

THE ANALYSIS OF DIGITAL PHASE-SHIFT MEASURING METHODS FOR DUAL-FREQUENCY LASER RANGE FINDER

Li Menglin¹, Xie Wenfeng^{1,2}, Zhu Jingguo¹, Ren Jianfeng¹, Xiao Fang¹, Meng zhe¹

¹ Academy of Opto-electronics, Chinese Academy of Sciences, Beijing, 100094, P. R. China

² University of Chinese Academy of Sciences

Abstract:

Phase-shift range finder is to measure the phase-shift of the modulation wave during its propagation. The precision of traditional phase-shift range finder is limited by measurement rate and the modulation depth. Usually the modulation depth of laser diode decreases with the increase of modulation frequency which is crucial for high precision with sinusoidal modulation. A new phase-shift range finder with dual-frequency He-Ne laser is introduced. The error model is built in order to analyze the factors influencing the precision of phase-shift laser range finder.

Two digital phase-shift measuring methods are discussed through the principle simulation. The white noise, the frequency offset and other error factors are introduced during the simulation. Then the measurement performances of all-phase spectrum analysis method and a new sub-sampling spectrum analysis are analyzed. The simulation results indicate that all-phase spectrum analysis method is advantageous for high speed and high accuracy measurement, owing to its better performance in error immunity. The sub-sampling spectrum analysis method reduces the hardware requirement and the simulation results show that the accuracy of phase-shift measurement can reach to the Cramer-Rao limit.

Keywords: Phase-shift range finder, Dual-frequency laser, all-phase spectrum analysis, sub-sampling spectrum analysis.

1. INTRODUCTION

Phase laser ranging indirectly measures the propagation time of laser through measuring the phase difference of laser modulating wave to provide high-precision distance measurement. Measurement precision and speed is the two important parameters of laser ranging^[1]. With increasing demands for various devices, the study on how to improve measurement precision and speed has practical significance.

In phase laser ranging, semiconductor laser is usually treated as light source and modulating wave is obtained by current modulation. Due to the intrinsic properties of semiconductor laser diode, modulating depth has great limitation. With rising modulating frequency, the modulating depth drops. Meanwhile, after modulation, the signal is likely to be distorted in high frequency resulting in serious wave form distortion. The precision of phase laser ranging technology is dependent to the laser modulation of high frequency and high depth. Therefore, it is urgent to locate a new method to solve the restriction of laser light source to modulation frequency. A new phase-shift range finder with dual-frequency He-Ne laser is introduced in the paper and the factors influencing the precision is discussed. Two methods for digital phase-shift measurement is analysed to achieve higher precision of measurement^{[2][3]}.

2. DUAL-FREQUENCY LASER RANGING

2.1 Principle of dual-frequency laser ranging

According to the principle of beat-wave, two rows of light beams of common vibration direction and similar frequency overlap together in the same propagation direction to form a composite wave, namely beat-wave. The frequency of envelope curve of beat-wave (amplitude variation) is the difference of frequencies of 2 light beams. Produce two light waves of frequency difference with dual-frequency He-Ne laser. After passing through analyzer, the two light waves can form detectable beat-wave signal which is an excellent measurement light source featured by stable frequency and simple system.

The beat-wave created by dual-frequency laser has incomparable advantages in serving as the light source of phase ranging system. It can help to obtain undistorted sinusoidal signal of 100% modulating depth within the range from hundreds of MHz and even 1GHz. Besides, its frequency stabilization system and signal processing circuit is comparatively simple and easy to be built without adding much cost. Therefore, to study this type of phase laser ranging system with dual-frequency laser as light source has very great practical significance.

Dual-frequency laser emits the light beams of frequency f_1 and f_2 . φ_1 and φ_2 is initial phase. The measurement light beam of overlapped frequencies returns to photoelectric reception device after the diffuse reflection on the surface of measured object. As reference light beam has optical path difference from measurement light beam, when dual-frequency laser reaches to some point before detector, it can be expressed as:

$$\begin{aligned} y_1 &= a \cos(2\pi f_1 t + \varphi_1 + \Delta\varphi_1) \\ y_2 &= a \cos(2\pi f_2 t + \varphi_2 + \Delta\varphi_2) \end{aligned} \quad (1)$$

$\Delta\varphi_1$ and $\Delta\varphi_2$ separately represents the phase change of lights caused by optical distance.

