Research Article

Application Research of Frequency-Modulated Continuous-Wave Displacement Sensor Based on Zero-Crossing Phase Detecting Algorithm

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Frequency-modulated continuous-wave (FMCW) interference, as a new technology of laser interferometry, has the advantages of length traceability, large range, high accuracy, simple structure, and optical fiber transmission. Based on the formula of FMCW laser interference displacement, a zero-crossing phase detection algorithm is proposed, which can accurately calculate the initial phase of a cosine signal in a modulation period, and it is successfully applied to the contact laser interference displacement sensor. The experimental results show that the FMCW technology based on the zero-crossing phase detection algorithm can achieve the technical specifications of the contact displacement sensor with a measurement range greater than 15 mm and the standard deviation is less than 0.01 μm . The conversion of noncontact measurement to contact measurement can realize the direct measurement of workpieces with complex surface conditions on the production line, breaking through the limitation of optical measurement and expanding the application of optical fiber interferometry.

1. Introduction

With the rapid development of modern technology and industry, many fields such as large-scale machining and equipment manufacturing have put forward higher requirements for the accuracy of part size measurement. These measurements often require large-volume workpiece measurement, field measurement, and measurement under difficult conditions. Laser-ranging technology has many advantages, such as high measurement accuracy, long working distance, and strong anti-interference ability, which can meet the requirements of industrial scientific research on ranging technology in other fields. The emergence and wide application of laser-ranging technology solve the problem that traditional measurement technology cannot solve, so the research and application of laser measurement technology is very important. Frequency-modulated continuous-wave (FMCW) laser-ranging system is a kind of noncontact laser interferometric displacement measurement

technology which is developing rapidly and widely used [1–3]. It has the advantages of high measurement accuracy and long working distance. FMCW laser-ranging technology combines the advantages of interference ranging technology and pulse ranging technology, which not only ensures that the measurement distance is far enough but also ensures the high precision of distance measurement. Compared with other laser-ranging methods, the interference signal obtained by FMCW interferometry is a time-dependent dynamic signal, which has a stronger anti-interference ability. FMCW interference uses a DFB semiconductor laser with a lower cost and simpler structure, so it has a broad development prospect in large-scale and high-precision measurement [4–6].

Iiyama [7] introduced a photoelectric negative feedback loop containing a reference interferometer and a phase comparator in the FMCW system to perform a nonlinear correction of the laser frequency. The spatial resolution of the ranging system was improved from 12 mm to 1.3 mm.

Schneider [8] adopted the calibration interference signal to compensate for the laser frequency modulation nonlinearity; the ranging accuracy was 0.5 mm. Jesse Zheng [9] conducted in-depth research on the FMCW theory and subsequently achieved a series of results [10–12]. Kakuma [13] built an FMCW interference system with a reference interferometer, which, respectively, conducted the optical frequency modulation of the two vertical-cavity surface-emitting lasers in opposite scanning directions and eliminated the offset error by averaging the phase shifts of the two beat frequency signals. When the target motion is 0.37 mm, the measurement error was reduced from 0.69 mm to 0.018 mm. The American National Institute of Standards and Technology Baumann [14] set up a set of optical frequency comb corrected FMCW Radar ranging system in the laboratory and realized the scanning measurement of cactus with a diameter of 75 μm within 4 m, where a measurement accuracy reached the submicron level. Mateo and Barber [15], researchers at the University of Montana, based on the principle of FMCW laser ranging, used a three-sided measurement method to scan a number of different shapes of processed aluminum plate with a distance of 1.5 m, and the repeated accuracy was about 100 μm . At present, high-precision FMCW ranging technology requires cooperation targets, which greatly limits the application of parts detection at the production sites.

Optical interferometry measurement technology has the advantages of high speed, high-precision, noncontact, anti-electromagnetic interference, and wide measurement range; of course, it also has its application limitations. For example, there are requirements for the surface quality of the workpiece to be tested: there should be no iron filings, no oil film, no roughness, or too smooth surface; the measured surface angle cannot be too large; the error of the air disturbance substitution is large, etc., so the application of an optical measurement is restricted to the measurement of workpieces in the production line. Then, combined with the characteristics of contact measurement and noncontact measurement, the optical system is transformed into contact measurement, which can give full play to the advantages of high precision and a large range of optical measurement. With the advantages of contact measurement, the application range of optical measurement can be expanded. For example, just finished from the machine tool, the surface of the workpiece has oil film and iron filings, and the contact method can easily achieve direct measurement. The processing and manufacturing site environment is complex, and this method can effectively prevent electromagnetic interference and avoid air disturbance. The surface inclination angle of free-form surface and special-shaped surface parts changes greatly, and the contact method can also be used to detect them directly. Therefore, this method has certain application advantages and is worth popularizing.

