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Wavelength scanning distance interferometry using inflection point retrieval for phase unwrapping

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ABSTRACT

A real-time wavelength scanning distance interferometry is proposed. The interference signal generated by the light wavelength modulation is transformed into preliminary conversion signal with the two summarized waveform transformation laws. Inflection points of the interference signal are retrieved with two complementary methods which are discontinuity point judgment (DPJ) and the adjacent null points distance judgment (ANPDJ). Based on the preliminary conversion signal and the retrieved inflection points, the orthogonal signal is constructed. Displacement is calculated after demodulating the phase shift with the orthogonal demodulation algorithm. When millimeters distance is measured, the fluctuation of the measured result is around micrometers in about one hour. The measurement complexity and cost are all decreased, while, ideal measurement results can still be obtained. The approach can be used in a multitude of applications.

1. Introduction

By converting the physical, chemical, and biological quantities into light phase-shift, optical interferometers have been widely used for sensing in these fields [1–4]. Contactless absolute distance measurement is one of the important applications of optical interferometers. After retrieving phase information encoded in the interference signals, we can measure large parts or matter properties which are unsuitable for contact measurement. A range of achievements have been obtained based on distance interferometry, for example, the applications in flying satellite missions [5], as well as refractive index [6], 3D surface profile [7–9], large scale distance [10], thin film thickness [11,12], and material shrinkage [13] measurements.

In order to recover phase shift from interference signal, high performance demodulation schemes for distance interferometry have been studied for years. By taking a high frequency modulation signal as a carrier, the demodulation algorithm based on the differential–cross-multiplying approach has been widely utilized [1,2,14]. Laser ranging system has been demonstrated by employing optical frequency comb sources [5–7]. By exploiting frequency scanning lasers, white light sources, or super luminescent laser diode, distance measurement with nanometers accuracy have been realized [8–12,15,16]. Based on the dual-wavelength heterodyne Michelson interferometer, absolute distance can also be measured [17]. However, many of these schemes require precise and delicate tuning of optical or mechanical devices, such as femtosecond optical frequency comb, swept laser, spectrometer, phase modulator, precise optical devices, and so on. The measurement systems are costly and complicated. So, the problem of how to devise an effective, simple and low cost interferometer demodulation mechanism becomes significant.

The orthogonal demodulation schemes for interferometer are one category of remarkable achievements. For example, the Hilbert transform generates a sine wave signal from a cosine signal [10], and the phase generated carrier demodulation scheme uses fundamental and second harmonic frequency wave of modulating signal to generate orthogonal signals [14]. These orthogonal signals constructing methods make the interferometer demodulation schemes have high resolution and large dynamic range. However, a linear tuning of light wavelength, and a reference interferometer or a gas absorption cell are essential for the Hilbert transform scheme, in order to make it clear what is the beginning and the final scanning wavelength. For the phase generated carrier demodulation scheme, a high frequency optical carrier is must needed. Furthermore, this scheme is confined to vibration measurement.

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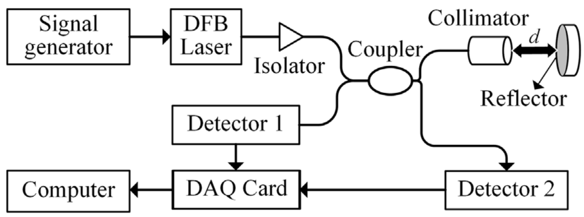

Fig. 1. Experimental set up based on a fiber Fizeau interferometer.

Absolute distance can be measured with wavelength scanning interferometer by counting interference fringes [18]. The determination of fraction fringes in one scanning period leads to the main measurement uncertainty. In this paper, we utilize two complementary methods for wavelength scanning interferometer fraction fringe inflection point position retrieval. Based on the retrieved inflection points, orthogonal signal is constructed by using triangular and point by point transformation program. A real time orthogonal demodulation scheme for interferometer is proposed. Absolute distance is measured after demodulating the phase shift amplitude generated by wavelength scanning. Experiment is carried out with fiber Fizeau interferometer. No precise and delicate tuning of optical or mechanical device is needed. The measurement complexity and cost are all decreased.

2. Experimental set up

Fiber Fizeau interferometer has proved its superiority over other fiber-based interferometers by the freedom from an additional reference arm. The experimental set up of the distance interferometry which is based on a fiber Fizeau interferometer is present in Fig. 1. All the devices are in very low prices and do not need delicate tuning. The distance between reflector and collimator is to be measured. The light source is a distributed feedback (DFB) laser with central wave length of 1550 nm. We utilize a 500 Hz modulation signal generated by a signal generator to modulate this wavelength. The isolator is used for preventing the reverse transmission light from entering the light source. The 2×2 3dB fiber coupler divides the light of DFB laser into two parts. One part is used for measurement. Another part is used for monitoring the light intensity fluctuation. The reflected lights from collimator end face and from reflector meet at detector 1. The interference signal is detected with detector 1. Detector 2 is utilized to monitor the wave length modulation caused light intensity variation. The analog signal from detectors 1 and 2 are collected by a DAQ card which has 16 bit accuracy and 200k Hz sampling frequency. The converted digital signals are sent to the computer for processing.

