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Ultra-resolution phase comparison method combining phase synchronous detection and common frequency source

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ABSTRACT

With the improvement of frequency standard comparison and precise frequency and phase processing technique, the high-precision frequency measurement, phase comparison, phase locked loop and signal processing are necessary. Combining phase synchronous detection principle and common frequency source, an ultra-high resolution phase comparison method is presented in this paper. Using the concepts of the equivalent phase comparison frequency, group period phase processing, phase group synchronization and phase quantization step and so on, and the high stability of common frequency source, the resolution with picosecond or subpicosecond can be easily obtained and ±1 count error in traditional phase comparison approach can be eliminated. Experimental results show that the measuring precision better than femtosecond in one hour can be achieved in the long-term frequency standard comparison.

1. Introduction

Phase processing method has the highest precision in signal processing. However, phase comparison approach has the highest resolution in phase processing method. It is widely used in high-precision frequency standard comparison [1,2]. The precision of some devices is depended on the method. In frequency standard comparison method, Dual mixer time difference measuring method is widely used in time and frequency measurement domain. It can achieve high-resolution phase and time difference measurement with the same frequency nominal value based on frequency conversion of intermediary source and multiplier effect. This method can be achieved from time analysis by introducing new phase processing approach. Consequently, the same high resolution with dual mixer time difference method can be obtained by the simpler approach, and the device is also easy to be implemented.

The accuracy of atomic frequency standard has at present increased to subfemtosecond, while the stability of super-high stability crystal oscillator has also been better than subpicosecond in 1 s, which force performance of the corresponding device widely used in high precision frequency standard comparison to be greatly improved at the same time. According to the above analysis, using the new concepts of the equivalent phase comparison frequency, group period phase processing, phase group synchronization and phase quantization step and so on, and combining phase synchronous detection principle and common frequency source, an ultra-high resolution phase comparison method is presented in this paper. Compared to double mixer approach, this method is based on the law of mutual phase relations among any signals, suitable for directly achieving high-resolution measurement and processing, while double mixer approach is only suitable for the measurement and processing with completely same frequency nominal value through frequency synthesis and transformation, such as mixing frequency.

2. Phase comparison principle and scheme

Based on the principle with super-high resolution of the phase variation between any frequency standard signal,

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the phase comparison approach with ultra resolution is at present developed in this paper. Especially, some new concepts of the equivalent phase comparison frequency, group period phase processing, phase group synchronization, group phase difference and phase quantization step and so on should be concerned [3–6]. It is well known that the traditional phase comparison method between the frequency signals has the same nominal frequency [7]. However, it is difficult for the conventional phase comparison method based on the compared signal period to obtain higher measurement precision. Reference [4] has in detail described the equivalent phase comparison frequency. Here, assume that there are two stable frequency signals with frequencies f_1 and f_2, and the corresponding periods T_1 and T_2. Let $f_1 = Af_{\max c}$ and $f_2 = Bf_{\max c}$. Where A and B denote two natural numbers with the greatest common divisor 1, and suppose that $A > B$ without the loss of generality. Then $f_{\max c}$ is called the greatest common factor frequency of this two frequencies. The period associated with $f_{\max c}$ is called the least common multiple period marked as $T_{\min c}$. The equivalent phase comparison frequency between them is

$$f_{\text{equ}} = \frac{f_1 f_2}{f_{\max c}} = ABf_{\max c} \tag{1}$$

It can be seen from Eq. (1) that the equivalent phase comparison frequency is much higher than the two compared frequencies. We can obtain the f_{equ} from GHz to THz in lower $f_{\max c}$. Therefore, a measurement resolution better than picosecond can be reached based on this periodic phase variation. For obtaining a higher equivalent phase comparison frequency, HP8664A frequency synthesizer is used to produce a common frequency source to generate a lower $f_{\max c}$. For example, with two frequency signals, 5 MHZ and 4 MHz, a 20.0000004 THz equivalent phase comparison frequency can be obtained by synthesizing one of the signal frequency into 5.0000001 MHz and the quantization step value of group phase difference, namely group phase quantum [8] is 5 fs.

According to the law of quantization step between any frequency signals, the phase coincidence always occurs between two signals. However, it is difficult to measure it for two frequency standard signals with the same nominal frequency, and the higher comparison resolution is, the more difficult measurement. If a common frequency is produced by HP8664A frequency synthesizer to generate a common frequency signal, then the phase coincidence is easy to be measured. Fig. 1 shows the measurement principle of the proposed method. In Fig. 1, the f_x is the measured frequency signal, the f_o is reference frequency signal, the f_c is a common frequency signal generated from f_o by HP8664A frequency synthesizer and the t is the gate time. The phase coincidences between f_x and f_c is used as start signal of the gate, while the phase coincidences between f_o and f_c is used as stop signal of the gate, as shown in Fig. 2.