2. Basic Principle of FMCW Ranging

FMCW laser-ranging system is a kind of ranging system which uses a frequency-modulated laser as a signal carrier to obtain the distance and velocity information of the target object. In this system, the optical frequency is linearly

modulated by the laser, and the time delay caused by the distance of the target is reflected in the form of the beat frequency of the interference signal. The difference frequency signal generated by the beat frequency is proportional to the distance to be measured, and the distance of the target to be measured is calculated by using this relationship.

As shown in Figure 1, the LFM laser generated by the DFB laser is divided into two beams after passing through the collimating lens, one of which is the reference beam. After being reflected by the reference mirror in the collimator, it enters the photodetector through the circulator. The other is the measurement beam, which is reflected by the measurement target mirror and interferes with the reference beam on the photodetector to generate a dynamic beat signal. The measured distance can be calculated by demodulating the beat frequency signal with frequency and phase. According to electromagnetic theory, a light wave is a kind of propagation of vibration electromagnetic field. If the electromagnetic field of a point light source vibrates along a fixed direction with a single frequency, the vibration electric field $E(t)$ can be expressed as [16]

$$\begin{aligned} E(t) &= E_0 \cos(\varphi), \\ &= E_0 \cos(\omega t + \varphi_0), \\ &= E_0 \cos(2\pi\nu t + \varphi_0), \\ &= E_0 \cos\left(\frac{2\pi}{T}t + \varphi_0\right), \end{aligned} \quad (1)$$

where E_0 is the vibration amplitude, φ is the phase, t is the time, φ_0 is the initial phase, ν is the temporal frequency, T is the temporal period, and ω is the temporal angular frequency.

Thus, the signals of the measurement beam $E_1(t)$ and the reference beam $E_2(t)$ can be expressed in the time domain as follows:

$$\begin{aligned} E_1(t) &= E_{01} \cos\left(\frac{2\pi}{T}t + \varphi_{01}\right), \\ E_2(t) &= E_{02} \cos\left(\frac{2\pi}{T}t + \varphi_{02}\right). \end{aligned} \quad (2)$$

Then, the beat signal generated by the interference of the two beams is expressed as

$$\begin{aligned} I(\tau_1, \tau_2, t) &= |E_1(\tau_1, t) + E_2(\tau_2, t)|^2, \\ &= [E_1(\tau_1, t) + E_2(\tau_2, t)][E_1(\tau_1, t) + E_2(\tau_2, t)]^*, \\ &= E_1(\tau_1, t)E_1^*(\tau_1, t) + E_2(\tau_2, t)E_2^*(\tau_2, t) \\ &\quad + E_1(\tau_1, t)E_2^*(\tau_2, t) + E_1^*(\tau_1, t)E_2(\tau_2, t), \\ &= E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos[\varphi(t - \tau_1) - \varphi(t - \tau_2)], \\ &= I_1 + I_2 + 2\sqrt{I_1 I_2} \cos[\varphi(t - \tau_1) - \varphi(t - \tau_2)]. \end{aligned} \quad (3)$$

Since the above two light waves originate from the same coherent FMCW light source, the initial phases of the two light waves are correlated. The light intensity of the synthesized field is

FIGURE 1: FMCW optical system diagram.

$$I(\tau, t) = I_0 \{1 + V \cos[\varphi(t) - \varphi(t - \tau)]\}, \quad (4)$$

where I_0 is the average intensity of the beat signal $I_0 = I_1 + I_2$, V is the contrast of the beat signal $V = 2\sqrt{I_1 I_2} / (I_1 + I_2)$, and $\tau = \tau_2 - \tau_1$ is the delay time of the second wave (usually called the signal wave) with respect to the first wave (usually called the reference wave).

In FMCW laser interference, the frequency modulation of the laser source can be a sawtooth wave, triangle wave, and sine wave. In this paper, the theory of FMCW interferometry is analyzed with a sawtooth frequency linear modulation light source as an example. Two beams are output by the modulated laser source, and the interference occurs at a point in space after propagating through different paths. The angular frequency waveforms of the two coherent light waves and the beat signal generated can be described as the curve shown in Figure 2, where the solid line represents the angular frequency of the reference light and the dotted line represents the angular frequency of the signal light.

