A Super High Resolution Phase Difference Measurement Method

Wei Zhou, Shengfeng Zheng, Zhiqi Li, Hui Zhou, Chunxu Wang
Dept. of Measurement and Instrument
Xidian University
Xi'an P. R. China

***Abstract*—Phase difference measurement techniques can be used widely in positioning and length measurement, and high resolution is necessary especially for some science research purposes. In this situation the request to the measuring device is different from that to the frequency standard comparison. It is difficult to improve the resolution of conventional counting measurement method with some high-resolution approaches and the phase noise and frequency instability of frequency sources will influence the measurement precision obviously. In this paper we present a super high-resolution phase difference measurement method that can show near 0.1ps resolution. With a high-linearity phase difference to voltage conversion approach and high-resolution voltage meter, it is possible to get very high phase measurement resolution, and the phase noise of frequency source used in the measurement can be filtered partly. When this method is used to measure the frequency stability of frequency standard, the integration time of voltmeter should be very short. However, when the measurement purpose is for length the integration time of volt measurement can be longer and it is favorable for high resolution. The method is suitable for a certain range distance measurement in a certain period.**

I. INTRODUCTION

Phase difference measurement techniques can be used not only in frequency standards comparison and transmission delay measurement of signal, but also in length measurement with high precision. Phase difference variation comparison is often used in frequency standard comparison, while the measurement of length and transmission delay pays attention to the phase difference.

II. THE MAIN METHODS ON PHASE DIFFERENCE MEASUREMENT AND THEIR COMPARISON

In phase difference measurement pulse average method and pulse count method are the main methods. With pulse count method, the phase measuring range can be wide, but it is difficult to obtain very high resolution. With the pulse average method very high resolution can be obtained, but it is difficult to obtain wide phase measuring range [1].

Using the linear phase comparator as well as the high-resolution voltage meter, not only long term performance of a frequency signal, but also its short - term performance can be measured with a high resolution[2]. This can be achieved with high linearity in phase comparison and proper response time, which guarantee the accurate correspondence of phase difference and the measurement results. High resolution can be gained with simple instruments in pulse average method, which is used frequently in measuring the variation of phase difference. Attention should also be paid to the response time in voltage measurement when the noise of the signal to be measured is required. Considering the measurement of length and phase difference, this method is more appropriate to indicate the variation of them. Similar to the full period ambiguity in the phase of carrier signal [3], wide phase difference variation is always bigger than the period of corresponding frequency signal in a wide length range. In addition, the linearity in wide rang, initial phase difference of the instruments, voltage drift, and trigger noises also exist in the pulse average method.

For the length measurement, comparison is often taken between two signals with the same nominal frequency. Some references have presented the feasible program [1][2].

In frequency standard comparison, one mainly pays attention to the measurement of phase difference variation, but the measurement of phase difference is more useful in positioning and length measurement. In a wide length range wide phase difference variation always is bigger than the period of corresponding frequency signal. The full period ambiguity is a big problem and should be solved, and some references have introduced suitable processing approaches [3] [4] [5].

III. HIGH RESOLUTION OF LINEAR PHASE COMPARISON METHOD

Implementation of high linearity in phase comparison is shown in our preceding paper [1][2], and based on it an improved device has been built by small signal reshaping to lower the trigger error.

The linear conversion of the phase difference to voltage was used. In practical, the linear phase comparison may be combined with the frequency conversion due to the high

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frequency of carrier signals, and the higher precision can be achieved.

The diagram of our experiment to implement the linear phase comparison of high precision is shown in Figure 1, which had been introduced in reference [2]. Figure 2 expresses the principle of which better linearity with high frequency can be obtained. Phase of one of the signals can be changed into the certain range in which good linearity of general phase detector is used.

When this method is used to measure the frequency stability of frequency standard, the integration time of voltmeter should be very short. The noise eliminated within a long integration time makes the measuring results trustless. Only short integration time can be taken into account considering the different noise ratio in different oscillators. However, when the measurement purpose is for length the integration time of volt measurement can be longer and it is favorable for high resolution. According to the time space relationship, with phase difference measurement to measure the length it is hopeful to filter the noise of the oscillator. So the integration time in length measurement can be much longer than that in the stability measurement of frequency standard.

