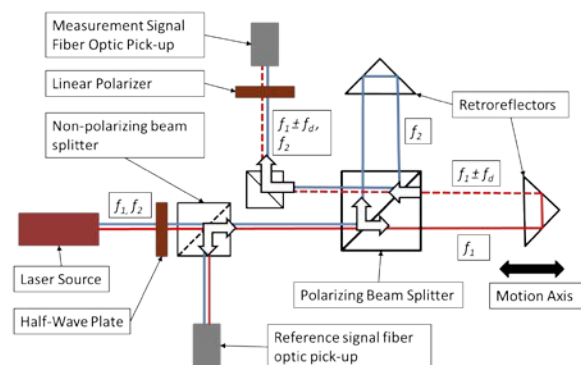


FIGURE 1. Interferometer setup with frequency leakage.

EXPERIMENTS AND RESULTS

Nonlinearity Correction (Constant Velocity)

Experiments were conducted to verify the nonlinearity correction. Initially, tests were conducted at constant velocity, v , stage motion. The randomly selected misalignments of the half wave plate and linear polarizer resulted in a mean first order periodic error of 8.2 nm and mean second order periodic error of 2.2 nm. Figures 2 and 3 show the first and second order periodic errors for different velocities. A

comparison of the results with and without the nonlinearity correction enabled is provided. Figure 2 shows that at stage velocities which produce a Doppler shift magnitude greater than 40 kHz (i.e., the stage speed is greater than 759.6 mm/min) there is a significant reduction in the first order periodic error magnitude. In the current configuration, the nonlinearity correction was not enabled when the Doppler frequency was less than 40 kHz. Because the periodic error correction algorithm implemented in this study does not address the second order component, there is little effect of enabling the nonlinearity correction; see Figure 3.

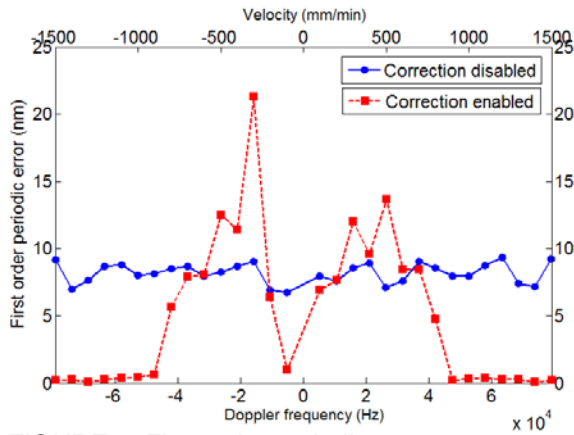


FIGURE 2. First order periodic error.

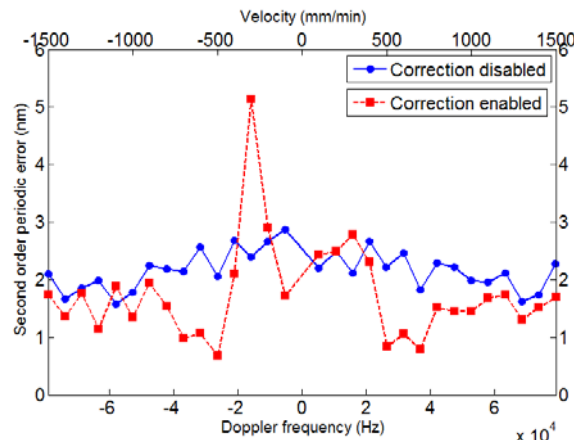


FIGURE 3. Second order periodic error.

Nonlinearity Correction (Sinusoidal Motion)

Tests were also conducted for non-constant velocity. The stage was commanded to move in a sinusoidal motion with a low range and high frequency. This ensured that the complete sinusoidal cycle was captured within a relatively small sampling time (32000 samples at a sampling rate of 312.5 kHz). The collected data was sectioned into small time intervals (0.00125

s, arbitrarily selected). Each section of the data was processed individually. The position data was converted to a stationary signal in the position domain using interpolation and the first and second order errors were then calculated for each section [6]. This technique is discussed in detail later. The results reported here are for the case when the stage was commanded to move in a sinusoidal motion with a total range of 0.4 mm at a frequency of 20 Hz.