In Fig. 2, the sampling time of the measurement, such as 0.1 s, 1 s, 10 s and so on, depends on delay control. The gate time t starts with the phase coincidences between measured frequency and common frequency, and stops with the phase coincidences between reference frequency and

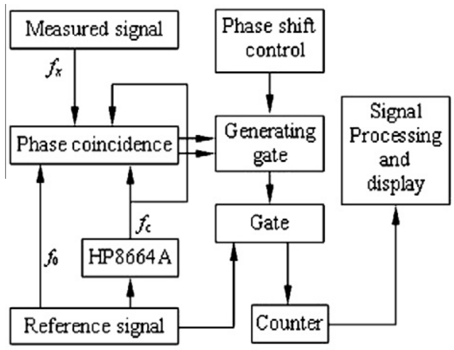

Fig. 1. Phase comparison scheme combining phase synchronous detection and common frequency source.

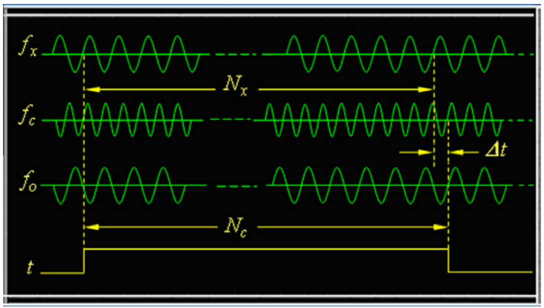

Fig. 2. The waveform in time interval measurement.

common frequency. In the gate time, the counted number of the common frequency signal is N_c. For using phase coincidence detection principle, ±1 count error is eliminated in the course of counted number of common frequency.

According the above method, the measured time interval can be obtained by the following equation:

$$\Delta t = N_c T_c - N_x T_x \tag{2}$$

In the practical measurement device, for simplifying the equipment, the common frequency source locked by the standard frequency signal is often used to replace the HP8664A frequency synthesizer. In this case, measurement precision can be further improved.

3. Experiment result and analysis

Fig. 3 shows super-resolution phase comparison experiment device combining phase synchronization detection and common frequency source. Here the common frequency f_c is very stable, because it is very important to decide the precision of the comparison system. Using f_0 as the reference signal of HP8664A frequency synthesizer, A suitable common frequency f_c is generated by HP8664A.

The frequency self-calibration gate generated by phase synchronization detection between f_o and f_c is used to measure the different output frequency of HP8664A. Some high-precision self-calibration experiment results with different common frequency are easily obtained. For example,

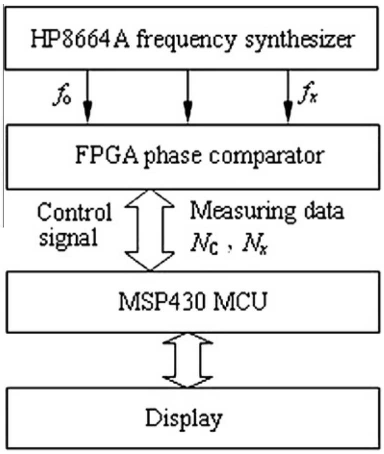

Fig. 3. Super-resolution phase comparison experiment device.

Table 1
Results of self-calibration experiment.

f_o (MHz)	f_c (MHz)	ΔT (fs)
10.000000	5.00001	199.9996
10.000000	10.000010	99.9999
10.000000	20.000010	49.999975
10.000000	100.00001	9.999999
10.000000	190.00001	5.263
f_{equ} (GHz)	σ (/s)	σ (/10 s)
5000.01	9.37×10^{-12}	1.64×10^{-13}
10000.01	7.17×10^{-12}	3.07×10^{-13}
20000.01	7.37×10^{-13}	8.24×10^{-14}
100000.01	3.95×10^{-13}	9.66×10^{-15}
190000.01	1.37×10^{-14}	6.38×10^{-15}

if f_o = 10 MHz and f_c = 100.00001 MHz, the phase quantum ΔT , namely quantized phase shift resolution is about 0.01 ps and the equivalent phase comparison frequency is 100.00001 THz, as shown in Table 1. Therefore, a resolution better than 1 ps can be obtained in theory by this method.

