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High-precision frequency measurement system based on different frequency quantization phase comparison

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ABSTRACT

Aiming at the requirements of phase comparison without frequency normalization, a high-precision frequency measurement system is proposed based on different frequency quantization phase comparison. Using group phase difference pulse in the least common multiple period, the period of frequency standard signal, the period of the measured signal and the pulse width of group phase difference can be respectively counted with the aid of FPGA technology. The obtained counter value is saved and sent to host computer. The measured frequency can be obtained by the data processing of the host computer. Experimental results show that the short-term frequency stability of the system better than E−12/s is achieved. Compared to the traditional frequency measurement system, the system have the advantages of wide measurement range, high frequency stability, low phase noise and low development cost. The system not only plays an important role in precise measurement physics fields such as high-precision transmission and comparison of time and frequency, measurement and suppression of phase noise, but also has a wider application in localization of spatial motion radiation source, satellite navigation equipment, precise time frequency measurement, communication, radar and other high-tech fields.

1. Introduction

Time and frequency are the basic physical quantities with the highest precision in today's physical quantities [1]. High-precision transmission and comparison, high-resolution phase noise measurement and suppression, new atomic frequency standard based on time and frequency measurement have already been a hot research in the field of precision measurement physics [2–4]. The traditional frequency measurement methods mainly include direct pulse counting method, multi period synchronous measurement method, analog interpolation method, time vernier method and so on [5–7]. Using an interpolator and a vernier oscillator respectively, the analog interpolation and the time vernier method can reduce the ± 1 word count error to about 1/1000 and reach ps-level measurement accuracy. However, they have a complex circuit design and a high instrument cost, which limit the universality of its application. The more popular method is at present a comprehensive application of various frequency measurement methods internationally. However, it is difficult for the method to avoid the ± 1 word counting error [8–10]. In order to improve the measurement accuracy, a high-precision frequency measurement system is proposed based on different frequency quantization phase comparison. The system analyzes the frequencies relations between the measured signal and the frequency standard signal based on the scientific change law of the greatest common factor period and the phase difference quantization processing method. The measured frequency can be accurately calculated by strict synchronization of phase differences in the least common multiple period. The system can eliminate the ± 1 word counting error in traditional frequency measurement and realize direct frequency measurement without normalization processing.

2. Measurement principle

Frequency signals are periodic motion phenomena in nature. In addition to their respective periodic variation characteristics, what is significant for the comparison and measurement is that the scientific law of phase difference variation between frequency signals [11–13]. However, an important characterization of the scientific law and frequency relations between two comparison signals are some concepts such as the greatest common factor period, the least common multiple period and phase quantization accumulation [14–16].

Suppose f_1 and f_2 are two periodic signals with stable frequency. T_1 and T_2 are their periods respectively. Let

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$$T_1 = AT_{\max c} \tag{1}$$

$$T_2 = BT_{\max c} \tag{2}$$

where A and B are two positive integers without common factor and $A > B$. The $T_{\max c}$ is here called the greatest common factor period between f_1 and f_2, and can be calculated by formula (3).

$$T_{\max c} = (T_1, T_2) \tag{3}$$

The least common multiple period between f_1 and f_2 can be obtained by formula (1)–(3).

$$T_{\min c} = ABT_{\max c} \tag{4}$$

Every phase difference result obtained in different frequency phase comparison is just quantized by $T_{\max c}$. With the time, there is a series of phase coincidences caused by the stability of electromagnetic wave signal transmission in the space or specific medium and the differences of two signals frequencies f_1 and f_2 in phase comparison. The obtained ideal coincidences are a minimum of phase comparison results f_{out}. The coincidences with a stable transmission can parallel shift with the time. When the shifting time is just multiples of the least common multiple period $T_{\min c}$, the coincidences occur again. As shown in Fig. 1. Where the θ is the initial phase difference between two comparison signals, and the PD_3, PD_2, PD_1 and PD_0 are a series of phase differences obtained by different frequency phase comparison.

It can be seen from Fig. 1 that the phase coincidences such as A, B have periodicity and constancy by the time interval $T_{\min c}$. The least common multiple period is the key physical characteristics of different frequency phase comparison. It reflects the continuity of the different frequencies phase comparison and the phase interconnections between two frequencies signals. As shown in formula (5).

$$T_{\min c} = m_1 T_2 = m_2 T_1 \tag{5}$$

It is not difficult to draw a conclusion that the direct phase comparison between two different frequencies is not possible when the period of any comparison signal (T_1 or T_2) is used as a reference. This is also the main reason of the frequency normalization in the traditional phase comparison method.

