A Robust Sinusoidal Signal Processing Method for Interferometers

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ABSTRACT

Laser interferometers are widely used as a reference for length measurement. Reliable bidirectional optical fringe counting is normally obtained by using two orthogonally sinusoidal signals derived from the two outputs of an interferometer with path difference. These signals are subject to be disturbed by the geometrical errors of the moving target that causes the separation and shift of two interfering light spots on the detector. It results in typical Heydemann errors, including DC drift, amplitude variation and out-of-orthogonality of two sinusoidal signals that will seriously reduce the accuracy of fringe counting. This paper presents a robust sinusoidal signal processing method to correct the distorted waveforms by hardware. A corresponding circuit board has been designed. A linear stage equipped with a laser displacement interferometer and a height gauge equipped with a linear grating interferometer are used as the test beds. Experimental results show that, even with a seriously disturbed input waveform, the output Lissajous circle can always be stabilized after signal correction. This robust method increases the stability and reliability of the sinusoidal signals for data acquisition device to deal with pulse count and phase subdivision.

Keywords: Sinusoidal signal, Waveform error, Laser interferometer, Waveform correction

1. INTRODUCTION

Interferometers are high precision displacement or profile measurement equipment, such as laser interferometer and white light microscope. It provides variable interferograms due to optical path difference (OPD) of two light beams (reference light and object light). For reliable bidirectional fringe counting, many interferometers produce two sinusoidal electrical output signals from their interferograms which should ideally be equal in amplitude, none DC bias, and with a phase difference of exactly $\pi/2$ [1]. Practically, these two sinusoidal signals have three fundamental errors which were described by Heydemann in 1981 [2], these are: (1) DC drifts (p and q) due to the background light and the unequal gain in the detector channels, as shown in Figure 1, (2) amplitude variation due to the geometrical errors and the speed of moving stage, as shown in Figure 3, and (3): out-of-orthogonality (α) due to the polarization of emitted light, the alignment error of polarizing beam splitters in the optical path and the circuit parameters, as shown in Figure 1 and Figure 2 [3].

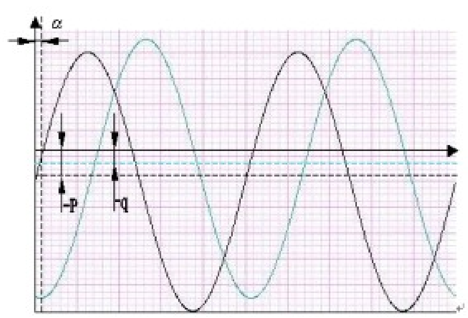

Figure 1. DC drift and orthogonal errors of quadrature waveforms signals in Lissajous diagram

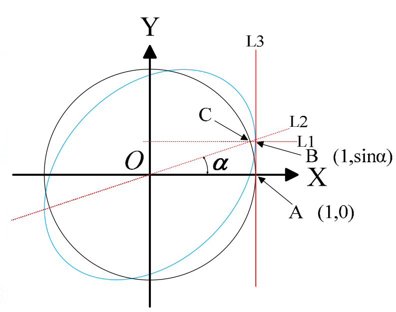

Figure 2. Orthogonal and non-orthogonal waveform

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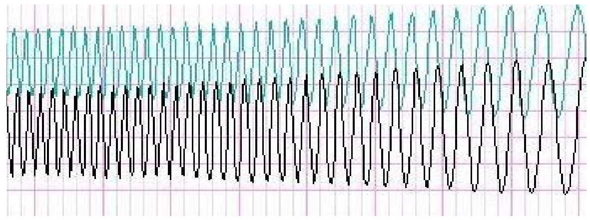


Figure 3. Amplitude variation of quadrature waveforms

In ideal case, these two sinusoidal signals can be expressed by

$$\begin{aligned} S_1 &= a\sin\phi \\ S_2 &= a\cos\phi \end{aligned} \tag{1}$$

In fact, however, due to the existed fundamental errors, the actual signals should be expressed by

$$\begin{aligned} S_1 &= a(t)\sin(\phi+\alpha)+p \\ S_2 &= a(t)\cos\phi+q \end{aligned} \tag{2}$$

