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Bench-top setup for validation of real time, digital periodic error correction

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Abstract

This paper provides experimental validation of the digital first-order periodic error reduction scheme described by Chu and Ray. A bench-top setup of a single-pass, heterodyne Michelson interferometer, designed to minimize common error contributors such as Abbe, dead path and environment, is described. Linear, reciprocating motion generation is achieved using a parallelogram, leaf-type flexure. Periodic error amplitude is varied through independent rotation of a half wave plate and polarizer. Experimental results demonstrate that the correction algorithm can successfully attenuate first-order error to sub-nm levels for a wide range of frequency mixing conditions.

Keywords: Interferometry; Heterodyne; Displacement; Nonlinearity; Cyclic

1. Introduction

Differential-path interferometry is used extensively in situations requiring accurate displacement measurements. Examples include lithographic stages for semiconductor fabrication, transducer calibration and axis position feedback for precision cutting and measuring machines. In many applications, a dual frequency (heterodyne) Michelson-type interferometer with single, double or multiple passes of the optical paths is implemented. These systems infer changes in displacement of a selected optical path by monitoring the optically induced variation in a photodetector current. The phase-measuring electronics convert this photodetector current to displacement by digitizing the phase progression of the photodetector signal. Due to non-ideal performance, mixing between the two heterodyne frequencies may occur, which results in periodic errors superimposed on the desired displacement data (i.e., the error amplitude varies cyclically with the target position). In practice, first-order periodic error, which appears as single sideband modulation on the data at a spatial frequency of one cycle per displacement fringe, often dominates. Second-order periodic error, with a spatial frequency of two cycles per displacement fringe, is also commonly observed.

Although modifications to traditional optical setups may be implemented to reduce periodic error, it is often inconvenient to make changes to existing configurations. Additionally, the extra optical components and/or hardware generally necessary to achieve decreased periodic error can be costly. As an alternative to changes in the interferometer setup, Chu and Ray have recently described a scheme to correct first-order periodic error in real time using digital logic hardware [1]. An overview is provided in Section 3.

The purpose of this study is to validate of the Chu and Ray approach using a bench-top setup of a single-pass, heterodyne Michelson-type interferometer. The setup enables: (1) isolation of periodic error as the primary uncertainty source in displacement measuring interferometry; (2) variation of the frequency mixing that leads to periodic error so that the error amplitude may be changed. During target motion, the real time first-order error correction is digitally applied in hardware and both the corrected and uncorrected measurement signals are recorded. Various frequency mixing levels are realized by adjustment of the setup optics; the periodic error levels before and after correction are presented for multiple cases.

2. Background

In this work we focus on heterodyne Michelson-type interferometers. In these systems, imperfect separation of the two

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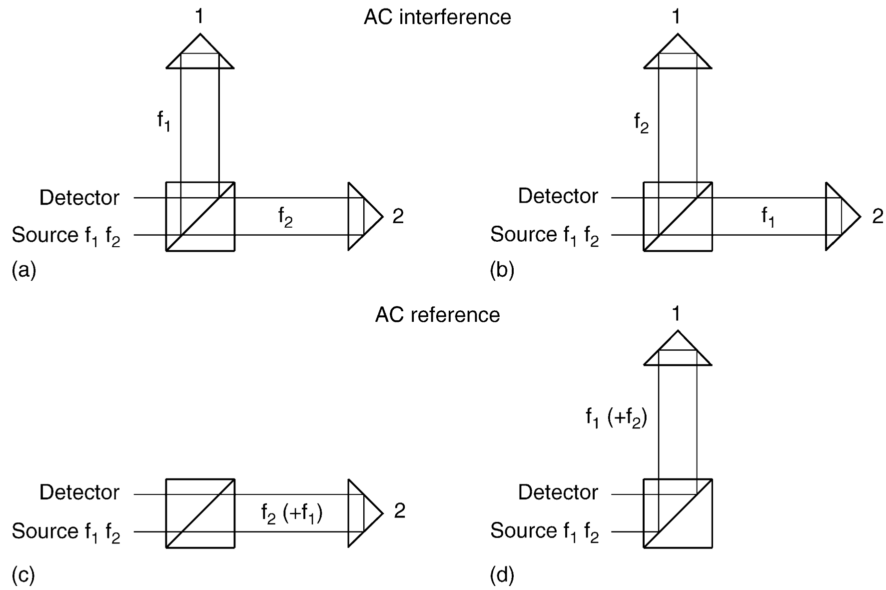