In fact, the process of different frequency quantization phase comparison is also the process of the quantization accumulation of the greatest common factor period. After the frequency relation of two comparison signals is fixed, the greatest common factor period is fixed. It is the least phase difference in different frequency phase comparison, the minimum phase unit for quantizing phase difference, represents the resolution of the phase measurement and reflects the minimum quantization error in phase difference measurement. At the same time, the greatest common factor period number is also fixed in the least common multiple period. It may be an increasing quantum accumulation, or a quantized accumulation of decreasing forms, or even a quantum accumulation without any regularity, all these depend on the complexity of the frequency relation of the two comparison signals.

According to the principle of different frequency quantization phase comparison, all phase differences obtained in phase comparison is processed. The front, trailing edge and width of each phase difference pulse are continuously counted by the time interval $T_{\min c}$. All counting values are saved and sent to the host computer for processing. The

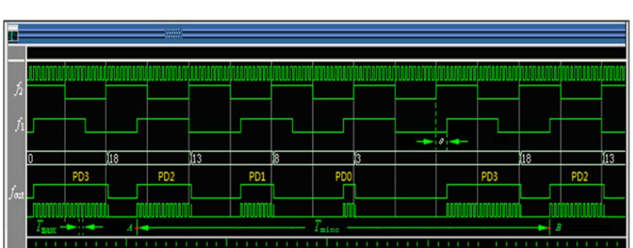

Fig. 1. The principle of different frequency quantization phase comparison.

frequency value of the measured signal is calculated by the following formula (6).

$$f_x = \frac{N_x}{N_0} \cdot f_0 \tag{6}$$

where f_x is the frequency of the measured signal, f_0 is the frequency of the frequency standard signal, N_x is the counted front edge number of phase difference pulses which represents the counting value of the whole period of the measured signal in a $T_{\min c}$, N_0 is the counted trailing edge number of phase difference pulses which represents the counting value of the whole period of the frequency standard signal, respectively.

3. System measurement scheme

The scheme of high-precision frequency measurement system is shown in Fig. 2. The hardware part of the system is completed in FPGA and the data processing part of the system is achieved by the host computer software.

The precise frequency source such as high stability crystal oscillator OCXO8607-BM and H800-U, Cesium atomic clock 5071A outputs standard sine wave, so the reference signal and the measured signal are digitally processed before being sent to the FPGA. According to the scheme shown in Fig. 2, the measurement process of the system is as follows.

First, the signal conditioning and the square wave shaping of the reference frequency and the measured frequency are completed by Schmitt trigger 74HCT14. The reference frequency is 4 KHz square wave and the measured frequency is 1 KHz square wave. The LSTTL level standard generated by the square waves is compatible with the IO output of the FPGA. The experimental result is shown in Fig. 3.

Second, the reference signal is sent to the FPGA. The standard clock signal with 200 MHz is produced by the frequency multiplier of the PLL in FPGA. The reference square signal with 4KHz and the measured signal are sent to pulse transform circuit. The front edge of these square waves are extracted and converted to a series of narrow pulses. The width of these narrow pulses is equal to a standard clock period. The experimental result is shown in Fig. 4.

Third, the two narrow pulse signals are sent to different frequency quantization phase comparison module to produce a series of phase differences which characterize the frequency relationship between the two comparison signals. All phase differences are quantized by the greatest common factor period and have a strict synchronization by the interval of the least common multiple period. The experimental result is shown in Fig. 5.

Finally, by processing the front edge, trailing edge and pulse width of all phase differences, the period of the reference signal and the measured signal, the size of all phase differences are continuously counted, and all counting values are saved. The saved counting values are sent to host computer by COM (cluster communication port) for data processing. By writing algorithm according to formula (6), the measured frequency is calculated and displayed on host computer.

4. Experimental results and analysis

A prototype of high-precision frequency measurement system based on different frequency quantization phase comparison has been developed. The frequency measurement range of the system is from 0.1 MHz to 210 MHz, and short-term frequency stability of the system is better than E − 12/s order.

4.1. Self-calibration experiment from the same frequency source

In the system self-calibration experiment, by using the common KEYSIGHT E8663D frequency synthesizer, which has external frequency standard OCXO8607-BM 10 MHz frequency signal, measured signal series with relative frequency deviation less than 100 Hz can be