According to the principle of optical superposition, the linearly polarized lights y_1 and y_2 in the same optical path can form beat-wave signal and its amplitude variation can be represented as:

$$A = 2a \cos\left(\frac{2\pi f_B t}{2} + \frac{\varphi_2 - \varphi_1}{2} + \frac{\Delta\varphi_2 - \Delta\varphi_1}{2}\right) \quad (2)$$

The $f_B = f_1 - f_2$ is the modulating frequency of beat-wave amplitude and equal to the frequency difference of dual-frequency lasers which form beat-wave. When f_1 and f_2 has little difference, modulating frequency is far lower than light frequency. Photoelectric device of receiving terminal can detect the variation of light intensity of beat-wave signal.

The light intensity of measurement light beam can be expressed as:

$$I_m = A^2 = 2a^2[1 + \cos(2\pi f_B t + 2\varphi + 2\Delta\varphi)]$$

$$\varphi = \frac{\varphi_2 - \varphi_1}{2}, \quad \Delta\varphi = \frac{\Delta\varphi_2 - \Delta\varphi_1}{2} \quad (3)$$

Similarly, the light intensity signal of reference light can be expressed as:

$$I_r = A^2 = 2a^2[1 + \cos(2\pi f_B t + 2\varphi)] \quad (4)$$

After the light intensity change detected by two photoelectric detectors is converted to electric signal, the electric signal is mixed and filtered. Through phase conversion algorithm, we can obtain the absolute phase of reference light and measurement light at some moment t_0 , φ_r and φ_m , and then get the relation of phase difference and distance Δl :

$$\Delta l = \frac{\Delta\varphi}{2\pi} \cdot \frac{c}{2f_B} = \frac{\varphi_m - \varphi_r}{2\pi} \cdot \frac{c}{2f_B} \quad (5)$$

As shown in Fig.1, dual-frequency laser creates the lasers of 2 different frequencies. After passing through analyzer, they become beat-wave light beams which are divided into 2 paths—reference light of lower energy and measurement light of most energy. The energy of reference light and the reflected energy of measurement light are passed to photoelectric reception device. After amplification, they are mixed with local frequency and then subjected to lowpass filtering to separate the difference frequency signal of lower frequency because lower frequency benefits the measurement of phase. Use high-speed AD sampling to digitize reference and measure signal, and the result is transferred to upper computer after pretreatment. Calculate the real-time phase difference of reference and measurement lights through digital phase discrimination algorithm in order to obtain distance information. Meanwhile, upper computer can obtain real-time frequency and signal amplitude information through frequency and amplitude estimation algorithm for the correction of measurement error.

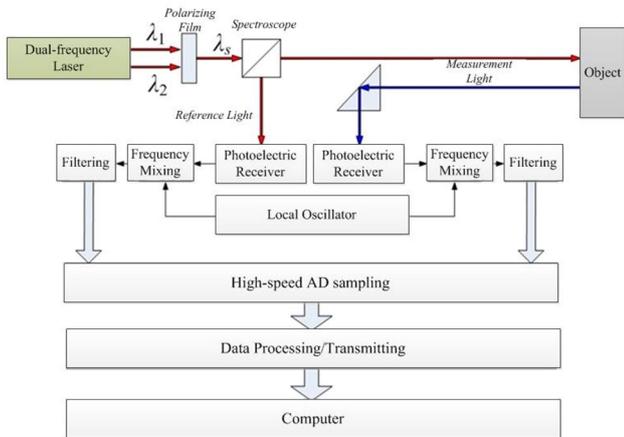


Fig.1: Principle diagram of dual-frequency laser beat-wave ranging system

2.2 The influences of the ranging precision

As reference light and measurement light has optical path

difference, we introduce the phase difference of beat-wave signal. Optical path difference can be divided into two types: one type is caused by the round trip of light between system and object; the other type is caused by other factors which make optical path different. That is $\Delta l = 2d + \Delta l_0$. Given Δl_0 is an offset component and will not make difference to measurement precision, ranging value and phase difference has the following relation:

$$d = \frac{1}{2} \times \left\{ \frac{\Delta\varphi \times c}{2\pi f_B} - \Delta l_0 \right\} = \frac{1}{2} \times \left\{ \frac{(\varphi_m - \varphi_r) \times c}{2\pi f_B} - \Delta l_0 \right\} \quad (6)$$

Analyze the error factors introduced from various parts of plan. As shown in Fig.2, they mainly include: amplitude-phase error caused by the variation of reception light intensity, detection circuit noise, phase error introduced by mixed frequencies, synchronous sampling error, frequency difference stability error caused by laser frequency variations, and phase discrimination deviation caused by finite length of data. By simulating the mechanism of each error and analysis on its influence on system measurement precision, it's found that, during the signal transfer process, the error from the phase discrimination contributed the greatest impact to the precision, thus, two methods for digital phase-shift measurement would be discussed in the next.