Where *a(t)* indicates the amplitude of wave is changing with time, α denotes the orthogonal error of two waves, and *p* and *q* are unequal DC drifts of these two waves. In order to correct the distorted waveforms, this paper presents a robust sinusoidal signal processing method together with a designed circuit board to prove the correctness of this method. Experimental tests use two different devices to analyze and compute sinusoidal signals to obtain displacement values from two different interferometers separately. One of the devices consists of a NI data acquisition card and PC software (referred to as PC program); another consists of a DSP processor, a quadrature decoder/counter and ADC chips (referred to as DSP program). One of the sinusoidal signals comes from the Polarizing Michelson Interferometer (PMI) of co-planar stage; another comes from the Linear Diffraction Grating Interferometer (LDGI) of a height gauge. We can verify the effectiveness and stability of the output signals after comparing the calculated displacement of the same input signals of these two devices. The purpose of using DSP program is to reduce the computational load on the PC. Especially when more than two axes of the stage move simultaneously, the PC program's response will be much slower.

2. SINUSOIDAL SIGNAL PROCESSING METHOD

2.1 Processing flow chart

Usually, laser interferometer outputs the interference signal into four orthogonal current signals by using four photo-detectors. Firstly, the current signal should be converted into voltage signal before processing. In this study, sinusoidal signal processing method consists of three parts: signal pre-amplification, orthogonalization processing and normalization processing, as shown in Figure 4. Details are described in the following sections.

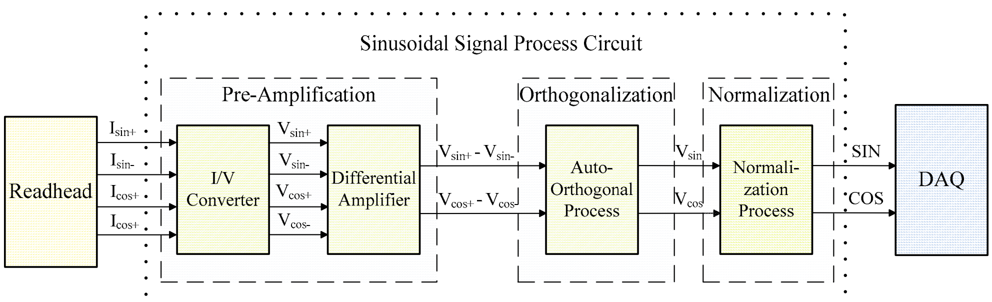


Figure 4. Sinusoidal signal processing flow diagram

2.2 Signal pre-amplification

A photo-detector is a sensor that converts optical energy into electrical energy via photoelectric effect [4]. Some interferometers such as Linear Diffraction Grating Interferometer (LDGI) [5] have four photo-detectors. The photo-detector array converts the interference fringe into a set of four sinusoidal current signals with a phase difference of π/2. For the convenience of processing, these current signals are converted by I/V conversion circuit into voltage signals, as shown in Figure 4. There are four output voltages corresponding to four sinusoidal waves, which are expressed by

$$\begin{aligned} V_1 &= k\sin\phi + p \\ V_2 &= k\sin(\phi + \frac{\pi}{2}) + q = k\cos\phi + q \\ V_3 &= k\sin(\phi + \pi) + p = -k\sin\phi + p \\ V_4 &= k\sin(\phi + \frac{3\pi}{2}) + q = -k\cos\phi + q \end{aligned} \tag{3}$$

Bidirectional optical fringe counting is normally obtained by using two orthogonally sinusoidal signals. Therefore, the two signals with a phase difference of π in the four channels of voltage signals converted should be differential amplified to eliminate the DC drift and common mode noise of the sinusoidal signal during the movement of the reader head, i.e.,

$$\begin{aligned} S_1 &= V_1 - V_3 = 2k\sin\phi = a\sin\phi \\ S_2 &= V_2 - V_4 = 2k\cos\phi = a\cos\phi \end{aligned} \tag{4}$$

Equation (4) is exactly the same as Eq. (1). Pre-amplification is the fundamental part of the signal processing.

2.3 Orthogonalization processing

Theoretically, the outputs should be quadrature form signals after pre-amplification. The actual signals expressed by formula (2) should have no DC drift. The basic operating principle of orthogonalization is that adding and subtracting the two vector signals when they have an equal of amplitude and no DC drift, and therefore producing a set of exactly orthogonal signals, as shown in Figure 5.

