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Resolution-enhancement and sampling error correction based on molecular absorption line in frequency scanning interferometry

Hao Pan, Xinghua Qu *, Chunzhao Shi, Fumin Zhang *, Yating Li

State Key Laboratory of Precision Measurement Technology and Instruments, Tianjin University, Tianjin 300072, China

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ABSTRACT

The non-uniform interval resampling method has been widely used in frequency modulated continuous wave (FMCW) laser ranging. In the large-bandwidth and long-distance measurements, the range peak is deteriorated due to the fiber dispersion mismatch. In this study, we analyze the frequency-sampling error caused by the mismatch and measure it using the spectroscopy of molecular frequency references line. By using the adjacent points' replacement and spline interpolation technique, the sampling errors could be eliminated. The results demonstrated that proposed method is suitable for resolution-enhancement and high-precision measurement. Moreover, using the proposed method, we achieved the precision of absolute distance less than 45 μm within 8 m.

1. Introduction

With the rapid development of industrial manufacturing, people are stricter and stricter on measuring accuracy and demanding for measurable objects. The demand for a new generation of industrial measurement has evolved from the cooperative target toward the diffuse surface object with faster measurement speed and higher precision. Presently, the methods for measurement of a diffuse reflecting target mainly include stereovision imaging technology [1], pulsed laser ranging technology [2], frequency scanning interferometry [3]. The stereovision method is low cost, mature and has strong portability. However, the imaging performance of this method especially relies on hardware performances and picture quality. For white shiny surfaces, smooth curvatures and edges, this method seems incapable of precise measuring. The pulsed laser ranging technology, also called the time of flight (TOF) technique, is commonly used in remote sensing monitoring, airborne lidar, unmanned vehicles and other fields. The measurement system of TOF imaging technique is simple, but measurement precision depends on accuracy of the counting circuit. Therefore, it is difficult to break the cm-level limit. On the other hand, the frequency scanning interferometry, which is also known as the frequency-modulated continuous wave (FMCW) ladar, has been used for high-precision measurement of noncooperative targets recently. In 2014, Baumann et al. [4] built a set of FMCW laser ranging systems calibrated by an optical frequency comb in the laboratory, which enables precise mapping of a cactus with spikes of about 75-μm diameter at stand-off distances of up to 4 m. The obtained precision was below 10 μm. Subsequently, Mateo et al. [5] proposed a trilateration based on high resolution FMCW ladar to realize the metrology of machined aluminum plate. The measured coordinate precision of less than 200 μm was achieved. In addition, the FMCW ladar was also used in the field of optical frequency domain reflectometry [6] (OFDR) for monitoring and measurement of fiber optic networks and for a variety of measurements in fiber networks, including imperfection detection and distributed temperature sensing. More recently, the FSI has been applied to the three-dimensional imaging system for surface asperities, such as Synthetic Aperture Radar (SAL) [7], and optical coherence tomography (OCT) [8].

Compared to other measurement techniques, the FMCW technology, which requires no cooperative target or mark points, can quickly measure the diffuse reflector surface with um-precision. However, its accuracy subjects to the stability of continuous-wave light source which cannot scan frequency linearly, which further leads to the instability of beat frequency and poor spectrum resolution. Generally, this problem can be solved by following two methods.

The first method is an active linearization of optical frequency sweeps. In 2009, Peter A. Roos et al. [9] proposed an external cavity tunable diode laser (ECDL) as a sweeping source, and used a delayed self-heterodyne fiber interferometer to measure the deviations from linear frequency sweeps. The error signal was respectively fed back to the motor, piezoelectric actuators (PZT), and current components according to the response bandwidth size to maintain sweep linearity.

* Corresponding authors.
E-mail addresses: zeratul_ph@tju.edu.cn (H. Pan), quxinghua@tju.edu.cn (X. Qu), shichunzhao@tju.edu.cn (C. Shi), zhangfumin@tju.edu.cn (F. Zhang), yating_li0520@tju.edu.cn (Y. Li).