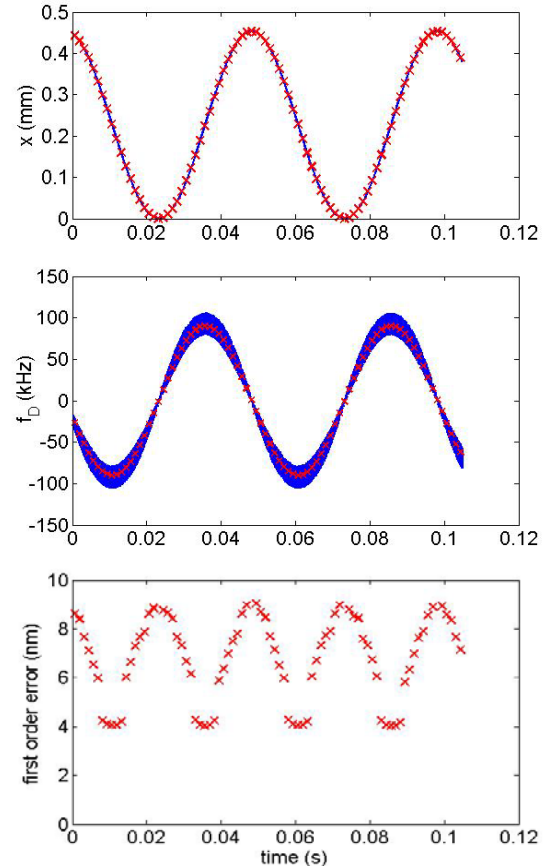


FIGURE 4. Position (x), velocity, and first order periodic error. Nonlinearity correction disabled.

Figure 4 shows the position, velocity, and first order periodic error magnitude as a function of time with the nonlinearity correction disabled. The second order periodic error was not analyzed. The measured motion amplitude is higher than the commanded amplitude. This could be due to overshoot and acceleration limitations of the stage. The red crosses indicate the calculated mean value of position and velocity for each section. The velocity was converted into a Doppler shift frequency using:

$$f_d \text{ (Hz)} = v \text{ (mm/s)} * (2/633) * 1 \times 10^6.$$

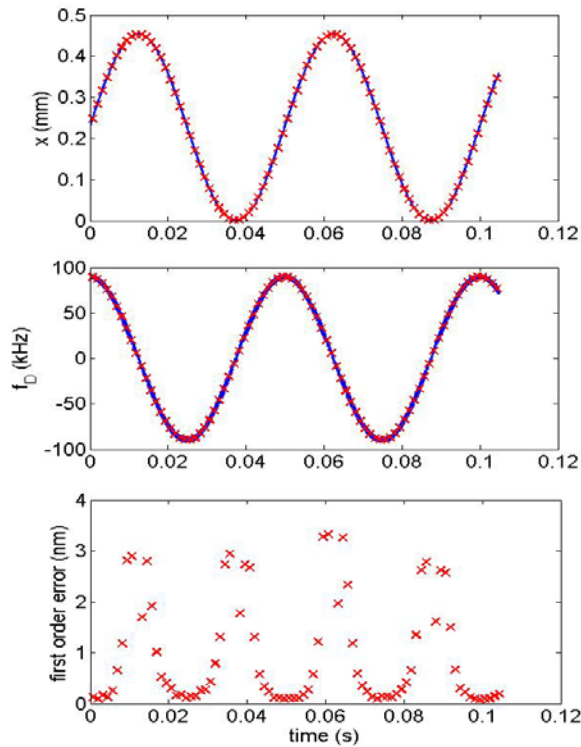


FIGURE 5. Position, velocity, and first order periodic error. Nonlinearity correction enabled.

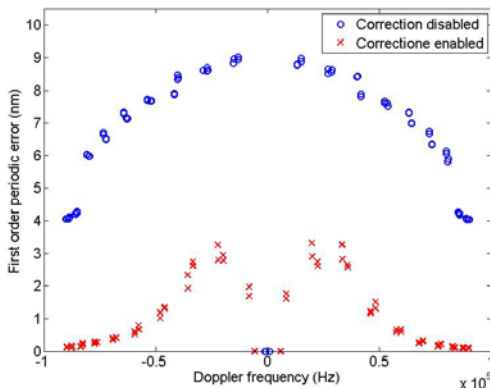


FIGURE 6. First order periodic error as a function of velocity (Doppler frequency shift).

Figure 5 shows the results for the same experimental conditions with the nonlinearity correction enabled. A decrease (improvement) in the first order periodic error is observed. However, at low velocities the error corrections are worse than at higher velocities. These are at the end of the oscillatory motion where the stage is reversing direction. In Figure 6 the first order periodic error is displayed as a function of the velocity (Doppler frequency shift). A considerable improvement in the error was

observed when the nonlinearity correction was enabled.

Position Domain Evaluation of Periodic Error

Each point (marked by the red 'x') in Figures 4 and 5 was obtained by partitioning the data into equal sections in the time domain and analyzing each section individually. The process of determining periodic error is discussed here. Figure 7a shows the total velocity profile and the cross indicates the section selected to illustrate the technique used to identify first and second order periodic errors. Figure 7b shows the motion profile of the selected section. A polynomial fit was applied to the position data. This polynomial fit was then removed from the raw position data to isolate periodic errors.

