A simple heterodyne laser interferometer without periodic errors

Ki-Nam Joo¹, Jonathan D. Ellis¹, Jo W. Spronck¹, Paul J. M. van Kan² and Robert H. Munnig Schmidt¹

¹ Mechatronic System Design, Department of Precision and Microsystems Engineering
Delft University of Technology, Delft, The Netherlands

² Department of Length, NMi Van Swinden Laboratorium BV, Delft, The Netherlands
Tel.: +31 [015] 278-3142  Fax: +31 [015] 278-1800  E-mail: k.joo@tudelft.nl

Abstract

We propose a simple heterodyne laser interferometer that theoretically has no periodic errors and is applicable to industrial fields. By spatially separating the measurement and reference beams in the interferometer, the occurrence of periodic errors is avoided and the combination of a right angle prism and a retroreflector makes the optical configuration simpler and alignment insensitive. An additional advantage of this interferometer is that the optical resolution is enhanced by a factor of two because the phase change direction is opposite between reference and measurement signals. The remaining periodic error is less than 0.15 nm with a commercial heterodyne laser source in the feasible experiment, which is mainly caused by the frequency mixing in the optical source itself.

Keywords: Heterodyne laser interferometer, periodic error, spatially separated beams

1. Introduction

Heterodyne laser interferometry has been widely used as a precise instrument for measuring displacements in both research and industrial settings because of its high dynamic range, high signal-to-noise ratio, and traceability to length standards. To achieve nanometer or sub-nanometer level uncertainty with heterodyne laser interferometers, however, care must be taken to eliminate several error sources: geometrical, instrumental, and environmental sources [1]. Among them, the periodic or nonlinearity error caused by frequency and/or polarization mixing, and ghost reflections limits the accuracy of the interferometers because it changes the amplitude and phase of the interference signals. Over the past 15 years, several researches including to theoretical models and compensation techniques have been investigated [2-6]. Hou and Wilkening analyzed the nonlinearity of heterodyne interferometers and proposed the method to measure and compensate it using two detectors per signal, with π phase difference between detectors [3]. The quadrature detection technique to evaluate and compensate all periodic errors was proposed by Eom, et al. and elliptical fitting of two phase quadrature signals obtained by a lock-in-amplifier was performed [4]. Recently, the real time first and second-order periodic error correction technique developed by Chu and Ray [5] was validated under various experimental conditions and it was reported that the periodic error was attenuated to sub-nm levels [6, 7].

On the other hand, non-polarizing optical configurations to eliminate theoretically the periodic errors have been designed [8-11]. They use spatially separated beams that have different frequency components. In these interferometers, the beams with different frequencies are never mixed before the photodetectors, so the nonlinearity can be theoretically eliminated. However, the optical setups are complicated because it should be guaranteed that both beams propagate separately, which requires additional optical components [8, 9]. Although Schmitz, et al [10] and Lawall, et al [11] reported simple heterodyne laser interferometers using an acousto-optic modulator (AOM) as a beam splitter, the AOM...
diffraction angle is small and their specific configurations limit the typical applications of measuring displacements in industrial settings.

In this investigation, we propose a simple and applicable design of heterodyne laser interferometer using spatially separated two beams to eliminate the periodic error. Two beams from the source are crossed by a right angle prism in the reference path and a retro-reflector in the measurement path. Because the two measurement beams have opposite directions of phase change due to a right angle prism and a retro-reflector simultaneously, the measuring resolution is enhanced by two compared to typical interferometers.

2. Interferometer concept without periodic errors

The periodic errors are typically caused by the heterodyne laser source and polarizing optics which are both non-ideal and are sensitive to alignment when the beams are split and recombined. To avoid the frequency and polarization mixing, two input beams with different optical frequencies were spatially separated in this optical configuration, as shown in Figure 1. This interferometer has two parallel beams from the optical source, each with the same polarization state and optical frequencies \( f_0 \) and \( (f_0 + f_s) \), respectively. The two beams propagate to a non-polarizing beam splitter (NPBS) where they are split into two sets of beams, reference beams and measurement beams. The reference beams are reflected by a right angle prism and the measurement beams are reflected by a retro-reflector. The retro-reflector has the symmetry with respect to a central point and the measurement beams are crossed each other while the reference beams have the line symmetric behavior by the prism [12]. Each set of beams travels back to the NPBS and is recombined to make two beat signals with the frequency of \( f_s \). Then the signals are detected by photodetectors, \( \text{PD}_R \) and \( \text{PD}_M \).