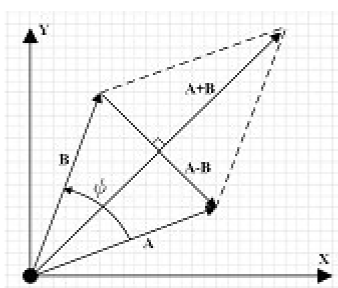


Figure 5. Vector operation of orthogonalization

After DC drift regulation and amplitude adjustment, the S_1 and S_2 signals described in formula (2) should be equal in amplitude but not orthogonal which can be expressed by

$$\begin{aligned} \vec{A} &= S_1 = a\sin(\varphi + \alpha) \\ \vec{B} &= S_2 = a\cos\varphi \end{aligned} \tag{5}$$

Adding and subtracting signal $\vec{A}$ by signal $\vec{B}$ respectively, we will get an expression as follows,

$$\begin{aligned} \left|\vec{A} + \vec{B}\right| &= \sqrt{2 + 2\cos\alpha}\,\sin(\varphi + \delta) \\ \left|\vec{A} - \vec{B}\right| &= \sqrt{2 - 2\cos\alpha}\,\cos(\varphi + \delta) \end{aligned} \tag{6}$$

where δ is expressed by

$$\delta = \tan^{-1}\left(\frac{\sin\alpha}{\cos\alpha + 1}\right) \tag{7}$$

From Eq. (6), we can find that the two signals are orthogonal and the corresponding Lissajous diagram shows an ellipse. It can be seen that after orthogonalization processing, we still need to adjust the amplitude so that the two signals are equal in amplitude and that the Lissajous circle diagram would become a perfect circle. The circuit design of the orthogonal processing is shown by the flow diagram in Figure 6. The output signals, V_{sin} and V_{cos}, are orthogonal sinusoidal signals with equal in amplitude.

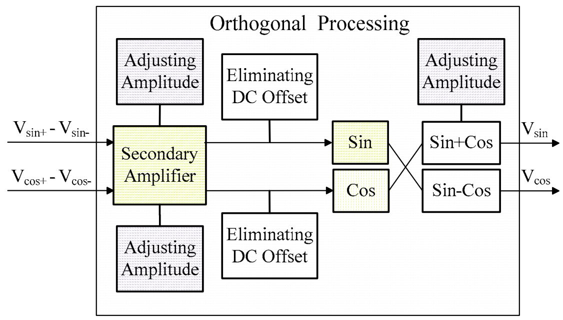


Figure 6. Orthogonal processing flow chart

2.4 Normalization processing

After orthogonal processing the two sinusoidal signals are of equal amplitude and phase difference of π/2. These two signals can be expressed by

$$\begin{aligned} S_1 &= a\sin\theta \\ S_2 &= a\cos\theta \end{aligned} \tag{8}$$

Where a is a function of time variable due to the geometrical errors and the speed of the moving stage. It means that the Lissajous circle will change the radius with time, being an unstable state. The variation of amplitude will affect the pulse counting when the radius is reduced to the threshold level. A normalization processing should be done after orthogonal processing in order to ensure the stability of the signals during movement of the stage and to obtain better resolution and accuracy. The principle of normalization processing can be expressed as follow,

$$\begin{aligned} S_1^{'} &= \frac{S_1}{\sqrt{S_1^{\ 2} + S_1^{\ 2}}} = \frac{S_1}{a} = \sin\theta \\ S_2^{'} &= \frac{S_2}{\sqrt{S_1^{\ 2} + S_1^{\ 2}}} = \frac{S_2}{a} = \cos\theta \end{aligned} \tag{9}$$

Where S1'and S2' are sinusoidal signals with unit amplitude after normalization processing. With the use of squaring circuit, square root circuit and divider circuit, the normalization process can be realized. The normalization processing's flow chart is shown in Figure 7.

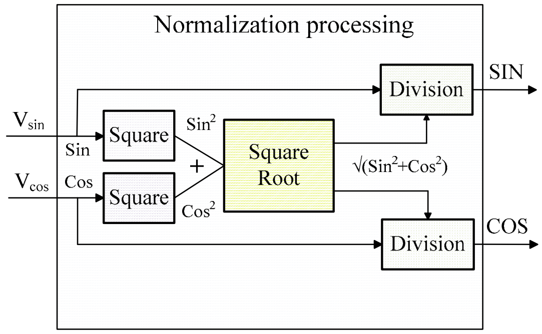


Figure 7. Normalization processing flow chart

3. EXPERIMENTAL TESTS

A corresponding circuit board has been designed by the author's group to test the validity of the signal processing method. An oscilloscope is used to observe the signals before and after orthogonal processing, and a NI data acquisition device is used to sample the signals before and after normalization processing during the movement of the stage. During the full range experiment, the Lissajous circle diagrams before and after orthogonal processing is shown in Figure 8. The elliptical circle can be shaped to a pure circle after orthogonalization. The Lissajous circle diagrams before and after normalization processing is shown in Figure 9. We can see that the output Lissajous circles become more stable after the signal processing.