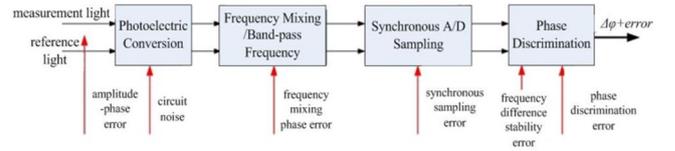


Fig.2: Errors introduced from each part of system

3. THE ANALYSIS OF DIGITAL PHASE-SHIFT MEASURING METHODS

3.1 Principle of all phase spectrum analytical method

All phase spectrum analytical method converts input signal sequence of the length $2N-1$ to the sequence of the length N after pre-processing of all phase data, and then conducts Discrete Fourier Transformation (DFT) to calculate the phase difference of reference signal and measuring signal and then phase difference. The DFT all-phase spectrum analysis basic on FFT algorithm is called as all-phase FFT method (all-phase FFT, apFFT for short)^[4].

All-phase data pre-processing process is shown in Fig.4. Vector y is the data weighting of convolution window w_c for the vector x of the length $2N-1$, and then the data of intervals of N delay units are overlapped and accumulated to form the vector y of the length N .

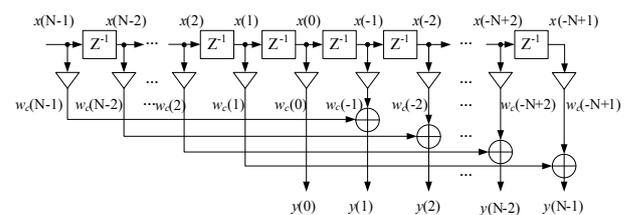


Fig.3: All-phase data pre-processing process diagram

According to the difference of convolution window, all-phase data pre-processing can be divided into non-window, single-window and double-window. In this topic, we only consider non-window all-phase data pre-processing, namely w_c is the convolution of two rectangular windows of the length N .

3.2 Simulation analysis of all phase spectrum analytical method

To study the applicable phase discrimination method for actual measuring system and give consideration to the comprehensive influence of input SNR, frequency deviation, spurious signals and harmonic interference on phase discrimination precision, this paper has compared the phase discrimination performance of all-phase spectral analysis and digital correlation method, digital orthogonal method and frequency domain digital phase discrimination method in the same conditions by simulation^{[2][5][6][7][8]}. The simulation sets the beat-wave frequency of reference signal is 120MHz and intermediate frequency 8MHz. Intermediate frequency of measuring signal is 8.02MHz and the phase difference between measuring signal and reference signal is 60° . Add quadratic and triple harmonic interference to measuring signal and power of harmonic interference is 1/100 of measuring signal; initial phase of spurious signal $\varphi_{sp}=0$, frequency $f_{sp}=4.3$ MHz, and power is the 1/100 of measuring signal. Sampling frequency of reference signal and measuring signal is $f_s=64$ MHz, and phase discrimination is conducted every 64 points. Conduct 1000 Monte Carlo simulations and make statistical analysis of measuring signals under different SNRs. The performance comparison of phase discrimination methods is shown in Fig.4.

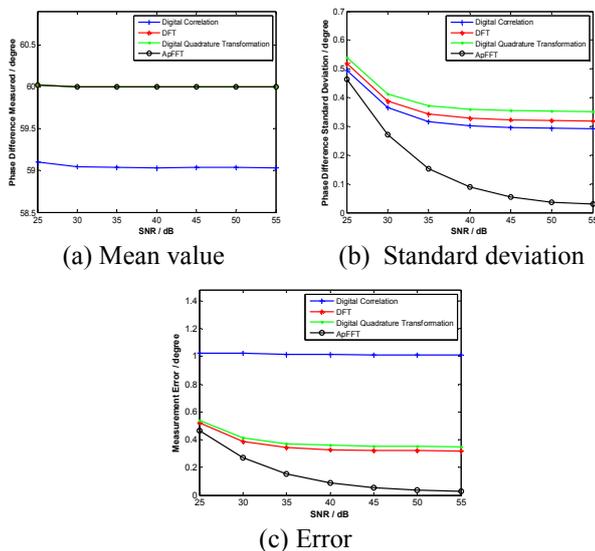


Fig.4: Phase discrimination performance of 4 methods under the influence of comprehensive factors

It can be seen from the figure that under the comprehensive influence of white noise, frequency deviation, spurious signal and harmonic wave, the phase discrimination result of all-phase spectral analysis is basically the same with actual value. With the increase of

SNR, phase discrimination error is decreased and precision improved. When modulation frequency is 120MHz and SNR 30dB, ranging precision of all-phase FFT method is 0.90mm and other methods larger than 1mm, and digital correlation method 3.54mm; when SNR is 50dB, ranging precision of all-phase FFT method can reach to 0.14mm and the precision of other methods is still larger than 1mm. It is easy to make the input SNR of digital phase discrimination system higher than 30dB through circuit treatment. Therefore, all-phase FFT method can meet the requirement of system better.