![Fig. 1. The optical configuration of simple heterodyne laser interferometer to reduce the periodic errors; NPBS, non-polarizing beam splitter; RAP, right angle prism; RR, retroreflector; \( \text{PD}_R \), \( \text{PD}_M \), reference and measurement photodetectors. The input beams are parallel and the solid is the upper beam and the dashed is the lower beam. They have the different optical frequencies, \( f_0 \) and \( (f_0 + f_s) \), respectively.](image)

While the retro-reflector is moving, the measurement beams are phase shifted caused by Doppler frequency shift and are measured by \( \text{PD}_R \) and \( \text{PD}_M \). In this case, the heterodyne signals from photodetectors give the same amplitude but the phase shift direction is opposite between the two signals, i.e., the two interference signals from \( \text{PD}_R \) and \( \text{PD}_M \) can be expressed by

\[
I_{\text{PD}_R} \propto \cos(2\pi f_s t - 2k\Delta L) \tag{1}
\]

\[
I_{\text{PD}_M} \propto \cos(2\pi f_s t + 2k\Delta L) \tag{2}
\]

where \( k \) is the wave number and \( \Delta L \) is the displacement of the retro-reflector. From Eq. (1) and (2), the phase difference between two photodetectors (\( \text{PD}_R \), \( \text{PD}_M \)) is \( 4k\Delta L \), which is an
effective optical resolution of four. The beams are spatially separated and the optical paths are not overlapped in the interferometer, therefore no leakage light is detected when barring ghost-reflections. The effect from ghost reflections can be minimized by proper anti-reflection coatings and alignment techniques. Moreover, polarizing optics are not used which can generate frequency and/or polarization mixing. The proposed optical configuration theoretically has no periodic errors. It also has the advantage of improving the measurement resolution by two using two heterodyne signals with opposite phase variations [12].

3. Experiment and analysis

To verify the effectiveness of the proposed interferometer, we performed experiments with a commercial heterodyne laser (Axiom 7701, Zygo Corp.) as an optical source, of which the original output has two orthogonally polarized frequencies. The laser has the frequency stability approximately $10^{-8}$ for 24 hours and has a 20 MHz split frequency using an acousto-optic frequency shifter (AOFS). However, the two different frequencies are spatially overlapped from a birefringent crystal (BC) inside of the laser. The distance between the AOFS and the BC is very short so the spatial separation of the beams is minute, only a small fraction of the beam diameter [13]. To obtain the two spatially separated beams successfully, we removed the BC and used two mirrors that can be tilt-adjusted as shown in Fig. 2 (a). The two beams from the AOFS are parallel to each other after reflecting from the mirror set. Because the beams from the AOFS have the same polarization state, it is not necessary to use any polarizers for detecting the interference beat signals in this interferometer. Figure 2 (a) shows the experimental setup and the two parallel beams are actually separated although they might seem overlapped.

![Fig. 2. (a) Experimental setup; AOFS, acousto-optic frequency shifter and (b) modified laser source to reduce the residual periodic errors; M, M₀, M₁, M₂, angle-adjusted mirrors; NPBS, non-polarizing beam splitter; RAP, right angle prism; RR, retro-reflector; PDᵣ, reference photodetector; PDₘ, measurement photodetector; PBS, polarizing beam splitter; P, polarizer.]