For the limited resolution of detection circuit, the noise of HP8664A frequency synthesizer and the performance of detection device, the practical precision is lower than the reached precision in theory. However, through further improvement of comparison device function, the frequency stability can reach 10^{-14} in 1 s. Besides, due to the limited start frequency in the system, the highest compared frequency is 190.00001 MHz in this method. At the same time, self-calibration resolution is also influenced by the synthetic frequency.

In the practical frequency standard comparison, in order to simplify calculating and measuring circuit for f_c, the common frequency source shown in Fig. 1 is usually adopted a 5.000001 MHz high-stable crystals oscillator locked by reference standard signal f_o, while the reference frequency is 10 MHz. In this case, the phase quantum can be calculated as follows:

$$\Delta T = \frac{1}{f_{equ}} = 0.02 \text{ ps} \tag{3}$$

The resolution with 0.02 ps is too high to obtain. Because the measurement resolution of phase detection circuit and the noise of frequency synthesizer or common crystals oscillator are obviously lower than the resolution. In all factor of impact resolution, the phase synchronization detection circuit is the most important.

Because the start and the stop of gate signal are decided by phase coincidence. It is evident that the measurement resolution is affected by its resolution. Furthermore, the actual measurement resolution is confirmed by the experiment that it is better than 1 ps.

Fig. 4 shows the drift of equipment itself caused by noise factor and so on in homologous self-calibration experiment, and it is also a test for the resolution of the method.

From Fig. 4 it can be seen that the choice of common frequency source is very important in this method. The higher stability of the common frequency source is, the more stable the measurement [9–11]. The higher frequency of the common frequency source is, the higher resolution of the measurement.

The proposed method can be implemented by FPGA shown in Fig. 3, including phase synchronization detection circuit, gate generator, delay control module, counter, etc. The measuring data, such as N_x and N_c, is sent to MSP430

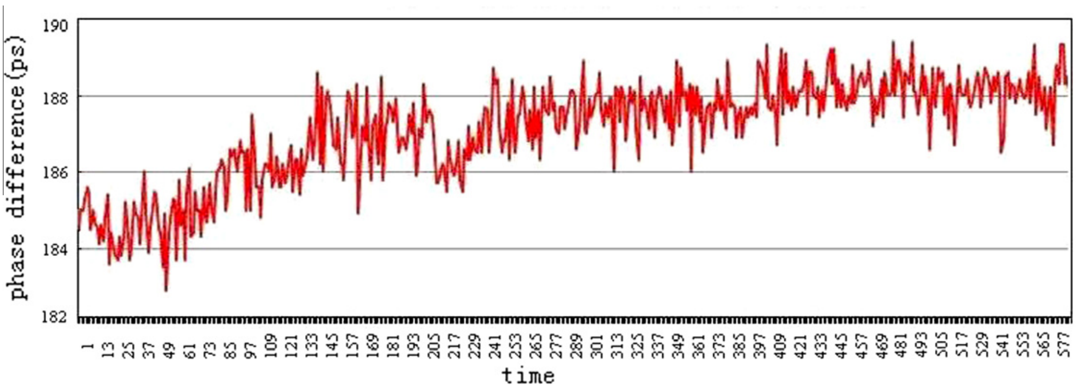

Fig. 4. The results of homologous self-calibration experiment.

MCU. From Eq. (2), the phase difference Δt between measured signal and reference signal can be obtained.

4. Conclusion

In summary, the phase comparison approach is high-resolution signal processing approach in precise phase and frequency measurement, and frequency standard comparison. Taking into account some factors of synthetic circuit noise caused by normalized frequency, the limited resolution of detection circuit and so on, it is difficult for the conventional comparison approach to obtain a high-precision measurement [12,13], while frequency standard comparison approach based on the equivalent phase comparison frequency between different frequencies signals features high precision, quick speed, easy implementation and low cost. From what has been discussed above, we may safely draw the conclusion that the resolution better than 1 ps and measuring precision higher than ps in 1 s can be easily obtained based on the new principle in the frequency standard comparison with 10 MHz frequency.

In long-term comparison of atomic frequency standard, the measuring precision can reached 10^{-17} in more several days. Compared to the traditional dual mixer approach, it uses the law of phase difference variation between different frequency signals, and features directly achieving frequency standard comparison, frequency measurement, phase locked control and signal processing without normalized frequency or frequency transform and synthesis. With the development of microelectronic technology, the improvement of production process, shorter gate delay of logic component, augment of logic gate capacity, lower cost and algorithm optimization [14,15], ultra-high precision phase comparison results can be achieved.

Acknowledgments

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