In conclusion, all-phase FFT method can still keep good phase discrimination performance under the influence of multiple factors, and is of great practical significance in the phase laser ranging system featured by high speed and high precision.

3.3 Principle of sub-sampling spectrum analysis method

If sampling object is intermediate frequency band-pass signal, we can adopt Nyquist sampling rate, which is lower than sampling theorem, to conduct analog-digital conversion. This way can improve the performance of ADC component and lower down the requirement for ADC component. Sub-sampling theorem is that in the range lower than frequency F_l and higher than frequency F_h , the frequency component of ideal band-pass signal is zero. Therefore, for band-pass Intermediate frequency signal, as long as sampling rate F_s is not lower than twice of signal bandwidth $B=(F_h - F_l)$, time-domain sampling will not cause the overlapping of signal frequency spectrum. This sampling method is called as Sub-sampling^[34]. This indicates that for the sampling of band-pass signal, sampling frequency can be far lower than the Nyquist frequency of traditional sense. However, the noise overlapping introduced by sub-sampling method is the main cause to the error of system measurement. Meanwhile, the phase discrimination anti-interference ability of frequency domain spectrum analysis is superior to other phase discrimination methods. Therefore, to reduce the influence of various interferences and improve the measuring precision of system, this paper adopts spectrum analysis for phase discrimination in Sub-sampling system^[9].

If sampling frequency is lowered down and Sub-sampling is conducted with $F_e < F_0$, frequency resolution will be decreased and the frequency of original signal cannot be identified. Complete duplication of Nyquist sampling spectrum analysis cannot obtain the required spectral line to calculate phase. It can be known from sampling principle that the signal after Sub-sampling is the frequency spectrum component of central frequency in $F_{alias}=F_0-nF_e$ with original signal transferred to frequency band $[0, F_e/2]$. During the shifting of frequency spectrum, signal frequency has linear shifting, but phase information is unchanged. Therefore, we can indirectly obtain the phase information of signal before sampling by analyzing the phase moved to F_{alias} signal.

3.2 Simulation analysis of sub-sampling spectrum analysis method

Validate the performance of traditional Sub-sampling digital synchronous demodulation (sub-DSD)^{[3][10]} and Sub-sampling spectrum analysis (sub-DFT) under the influence of white noise through simulation method. Set the SNR of launching reference signal as 50dB, modulation frequency $F_0=8\text{MHz}$ and sampling frequency 6.4MHz. To guarantee the comparison of two methods in the same measurement speed, we conduct phase discrimination every 64 dots and measuring rate is 0.1MHz. Suppose measuring signal SNR increase from 25dB to 60dB, increasing every 5dB, and the phase difference between launching reference signal and measuring signal is 15° . Under different SNRs, conduct 1000 Monte Carlo simulations and then statistical analysis. The result is shown in Fig.5.

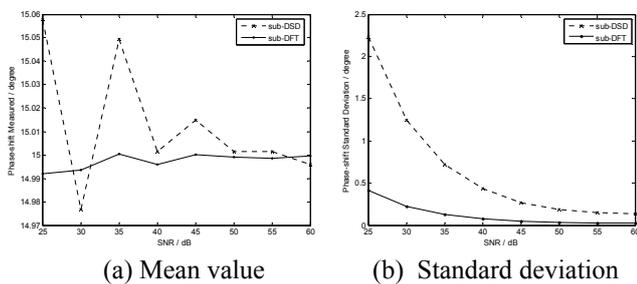


Fig.5: Phase discrimination performance of two methods under different SNRs

It can be known from Fig.5 (a) that the measurement mean of two methods gradually gets close to actual value with the increase of SNR. The measurement mean value obtained by phase discrimination of Sub-sampling spectrum analysis will have less fluctuation and be closer to actual phase difference. Under the situation of lower SNR ($\text{SNR} < 45\text{dB}$), the phase discrimination error of Sub-sampling spectrum analysis is far lower than Sub-sampling digital synchronous demodulation method. It can be known from Fig.5 (b) that the standard deviation of phase discrimination of Sub-sampling spectrum analysis is always superior to synchronous demodulation method and the value is less than 0.5° ; with increasing SNR, the phase discrimination standard deviation of two methods gradually increases. When SNR is larger than 35dB, the standard deviation of phase discrimination error of Sub-sampling spectrum analysis is smaller than 0.2° .