Fig. 1. Physical sources of *ac interference* and *ac reference* terms: (a) the intended *ac interference* term is derived from interference of frequency 1, f_1, light following path 1 and f_2 light following path 2; (b) the leakage-induced *ac interference* term, which occurs when the f_1 light follows path 2 and vice versa, causes second-order error; (c) and (d) *ac reference* terms are generated when both frequencies exist in a single path and lead to first-order periodic error [33].

light frequencies into the measurement (moving) and reference (fixed) paths has been shown to produce first- and second-order periodic errors. The two heterodyne frequencies are typically carried on collinear, mutually orthogonal, linearly polarized laser beams in a method referred to as polarization-coding. Unwanted leakage of the reference frequency into the measurement path, and vice versa, may occur due to non-orthogonality between the ideally linear beam polarizations, elliptical polarization of the individual beams, imperfect optical components, parasitic reflections from individual optical surfaces and/or mechanical misalignment between the interferometer elements (laser, polarizing optics and targets). In a perfect system, a single frequency would travel to a fixed target, while a second, single frequency traveled to a moving target. Interference of the combined signals would yield a perfectly sinusoidal trace with phase that varied, relative to a reference phase signal, in response to motion of the moving target. However, the inherent frequency leakage in actual implementations produces an interference signal, which is not purely sinusoidal (i.e., contains spurious spectral content) and leads to periodic error in the measured displacement.

Fedotova [2], Quenelle [3], and Sutton [4] performed early investigations of periodic error in heterodyne Michelson interferometers. Subsequent publications identified and described these periodic errors and built on the previous work [5–32]. Specific areas of research have included efforts to measure periodic error under various conditions (e.g., references [5–8]), frequency domain analyses [9–11], analytical modeling techniques [12–16], Jones calculus modeling methods [8,17] and reduction of periodic errors (e.g., references [9,18,30,32]).

Schmitz and Beckwith [33] summarize the potential periodic error contributors using a frequency–path, or F–P, model, which identifies each possible path for each light frequency from the source to detector and predicts the number of interference terms that may be expected at the detector output. For the single-pass, heterodyne Michelson interferometer used in this study, it is shown that 10 distinct interference terms exist in a fully leaking interferometer (i.e., both frequencies exist in both the measurement and reference paths). However, these interference terms may be grouped by optical path change dependency into only four categories: (1) o*ptical power* which contributes a constant intensity to the photodetector current independent of optical path changes; (2) *ac reference* terms with phase that varies by one full cycle over the synthetic wavelength, or the distance defined by the difference in wave numbers (i.e., the reciprocal of the wavelength) between the source frequencies in question and occur at the split frequency, or the difference between the heterodyne frequencies; (3) *dc interference*, which are Doppler shifted up from zero frequency during target motion and represent the signal of choice in homodyne interferometers; (4) *dc interference* terms which produce a time harmonic variation in the detector current at the split frequency and are Doppler shifted up or down during target motion depending on direction. With respect to periodic errors, the leakage-induced *ac interference* term leads to second-order error, while the *ac reference* terms cause first-order error. The physical sources of the *ac interference* and *ac reference* terms are shown in Fig. 1.

3. Overview of error correction approach

3.1. Periodic error measurement

In Chu and Ray's method [1], first-order periodic error, Δs, is modeled as a periodic function of ideal position s as $\Delta\phi = \frac{1}{2\pi}\tan^{-1}\left[\frac{r\sin(-2\pi(\phi-\theta))}{1+r\cos(-2\pi(\phi-\theta))}\right]$, where $\Delta\phi = \frac{2\Delta s}{\lambda}$ and $\phi = \frac{2s}{\lambda}$ are expressed in unit intervals, UI, where $1\,\mathrm{UI} = 2\pi$ rad. This represents a single sideband (SSB) modu-