When these two waves interfere, the interference signal light intensity $I(\tau, t)$ can be expressed as

$$\begin{aligned} I(\tau, t) &= |E_1(t) + E_2(\tau, t)|^2, \\ &= I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(\alpha\tau t + \omega_0\tau), \\ &= I_0 [1 + V \cos(\alpha\tau t + \omega_0\tau)], \end{aligned} \quad (5)$$

where I_1 and I_2 are the intensities of the reference wave and signal wave, I_0 is the average intensity of the beat signal, and V is the contrast of the beat signal.

It can be concluded from the above equation that the relationship of the OPD between the reference wave and the signal wave in one modulation period is as follows:

$$\begin{aligned} I(\text{OPD}, t) &= I_0 \left[1 + V \cos\left(\frac{2\pi\Delta\nu\nu_m \text{OPD}}{c} t + \frac{2\pi}{\lambda_0} \text{OPD}\right) \right], \\ &= I_0 [1 + V \cos(2\pi\nu_b t + \varphi_{b0})], \end{aligned} \quad (6)$$

where $\Delta\nu$ is the optical frequency modulation excursion, ν_m is the frequency the modulation signal, c is the speed of light in free space, λ_0 is the central optical wavelength, and ν_b and φ_{b0} are the frequency and the initial phase of the beat signal.

$$\varphi_{b0} = \frac{2\pi \text{OPD}}{\lambda_0}. \quad (7)$$

It can be seen from equation (7) that each time the OPD changes by one wavelength, the initial phase of the cosine

FIGURE 2: The angular frequency relationship of FMCW interference signal under sawtooth wave modulation.

signal changes 2π , and the beat signal shifts by one cycle. Therefore, the OPD can be calculated by measuring the amount of change (phase shift) of the initial phase of the beat signal. Usually, the calculation of φ_{b0} uses the cycle counting method, which continuously records and accumulates the amount of change in the phase shift during the measurement to calculate the total phase shift amount $\Delta\varphi_{b0}$ during the entire measurement process.

3. Phase Algorithm Based on Zero-Crossing Method

3.1. System Design. As shown in Figure 3, the FMCW laser interferometry system is based on the structure of the Fabry Perot FMCW laser interferometer. The optical fiber displacement sensor consists of a single-mode DFB semiconductor laser, optical fiber circulator, optical fiber collimator, partial mirror, total mirror (object to be measured), and photodetector. The DFB laser emits a frequency linearly modulated frequency-modulated continuous-wave laser. The laser is coupled to the input port 1 of the optical circulator through an optical fiber and output from the forward adjacent port 2 of the optical circulator. The output light is incident to the optical fiber collimator through the optical fiber, and part of the light is reflected by the optical fiber collimator through the partial mirror. As the reference light, part of the light is transmitted to the total reflector attached to the surface of the moving object to be measured and returned as the signal light. The signal light and the reference light are superposed and interfered at the output port 3 of the optical circulator to form a beat signal. The interference optical signal is converted into an electrical signal by the photodiode, processed by amplifying and filtering circuit,

FIGURE 3: FMCW optical fiber measurement system structure diagram.

and converted into a digital signal by the built-in AD of STM32F407 microprocessor. Finally, the relative displacement of the target is accurately measured by the phase discrimination algorithm.

3.2. Phase Detection Algorithm. According to formula (7) in the second section, as long as the amount of change in the initial phase of the cosine signal between two adjacent modulation periods is calculated, the amount of change in the displacement between the two modulation periods can be calculated. So, the primary goal of the phase detection algorithm is to calculate the initial phase of a cosine signal in a modulation period.

Figure 4 shows the flow chart of the FMCW interference signal phase detection algorithm. The cosine signal from the beat frequency is subjected to amplitude correction, software filtering, searching for extreme values, and zero-point positioning to calculate the initial phase of the interference cosine signal. In the FMCW interference signal based on the sawtooth wave, part of the waveform has irregularities, so in the digital phase detection process, the regular part of the signal waveform is taken for processing. In the experiment, the number of sampling points for each modulation cycle is 3000, and the signal corresponding to 500–2500 points is taken as the useful signal. Each step of the phase detection algorithm is explained in detail as follows.