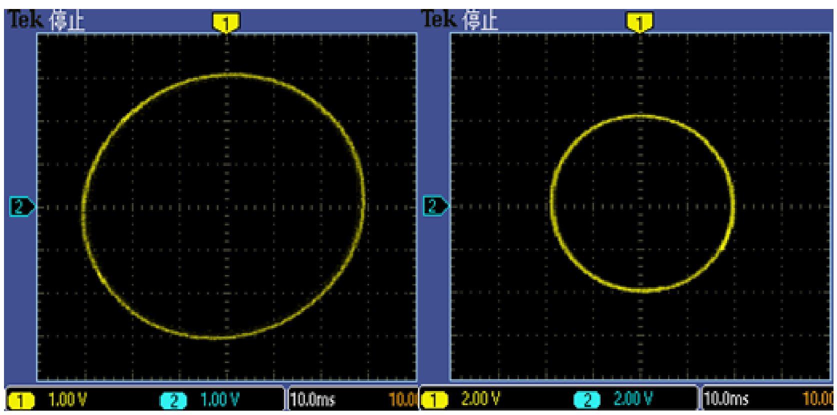


Figure 8. Lissajous circle diagram before (L) and after (R) orthogonal processing

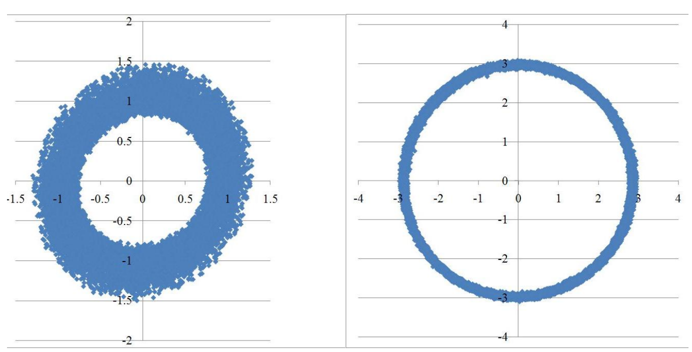


Figure 9. Lissajous circle diagram before(L) and after(R) normalization processing

3.1 Experiment 1

The sinusoidal signal processing circuit board is employed to a co-planar stage, which displacement movement is detected by the Polarizing Michelson interferometer (PMI) in each axis [6].

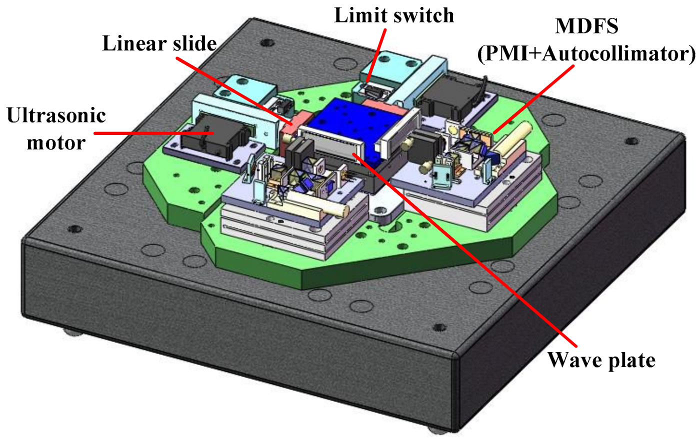
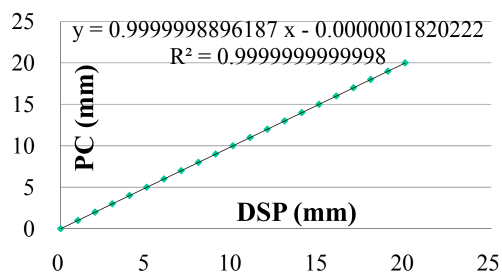


Figure 10. The structure of Co-planar stage

The processed signals are connected to both PC program and DSP program. The stage is driven by the ultrasonic motor and moves 1 mm each time during the 20 mm stroke. The measurement results show that the residual error is within ± 4.8 nm by comparing DSP program and PC program, as shown in Figure 11. The difference is begligible.