With the linear phase comparison method the influence of trigger error is averaged in the average time of voltage measurement. Therefore, it is much less than that of count measuring case. The average trigger error is

$$\delta_2 = \frac{1}{N}\sum_{k=1}^{N}\frac{U_{n1k}}{2\pi U_{s1k}} + \frac{1}{N}\sum_{k=1}^{N}\frac{U_{n2k}}{2\pi U_{s2k}} \qquad (1)$$

Here, N is the number of the triggers in the average time of voltage measurement. Therefore, with the pulse average approach, it is favorable to long term frequency stability and length measurement, and obtain higher resolution.

Therefore, the influence of trigger error is improved. From equation (1) one can also find that the higher the phase comparison frequency is, the less influence of the trigger error can be.

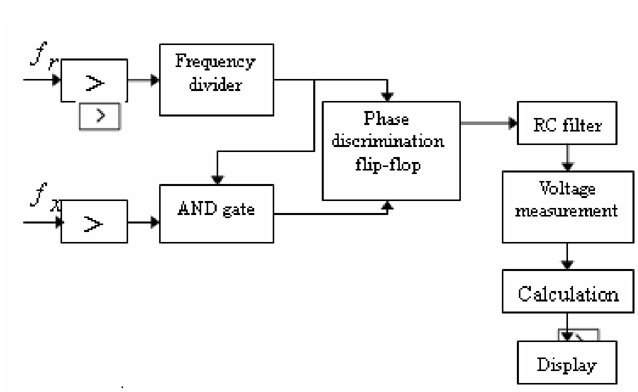

Figure 1. Example of a figure caption. *(figure caption)*

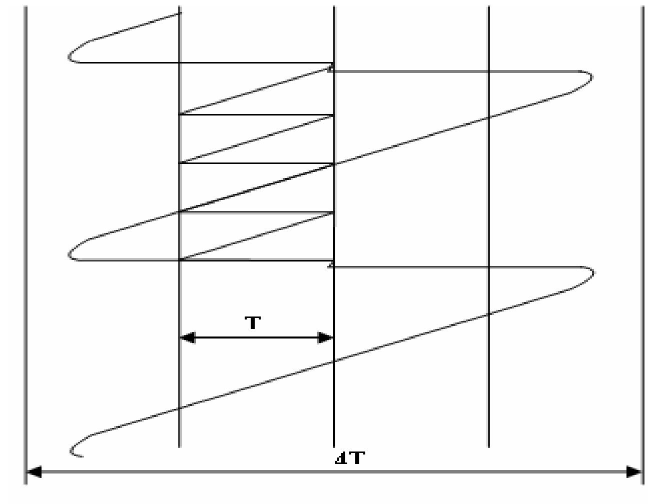

Figure 2. Example of a figure caption. *(figure caption)*

Correction should be added in addition to the stability assurance of the variation of the output voltage drift, variation of supply voltage and amplitude variation of the input signal, to guarantee the performance. Thus the reshaping circuit is necessary and it is crucial to improve the performance of the system. Besides, the noise ratio of the supply voltage needs optimizing. The multiple relations of the integration time of the voltmeter and the period of noise signal, and the calibration of the comparator also do help to the systemic performance. Different from the usual comparison methods only in the measuring range, the exact relation between the output voltage and the phase difference is needed. Better results can be achieved through adjusting the order of zero, full-scale value, and the resolution, or combining with other methods.

It is obviously different between length measurement and frequency & frequency standard stability measurement. In the length measurement, periodic ambiguity should be taken into account. The measurement range of the phase comparator is the full period of compared signal. Based on this case, it can exert preponderance of the method on resolution. Considering conflict between measurement range and resolution, the equivalent frequency of phase comparison shouldn't be too high. In this way, the length in a full period is much wider. Furthermore, full-periodic ambiguity is easy to be disposed with wider measurement range.