- (1) Amplitude correction is the normalization of the digital cosine signal amplitude. It can be seen from Figure 5 that when the modulation current changes linearly, the amplitude of the interference signal also changes linearly; then the amplitudes of the obtained cosine signals will be inconsistent. In order to improve the phase discrimination accuracy of the cosine signal, the amplitude normalization correction of the signal needs to be performed first. The amplitude correction is the normalization of the digital cosine signal amplitude. The modulation current is controlled by the DA in the ARM processor

(STM32F407). The sampling point of the obtained cosine signal divided by the corresponding DA setting value is the adjustment value of the output cosine amplitude. In view of the threshold current of the DFB laser, the DA set value needs to be subtracted from the threshold current value during the correction.

- (2) Digital signal software filtering: Due to multiple interference and operational amplification during signal wave transmission, the final collected signal has noises. In order to accurately find the extreme value, the digital cosine signal needs to be filtered by software to remove interference. Common filtering methods include finite amplitude filtering, median filtering, and mean filtering. In view of the advantages of moving average filtering, that is, not only can the phase of the cosine signal remain unchanged, but also the algorithm is simple. The subject uses moving average filtering to denoise the FMCW interference signal.

Figure 6 shows the effect after filtering the interference cosine signal. Compared with Figure 5, it can be seen that the glitch on the signal curve is clearly reduced, the curve is smooth, and the filtering effect is significant.

- (3) Searching extreme values: That is to find the position of the peak (maximum value) and trough (minimum value) of the cosine signal. The experiment uses the method of judging monotonicity to find the extreme points of the cosine signal: firstly, select 10 points in sequence and search the maximum value of the 10 points by bubbling, and determine the monotonicity of the area where the 10 points are selected; secondly, select 10 points in turn and continue to find the maximum value of the 20 points by bubbling, and then judge the monotonicity of the area where the 10 points are selected for the second time. If the monotonicity for the first time is decreasing and the value is increasing in the second time, the minimum value of the 20 points is

FIGURE 4: Flow chart of the phase detection algorithm.

(a)

(b)

FIGURE 5: Amplitude correction of the acquired signal. (a) Original signal. (b) Amplitude corrected signal.

FIGURE 6: Filtered interfering cosine signal.

FIGURE 7: Extreme values of interfering cosine signals.

the minimum value. On the contrary, if the monotonicity is determined to be increasing in the first time and the value is decreasing in the second time, the maximum value of the 20 points is the maximum value. All the extreme points of the interference signal can be found if the whole interference cosine signal is traversed as described above.

Figure 7 shows the maximum and minimum values obtained by the extreme value finding algorithm.

Due to the limitation of the excitation characteristics of the DFB laser, the interference signal has irregularities at both ends of the modulation period. When looking for the extreme value, it is necessary to find the extreme value from the regular cosine signal for the whole period. As can be seen from Figure 7, the algorithm can accurately find the five maximum and minimum values in the cosine signal in a modulation period.

- (4) Zero-point positioning: Zero-coordinates of interference cosine signals are located by linearly fitting the maximum and minimum values. First, calculate the amplitude and offset corresponding to the cosine signal from the extreme value. If it is on the falling edge of the cosine signal, look backward from the minimum value for the coordinate value corresponding to the upper limit and vice versa. Once the values of the upper and lower limits and the corresponding coordinates are determined, the required slope K and offset B are calculated by the linear fitting. Finally, the fitting equation is used to solve and determine the position of the zero points.

As shown in Figure 8, the green point is the determined zero point of the cosine signal. The period and phase of the cosine signal can be determined according to the zero-coordinate value and the trigonometric function. By comparing the phase with the phase of the zero points obtained in the previous modulation period, the amount of change in the zero phases of the two modulation periods can be calculated. The phase and phase change of each cycle are calculated in the same way, and the phase change of the entire displacement process can be obtained by accumulating the phase change. Finally, using formula (7) in the second section, the change of displacement can be calculated.