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After active controlling, the standard deviation of sweeping errors was decreased to 34 ppb, and the precision was improved to 86 nm within the range of 1.5 m. The closed-loop system is excellent in locking very large frequency bandwidths but slow, and it will lose lock in the case of a long-term phase-locked loop (PLL). To improve this situation, Xie et al. [10] proposed an ultra-short delay Mach–Zehnder interferometer (MZI) and a digital phase compensation technique to suppress the phase error, which led to the short lock time of 8 us and robust operation in a disturbed environment. The standard deviation of sweeping errors was decreased to 55 kHz at 80 GHz during 2-ms scanning, and the range window was increased by 60 times at the mean time. In order to further decrease the sweep linearity error, Barber et al. [11] used an optical frequency comb with high accuracy and stability (10^{-12}) as an aligning tool to calibrate the ECDL source, and the chirp linearity was increased to 15 ppb. However, this system is expensive and has a large volume. In 2017, Behnam et al. [12] used an integrated electronic–photonic PLL to calibrate sweeping error of a tunable laser for 3D imaging, which makes the FMCW imaging technology more compact and less expensive. Besides, the FMCW imaging system can perform 180,000 range measurements per second with precision of less 8 μm at distances of 50 cm.

The other method is a non-uniform interval resampling method [13], which belongs to the post-processing schemes and uses the zero-crossings or peaks of a long delay Mach–Zehnder interferometer (MZI) signal as triggers for acquiring the measurement signal data. The method is low cost, easy to be integrated into FMCW ladar system, and especially suitable for short-range small-band scanning measurements. However, in the large-bandwidth long-distance measurement cases, due to the jitter and dispersion of a long fiber, the spectrum obtained by this method is deteriorated containing the spectral broadening and distance shifting, so the range position cannot be determined precisely. To address this problem, Liu et al. [14] used an iteration method based on focus definition evaluation functions to find the best phase compensation value to recover the real spectrum. In our previous work [15], we proposed an eigenvalue decomposition of a resampled signal by using the multiple signal classification (MUSIC) algorithm, and determined dimensions of a signal subspace with the Akaike information criterion (AIC) to reconstruct the range spectrum, so as to compensate the dispersion mismatches. These methods have high efficiency in the case of shorter data measurements, but they become very time-consuming as the amount of resampled data increases.

In this paper, rather than actively linearize the laser source, we propose the non-uniform interval resampling method for absolute distance measurement. Then, we analyze the frequency-sampling error caused by dispersion mismatch and calibrate it based on the molecular absorption line. The proposed method was verified by experiments.

2. Theory background

The external cavity tunable laser was used as a light source in our experiment, and the chirp curve was not an ideal triangular wave. It was assumed that the chirp curve is a quadratic function, which can be expressed as:

$$\upsilon(t) = f_0 + \gamma_1 t + \gamma_2 t^2 = \frac{1}{2\pi}\frac{d\Phi}{dt} \tag{1}$$

where f_0 is the initial optical frequency, γ_1 is the first order chirp rate coefficient, γ_2 is the second order chirp rate coefficient, and Φ is the instantaneous phase of optical frequency.

The electric field in the free running can be expressed as:

$$E(t) = E_0 e^{i\cdot\Phi(t)} \tag{2}$$

where E_0 is the field amplitude, and the E field of the laser has quadratic and cubic phase terms and can be defined by:

$$\Phi(0,t) = \omega_0 t + \frac{1}{2}at^2 + \frac{1}{6}bt^3 \tag{3}$$

where a and b are the first and second order phase coefficients, a can be determined as $a = 2\pi\gamma_1$, b can be determined as $b = 2\pi\gamma_2$; and ω_0 is the initial angular frequency, which is defined as $\omega_0 = 2\pi f_0$.

After propagating in a dispersion medium of length L_r, the phase of the electric field of a light pulse can be expressed as [16]:

$$\Phi\left(L_r,t\right) = \omega_0 t - \beta_0 L_r + \frac{1}{2}a'\left(t-\beta_1 L_r\right)^2 + \frac{1}{6}b\left(t-\beta_1 L_r\right)^3 \tag{4}$$

where a' is the chirp rate coefficient after propagation through the dispersion medium with fiber delay, and it can be expressed as $a' = a(1 - a\beta_2 L_r + o(a\beta_2 L_r)^2)$, where $o(a\beta_2 L_r)^2$ refers to the error of higher order terms which can be ignored; where $\beta_0 = n/\omega_0 c$, and c is the speed of light in the vacuum, $\beta_1 = 1/\upsilon_g$ where υ_g denotes the group velocity, and β_2 is the dispersion coefficient of a single-mode optical fiber.