IV. Experiment and Results

We have done many experiments to verify the high resolution, systemic linearity and other factors that influence on linear phase comparison. Most of these experiments aimed at precision analysis in phase comparison.

For the resolution of the comparator, the method of comparison between crystal oscillators is adopted. It is calculated using Allan Variance as follows:

$$\sigma_y(\tau) = \frac{1}{\tau}\sqrt{\sum_{i=1}^{m}\frac{[(T_{i+1}-T_i)-(T_i-T_{i-1})]^2}{2m}} \qquad (2)$$

The measurement of non-oscillators noise, we can see from the experiment results, can achieve the resolution of 0.1ps in reasonable integral time, which is much higher than that of pulse count method. In the obviously long integral time, noise of the oscillator can be filtered out. Certainly, higher-resolution requirement will be influenced by frequency stability of the oscillator.

Linearity test with high requirements is difficult to be implemented. The frequency standard signal of the synthesizer HP-3335A and synthesized signal with the same frequency of the frequency standard signal were sent to the comparator. Synthesized output signal can be changed in phase through setting the degree. The results from the comparator for 10MHz compared signal are shown in table 2, with the phase variation 10ns each time.

For measurement results of the phase variation with the minute variation of the length, experiment was done to test the response when the length changed with temperature. Put a coaxial line connected in an input port of the comparator in the oven and record the output voltage of the phase comparator, shown in table 3.

From the table we can see that the voltage variation of comparator output was 0.1mv between 40 and 50 deg. C temperature. The voltage varies with phase corresponding to 10ps in time. Based on a speed of transmission in the cable, we can figure out 10ps in time corresponding to 2mm in length. In low temperature range, great error is caused by the heating imbalance, and in high temperature range, great error is caused by for the nonlinear swelling of the cable. While in an appropriate temperature range, we can see, phase variation caused by the change of length can be detected effectively using phase comparison method.

In a word, stability of 0.1ps can be achieved in this experiment, i.e. a length of several tens μm can be distinguished.

V. CONCLUSION

Linear phase comparison is a method with simple structure and high precision when the high resolution is required. With the high resolution, this method can be used in length measurement and positioning combined with other techniques and good results can be obtained.

TABLE I. THE RELATIONSHIP BETWEEN THE CALCULATED STABILITY AND THE INTEGRATION TIME

$\sigma_y(\tau)$ integration time	Oscillator 1 $2.4\sim4.1\times10^{-10}$ s	Oscillator 2 $2.8\sim3.3\times10^{-12}$ /s	Oscillator 3 $3.5\sim4.2\times10^{-13}/s$
1s	4.5×10^{-12} /s	$0.7\sim1.2\times10^{-12}$ /s	$1.5\sim0.9\times10^{-13}/s$
100 ms	5.0×10^{-12} /s	$1.0\sim1.4\times10^{-12}$ /s	$0.8\sim1.5\times10^{-13}/s$
20 ms	6.7×10^{-12} /s	$1.2\sim1.7\times10^{-12}$ /s	$1.2\sim1.9\times10^{-13}/s$
2.5 ms	1.9×10^{-10} /s		
1 ms	$2.3\sim3.5\times10^{-10}$ /s	$2.6\sim2.9\times10^{-12}$ /s	$3.5\sim4.1\times10^{-13}/s$
0.3 ms	$3.2\sim3.8\times10^{-10}$ /s		

TABLE II. LINEARITY TEST RESULT

	F_o =10MHz F_x =10 MHz																		
Test results（ns）	30.0	40.0	50.0	60.0	70.0	80.0	89.9	10.0	19.9	29.9	40.0	49.9	60.0	70.0	80.0	89.8	10.0	19.9	29.9

TABLE III. MEASUREMENT RESULT OF THE PHASE VARIATION

Output voltage /V	0.8296	0.8309	0.8322	0.8323	0.8324	0.8318
t/℃	30	35	40	45	50	55

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