4. Application and Experiment

4.1. Mechanical Structure Design of Contactlarge-Range Displacement Sensor. With the continuous development of the manufacturing industry, displacement sensors play an increasingly important role in aerospace, ultraprecision machining, and measurement fields. They are mainly used in the measurement of the size and surface morphology of parts in precision machining, displacement measurement of precision motion, and so on. The contact sensor can accurately realize the micron level surface profile of the object through contact or noncontact measurement, so it is widely used in the field of equipment manufacturing. The feature size of precision machining technology and biotechnology continues to reduce gradually into submicron or even nanometer-level accuracy, which puts forward higher requirements for displacement sensors. However, there is a certain measurement error in the measurement principle of inductive sensors, and it is difficult to ensure high accuracy and consistency in the winding and parts processing technology. The measurement value needs to be transferred through comparison, so it cannot solve the common problems of small range, low accuracy, large drift, poor stability, and so on. Taking Mahr's (Germany) axial inductance sensor P2010M as an example, as shown in Figure 9, the maximum measurement range is 10 mm (-5 mm to $+5$ mm), and the linear deviation is $20\text{ }\mu\text{m}$. Therefore, it is difficult to meet the requirements of large-size and high-precision parts detection.

Referring to the characteristics of simple structure and easy installation of contact inductance sensor, the research

group innovatively developed a large range and high-precision contact displacement sensor based on FMCW laser continuous-wave frequency modulation technology. The sensor is compact, flexible, and easy to install. The laser interferometry with the cooperative target is embedded in the sensor cavity to replace the noncooperative target technology, which reduces the difficulty and cost of the optical system. By converting noncontact measurement to contact measurement, the direct detection of the part surface profile is realized, the application of laser interferometry with the cooperative target is expanded, and the problem of large-scale and high-precision measurement in the industrial field is effectively solved.

The structure of the contact laser interference displacement sensor is shown in Figure 10. The measuring rod moves through the sliding pair in the axle sleeve. Under the guarantee of precision assembly, the radial clearance of the measuring rod is less than $1\text{ }\mu\text{m}$. The reflector is placed at the front end of the measuring rod. The laser collimator is fixedly mounted at the tail of the sensor. The laser beam forms a measuring interference cavity through the hollow measuring rod and the reflector. As the upper and lower limits are adjusted, the measuring range of the sensor can be adjusted. The sensor probe is rigidly connected with the measuring rod, and it will be changed with the contour of the measured part, causing the reflector to move with the measuring rod and forming a varying interference cavity. The laser interference signal is sent to the measurement processing circuit through the optical tail fiber and is sampled and calculated by the ARM processor, so that accurate displacement measurement can be realized.

4.2. Experiment. As shown in Figure 11, the contact laser interference displacement sensor is mounted on a precision reference benchmark platform. Based on the lower machine of the STM32F407 microprocessor, the FMCW is transmitted to the displacement sensor through the optical fiber and the beat signal is received and converted to a digital signal. The initial phase of the interference cosine signal is calculated after the digital signal is subjected to amplitude correction, amplification, and filtering, searching for extreme values and zero positioning in order, and then the displacement variation can be obtained by formula (6). The host computer collects, displays, and saves the measurement data in real time through the serial port. The software based on VC can also display the measurement curve in real time.

In the experiment, a precision benchmark platform stroke (BCT-5C) and a grade 0-gauge block were used to linearly verify the measurement range of the sensor. As shown in Figure 6, the upper computer samples and fits the curve, and Figure 6(b) shows that the linear range of the sensor is $<15\text{ mm}$. In order to verify the uncertainty and stability of the displacement sensor, in a constant temperature and humidity experiment environment, the displacement sensor was placed at a position of 12 mm through a 0-level gauge block. In order to facilitate the analysis, the sensor display value is set to zero, and continuous sampling is performed at the same time. Figure 12(a) is a scatter plot of

FIGURE 8: Zero-point determination of interference cosine signal.

FIGURE 9: Mahr-P2010M axial inductive displacement sensor.

FIGURE 10: CAD of contact laser interference displacement sensor.

(a)

(b)

FIGURE 11: Displacement sensor measurement experiment. (a) Experimental device. (b) Full range linear curve of displacement sensor.

FIGURE 12: Stability curve of displacement sensor. (a) Scatter plot of displacement sensor stability. (b) Normal distribution curve.

the corresponding location samples, and Figure 12(b) is the corresponding normal curve distribution. By calculation, the standard deviation of the normal distribution curve is 8.9 nm.

5. Conclusion

Based on the principle of FMCW, this paper deduces the calculation formula of FMCW, designs the optical system and data acquisition circuit, proposes an FMCW technology with a zero-crossing phase detection algorithm, and successfully applies it to contact laser interference displacement sensor. The results show that the performance of this laser interferometric displacement sensor is one order of magnitude better than that of the current inductive displacement sensor, which fulfills the high-precision inspection requirements of large-size components in the equipment manufacturing field.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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