Lower limit of Cramer-Rao of phase discrimination method can be defined as:

$$\sigma_{\Delta\varphi-CR}^2 \geq \frac{1}{N} \left(\frac{1}{\text{SNR}_1} + \frac{1}{\text{SNR}_2} \right) \quad (7)$$

In the formula, N is the data number joining operation. SNR_1 and SNR_2 is separately the SNR of launching reference signal and measurement signal. Compare the phase discrimination precision of two methods under each SNR with the lower limit of Cramer-Rao, and we can have Fig.6.

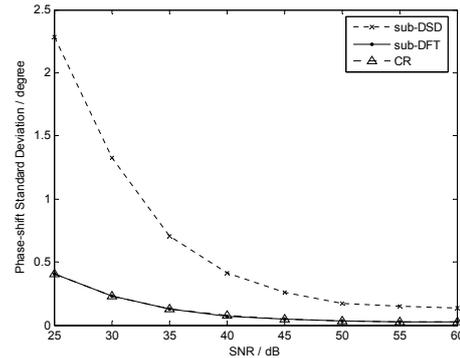


Fig.6: Comparison between phase discrimination standard deviation and lower limit of Cramer-Rao

It can be seen from the figure that the measuring standard deviation curve of Sub-sampling spectral analysis phase discrimination coincides with lower limit curve. This indicates that under the influence of noise, the standard deviation of Sub-sampling spectral analysis phase discrimination reaches to the lower limit of Cramer-Rao.

4. CONCLUSION

Compared with pulsed laser ranging, phase laser ranging can provide higher precision of measurement and has been widely applied to various devices, such as distance meter, total station, 3D laser scanner and so on. A new Phase laser ranging method with dual frequency laser was introduced to improve measurement precision and speed. The error model of measurement was analyzed, and two digital phase-shift measuring methods meet different requirements was discussed by simulation. It's showed that, the all-phase FFT method can still keep good phase discrimination performance under the influence of multiple factors, and the sub-sampling spectrum analysis method reduced the hardware cost of phase laser ranging.

REFERENCES

- [1] Wang Xuangang, Gou Ningyi, Zhang Keshu. ApFFT phase discrimination in phase-shift laser range finder[J]. INFORMATION AND ELECTRONIC ENGINEERING, 2012.12,10(6), pp.725-729.
- [2] Gou Ningyi, Zhang Keshu. High speed digital phase-difference measuring methods simulation and implementation in phase-shift laser range finder[J]. Infrared and Laser Engineering, 2012.9,41(9), pp.2358-2363.
- [3] Wang Xinyao, Zhang Keshu. Digital phase-shift measuring methods based on sub-sampling in laser range finder[J]. Infrared and Laser Engineering, 2013.5,42(5), pp.1330-1337.
- [4] Zhang Yigang, Fu Ping, WANG Li. Phase-shift measuring using digital correlation method[J]. Acta Metrologica Sinica, 2000.7,21(3).
- [5] Jin Yongbin. Research of Phase-Shift Laser Rangefinder System base on Digital Synchronous Demodulation for Phase-shift Measuring[D]. Nanjing University of Science and Technology, 2007.
- [6] Lu Yanjie, Xi Zhihong, Wang Jiangbo. Analysis and comparison between FFT and digital correlation theory

- inphase difference measurement [J]. Information Technology, 2007,12, pp.105-108.
- [7] Xie Lei, Li Ji, Chen Jiexiang, et al. Realization of digital phase detector based on FFT algorithm in laser distance measurement system[J]. Chinese Journal of Quantum Electronics, 2003,20(1), pp.85-89.
- [8] Wang Zhaohua, Huang Xiangdong, Yang Wei. The measuring phase method of all-phase FFT [J]. World SCI-TECH R & D, 2007, 29(4), pp.28-32.
- [9] Stephane Poujouly, Bernard Journet, Dominique Miller. Laser range finder based on fully digital phase-shift measurement[C]. Instrumentation and Measurement Technology Conference, Proceedings of the 16th IEEE, 1999,3, pp.1773-1776.
- [10] Sun Maoheng, Zhao Wen. Precision improvement of undersampling theory using phasic laser rangefinder[J]. Infrared and Laser Engineering, 2009,38(1), pp.70-73.