The measurements of the residual periodic errors are performed by the detection of amplitude modulation [4, 8]. The two interference signals from PDᵣ and PDₘ were electrically mixed with a common reference frequency of 19.9 MHz from a function generator (33220A, Agilent). This mixing allowed for a 100 kHz signal to be generated, which was then possible to measure using a commercial lock-in amplifier (5210, Signal Recovery). The bandwidth of the lock-in amplifier is 120 kHz and it can remove the harmonic contents of the heterodyne signal and the electrical frequency sum. The measured phase change from the lock-in amplifier is caused by the Doppler frequency of the moving target, with the relationship of $4kΔL$, and the measured amplitude is related to the periodic phase error $dφ$ as [9]
\[ |d\phi| = \left| \frac{dR}{R} \right| \]  

(3)

where \( R \) is the measured amplitude from the lock-in amplifier and \( dR \) is the amplitude change. Ideally, \( R \) should not be changed but the periodic nonlinearity can lead to fluctuations of \( R \) and the periodic phase error can be calculated using Eq.(3). The phase noise and amplitude noise of lock-in amplifier were 0.005° (rms) and 0.1 mV respectively in our experiments.

The amplitude of the lock-in signal between the reference and the measurement signals was measured while the retro-reflector in Fig. 2(a) was slowly translated using a piezoelectric driven stage (MAX311, Thorlabs) which was operated in open loop. To reduce the noise from mechanical motions and vibration, 100 data points were averaged per sample. Figure 3(a) show the experimental periodic errors in the system. The errors were below ±1 nm and the period was half the fringe number because the measured phase is \( 4k\Delta L \). As previously stated, the proposed interferometer has no periodic error theoretically. If the two beams from the source have a leakage component before the interferometer, however, this can lead to frequency mixing and thus, periodic errors. The AOFS is a non-ideal component and the original beam and the diffracted beam from the AOFS have leakage frequency components.

The frequency mixing effect from the source was reduced by using an unmodified commercial heterodyne laser and another AOFS, as shown in Fig. 2(b). The coaxial beam with two orthogonal frequencies from the laser is split into two beams, \( f_1 \) and \( f_2 \) \((f_2-f_1=20\) MHz) by a PBS. The beam with \( f_1 \) is incident to the second AOFS induces a frequency shift, \( \delta f \) (19.9 MHz). The diffracted beam from the AOFS \((f_1+\delta f)\) and the reflected beam from the PBS \((f_2)\) are adjusted to be parallel by mirrors and become the same polarization state after a polarizer. The heterodyne frequency is then \( f_2-(f_1+\delta f) \) from two beams and is 100 kHz. Although the leakage frequency component of each beam is not completely removed, from the schematic in Fig. 2(b), the ratio can be significantly reduced [12]. In this case, the phase error and the amplitude change can be expressed as

\[ d\phi = 2\varepsilon_1\varepsilon_2 \sin(2k\Delta L) \]

\[ \frac{dR}{R} = 2\varepsilon_1\varepsilon_2 \cos(2k\Delta L) \]  

(4)

where \( \varepsilon_1 \) is the leakage ratio from the laser and the PBS, \( \varepsilon_2 \) is the leakage ratio of the AOFS. Figure 3(b) shows the measurement results of the periodic error in the modified system. The error was also equal to half the period frequency and the amplitude was below 0.15 nm.

For the successful implementation of the proposed interferometer, the laser source must be free from frequency mixing. Employing two AOFSs with different frequency shifts has been shown to remove the frequency mixing [11]. This laser system, however, increases the
overall cost due to two AOFSs, which is not desirable for both research and industrial fields. The use of a two longitudinal modes He-Ne laser and an AOFS can reduce the frequency mixing of each beam [12]. In this research, a frequency stabilized and an offset-locked laser set will be applied to improve the performance of the interferometer and this laser stabilization system is currently under construction.

4. Conclusion
In this investigation, we present a simple design of heterodyne laser interferometer free from periodic errors. To eliminate the periodic errors in the optical configuration, the two beams with different optical frequencies were spatially separated. Moreover, the optical resolution was enhanced by a factor of two because the phase change direction was opposite between reference and measurement signals. Experimental results showed the periodic error less than 0.15 nm, which was caused by the frequency mixing of the optical source. This work is now patent pending. Future research will incorporate the modifications to reduce the periodic non-linearity errors further.

5. Acknowledgements
This work was supported by the Dutch IOP (project 04001) and NMi in the Netherlands.

References