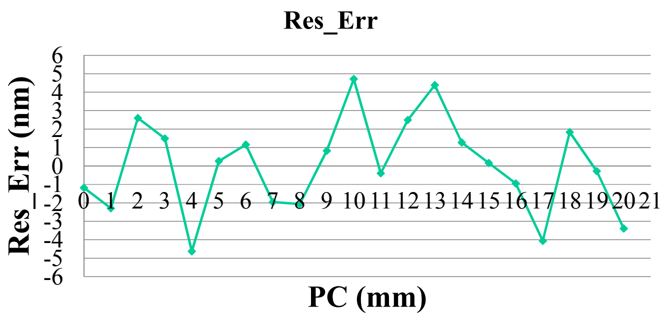


Figure 11. DSP vs PC residual error for PMI

3.2 Experiment 2

The sinusoidal signal processing circuit board is adopted to the height gauge, which is equipped with a linear diffraction grating interferometer (LDGI) for height sensing, a shown in Figure 12 [7]. The Z-axis moving is driven by DC motor and LDGI measures the height displacement.

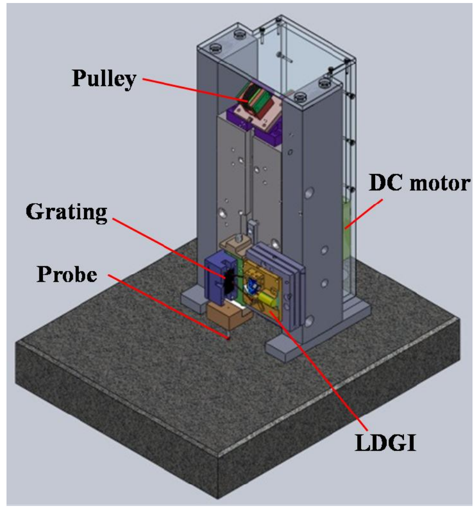
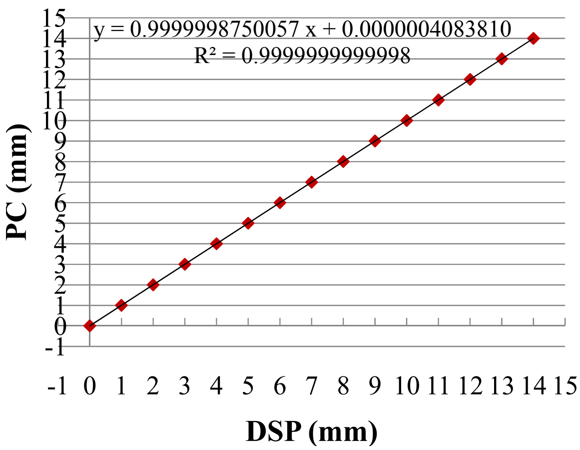


Figure 12. The structure of height gauge

As same as Experiment 1, the processed signals are connected to both PC program and DSP program. The height gauge measures the height of grade 1 gauge block; each time increases 1 mm of gauge block to the total range of 14 mm. The measurement results show that the residual error is within ±3.7 nm by comparing DSP program and PC program, as shown in Figure 13. The difference is negligible.



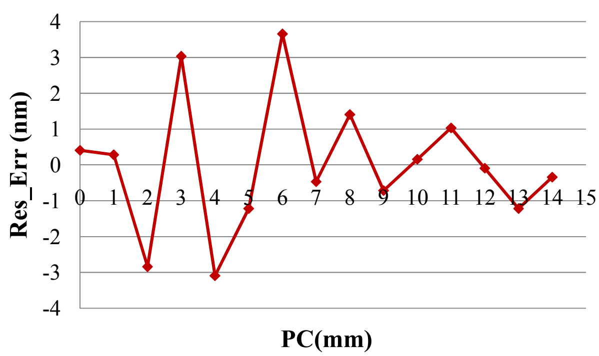


Figure 13. DSP vs PC residual error for LDGI

4. CONCLUSIONS

This report proposes a robust sinusoidal signal processing method to correct and process waveform signals obtained from a laser interferometer or a grating interferometer. Moreover, a corresponding circuit board has been designed and produced. The three Heydemann waveform errors are corrected by the designed circuit board prior to the pulse counting and phase subdivision processed. The corrected waveforms output very stable Lissajous circular diagram and are robust to any disturbance. Experimental results show the developed DSP-based signal processing performs almost the same result as our previously developed PC-based signal processing. This hardware processing circuit board can be a stand-alone module that does not require PC computation. It can also be applied to any scale if the outputs are in sinusoidal signals.

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