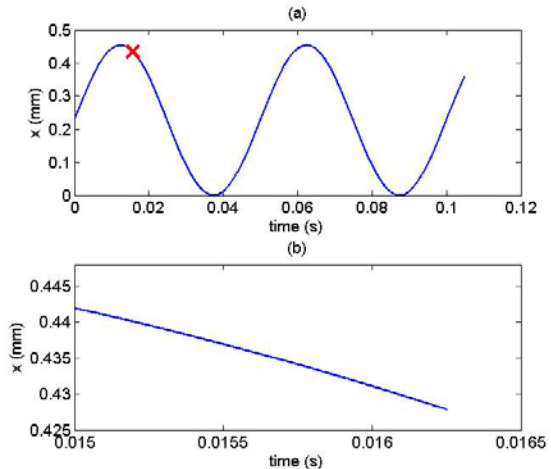


FIGURE 7. Total motion profile. 'X' identifies the selected section (a); the motion profile for the selected section (b).

Figure 8a displays the periodic errors for the selected section. Note that the horizontal axis now denotes position and the error is plotted as a function of position change. This error data was interpolated at equal positional increments, thereby providing equally spaced data in the position domain. Figure 8b shows the interpolated data. Note that only a small fraction of the data in 8a has been plotted in 8b (change in horizontal axis scale). The Fourier transform of this error data in the position domain was then calculated. Figure 8c shows the result, where the horizontal axis was normalized to identify the harmonics of the change in the optical path difference in the interferometer. The first and second order errors are easily identified.

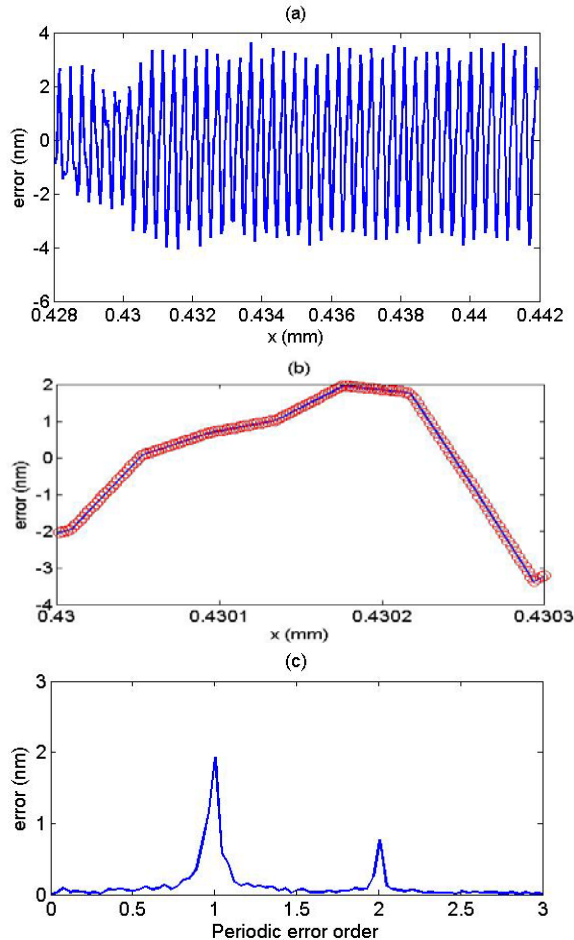


FIGURE 8. Periodic error as a function of position (a); interpolated periodic error (one cycle only) (b); Fourier transform of periodic error (c).

DISCUSSION

In these experiments, the nonlinearity measurement was automatically inactivated when the measured instantaneous Doppler shift magnitude was less than 40 kHz. This was necessary because at a zero Doppler frequency both the intended interference signal and the periodic error components occur at the same frequency, which makes their separation impractical using this algorithm. The exact choice of 40 kHz deserves further investigation because it represents a tradeoff. A larger value allows for a better worst case scenario (when the stage slows to zero velocity after previously travelling at non-zero velocity), but it also reduces the overall average accuracy of the correction. In a system that travels at non-zero velocity, but then crosses below the 40 kHz boundary, nonlinearity measurement would cease, but correction would still continue given

the previously measured parameters. Because the 800 mm/min data is near the limiting velocity (759.6 mm/min), interesting results are observed (Figure 2). Even though the true velocity varied only slightly due to the large periodic error magnitudes, the measured velocity (Doppler frequency) often fell below the cutoff frequency for nonlinearity measurement.

CONCLUSIONS

This paper presented experimental results for a new phase digitizing nonlinearity correction algorithm. It was demonstrated that periodic error was significantly reduced, provided the limiting Doppler shift magnitude of 40 kHz was exceeded. Similarly, for sinusoidal motion profiles it was shown that the correction in periodic error was better at higher velocities and was the worst at the positions where the stage reversed its direction (Figure 5).

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