In the auxiliary MZI, a detectable beat signal was produced when the returned light was mixed with the local oscillator (LO) light at photodetector, and it can be defined by:

$$\begin{aligned} U_{aux}(t) &= \cos[\Phi(0,t) - \Phi\left(L_r,t\right)] \\ &= \cos[\beta_0 L_r + 0.5\cdot(a-a')t^2 + a'\beta_1 L_r t - 0.5\cdot a'\left(\beta_1 L_r\right)^2 \\ &\quad + 0.5\cdot b\beta_1 L_r t^2 - 0.5\cdot b(\beta_1 L_r)^2 t] \\ &\approx \cos[0.5\cdot a^2\beta_2 L_r t^2 + (a - a^2\beta_2 L_r)\tau_{aux} t \\ &\quad - 0.5\cdot(a - a^2\beta_2 L_r)(\tau_{aux})^2 \\ &\quad + 0.5\cdot b\tau_{aux} t^2 - 0.5\cdot b(\tau_{aux})^2 t + \beta_0 L_r] \\ &= \cos[2\pi(\pi\gamma_1^2\beta_2 L_r)t^2 + 2\pi\tau_{aux}\upsilon(t) - \pi\gamma_1\tau_{aux}^2]. \end{aligned} \tag{5}$$

Without the consideration of a dispersion, the beat signal was resampled at zero-crossings of the auxiliary MZI in uniform intervals $\Delta\upsilon = (2\tau_{\rm aux})^{-1}$. However, the non-uniform sampling errors occurred in considering the effects of fiber dispersion, and the $k$thinterval departed from $(2\tau_{\rm aux})^{-1}$ by some amount $\delta\upsilon_k$, and new nonuniform frequency intervals were as follows:

$$\Delta\upsilon_k = (2\tau_{aux})^{-1} + \delta\upsilon_k. \tag{6}$$

To derive the sampling error $\delta\upsilon_k$, we resampled the beat fringe pattern at the time series $\{t_k\}$. In the adjacent time between t_k and t_{k+1}, the phase experienced a change of π,

$$2\pi(\pi\gamma_1^2\beta_2 L_r)(t_{k+1}^2 - t_k^2) + 2\pi\tau_{aux}[(2\tau_{aux})^{-1} + \delta\upsilon_k] = \pi. \tag{7}$$

Solving this equation, the sampling error $\delta\upsilon_k$ can be determined as:

$$\begin{aligned} \delta\upsilon_k &= -\frac{\pi\gamma_1^2\beta_2 L_r}{\tau_{aux}}(t_{k+1}^2 - t_k^2) \\ &\approx -\frac{\pi\beta_2 L_r}{\tau_{aux}}(\gamma_1^2 t_{k+1}^2 - \gamma_1^2 t_k^2) = -\frac{\pi\beta_2}{\beta_1}(\upsilon_{k+1}^2 - \upsilon_k^2). \end{aligned} \tag{8}$$

In a ranging measurement to the target at air distance of R, we ignored the air dispersion. The beat signals at the photodetector can be expressed as:

$$\begin{aligned} U_{mea}(t) &= \cos[\Phi(0,t) - \Phi\left(0,t-\tau_{mea}\right)] \\ &= \cos[0.5b\tau_{mea}t^2 + (a\tau_{mea} - 0.5b\tau_{mea}^2)t \\ &\quad + (\omega_0\tau_{mea} - 0.5a\tau_{mea}^2 + 0.5b\tau_{mea}^3)] \\ &\approx \cos[\frac{1}{2}b\tau_{mea}t^2 + (a\tau_{mea} - \frac{1}{2}b\tau_{mea}^2)t + (\omega_0\tau_{mea} - \frac{1}{2}a\tau_{mea}^2)] \\ &= \cos[2\pi\tau_{mea}\upsilon(t) - \pi\gamma_1\tau_{mea}^2]. \end{aligned} \tag{9}$$

After resampling at the zero-crossings points using Eq. (6), the sampled signals can be written as:

$$\begin{aligned} U_{mea}(k) &= \cos[2\pi\tau_{mea}((2\tau_{aux})^{-1} + \delta\upsilon_k)\cdot k - \pi\gamma_1\tau_{mea}^2] \\ &= \cos[2\pi\tau_{mea}(2\tau_{aux})^{-1}\cdot k \\ &\quad + 2\pi\tau_{mea}(-\frac{\pi\beta_2 L_r}{\tau_{aux}}(\upsilon_{k+1}^2 - \upsilon_k^2))\cdot k - \pi\gamma_1\tau_{mea}^2] \\ &= \cos\{2\pi\frac{\tau_{mea}}{2\tau_{aux}}[1 - 2\pi\beta_2 L_r(\upsilon_{k+1}^2 - \upsilon_k^2)]\cdot k - \pi\gamma_1\tau_{mea}^2\}. \end{aligned} \tag{10}$$

From this resampling beat note, we can see that introduction of the second order dispersion coefficient β_2 deteriorated the frequency