The output signals of detector 1 and 2 can be expressed as:

$$S_1(t) = I_{01}[1 + m\cos(\omega t)]\,\{\alpha + \beta\cos[\varphi(t)]\}\,, \tag{1}$$

$$S_2(t) = I_{02}[1 + m\cos(\omega t)], \tag{2}$$

here, I_{01} and I_{02} are parts of the light intensity when there is no modulating signal, m is the light intensity modulation factor, ω is the angular frequency of the modulating signal, α and β respectively represent the dc and ac component proportionality coefficient of the interference light intensity, d is the distance from fiber collimator end face to reflector, and $\varphi(t) = 4\pi d/[\lambda + \Delta\lambda\cos\omega(t-\tau)]$ is the modulated phase, where λ and $\Delta\lambda$ respectively represent the light wave length and the wave length modulation depth, τ is the time lag of the wavelength with respect to the light intensity when DFB laser is modulated. When the frequency of the modulating signal is 500 Hz, the output signals of detector 1 and 2 are shown in Fig. 2(a) and Fig. 2(b). After dividing Eq. (1) with Eq. (2), the modulation induced light intensity variation is eliminated. The signal processing result is expressed as:

$$S(t) = C\,\{\alpha + \beta\cos[\varphi(t)]\}\,, \tag{3}$$

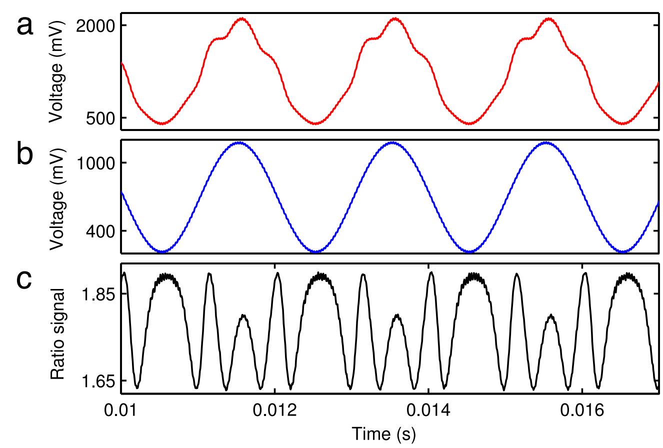

Fig. 2. (a) and (b) are the output signals of detector 1 and 2 respectively. (c) is the interference signal which has eliminated the light source modulation induced light intensity variation.

where, C is the proportionality coefficient. The signal of Eq. (3) is shown in Fig. 2(c) which is acquired by dividing Fig. 2(a) with Fig. 2(b).

3. Orthogonal demodulation principle

Eq. (3) can be normalized with the normalization algorithm based on LabVIEW program. The normalized interference signal is written as:

$$I_1(\mathrm{t}) = \cos[\varphi(t)]. \tag{4}$$

The orthogonal signal of Eq. (4) is shown as:

$$I_2(\mathrm{t}) = \sin[\varphi(t)]. \tag{5}$$

Eq. (5) could be obtained with triangular and point by point transformation method after retrieving the inflection points. This will be introduced in the next sections. The phase shift $\varphi(t)$ can be demodulated with Eqs. (4) and (5) by using the orthogonal demodulation algorithm [2]. The Taylor series of $\varphi(t)$ is expressed as:

$$\varphi(t) = \frac{4\pi d}{\lambda}[1 - \frac{\Delta\lambda}{\lambda}\cos\omega(t-\tau) + [\frac{\Delta\lambda}{\lambda}\cos\omega(t-\tau)]^2 - \cdots] \tag{6}$$

After band pass filtering of $\varphi(t)$ around angle frequency ω, $\varphi_1(t)$ which is the second term of Taylor series of $\varphi(t)$ can be get,

$$\varphi_1(t) = \frac{4\pi d}{\lambda^2}\Delta\lambda\cos\omega(t-\tau). \tag{7}$$

If λ and $\Delta\lambda$ are known constant, we can calculate distance d from Eq. (7). The flow chart of the interferometer orthogonal demodulation scheme is shown in Fig. 3.

4. Method to obtain the orthogonal signal

4.1. Method to acquire the preliminary conversion signal

Low order smoothing filter is used for smoothing Fig. 2(c). Then, the smoothed Fig. 2(c) is normalized by calling the normalization algorithm based on the LabVIEW program. The normalized interference signal is shown in Fig. 4(a). There are 400 sampling points in one modulation period. We process 10k data points at a time. In order to show the details of normalized interference signal, only two periods are shown in Fig. 4(a).

The default value range of the inverse cosine function is [0∼π] in LABVIEW program. But [0∼π] is not a full period for the sine function. The way to obtain the orthogonal signal by solving inverse cosine and sine function is impracticable. However, by analyzing Eq. (4) and Fig.