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Characteristic pulse detection method for fuzzy area

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Abstract. In order to achieve higher frequency measurement accuracy, this paper proposed a characteristic pulse detection method of fuzzy area based on the quantized phase processing method of different frequency groups. First, the fuzzy area of the group phase coincidence points continuously moved on the time axis after passing through delay elements. The moving distance, that is, the number of the delay elements was determined by the main clock cycle of the D flip-flop. After that, three groups of phase coincidence detection fuzzy areas in different positions were sent to the digital logic module to extract the edge pulses of the phase coincidence detection fuzzy area. The pulse width is determined by the difference between the clock cycles of the delay elements. The clock cycles of different delay units were adjusted to obtain nanosecond or even picosecond circuit detection resolution. Finally, the pulses generated at the edge of the phase coincidence fuzzy area are taken as the switching signal of the frequency signal counter, so the stability of the gate signal and the accuracy of the gate time measurement are improved. The experimental results show that frequency stability can reach the order of E–13/s. In addition, compared with the traditional measurement method, it is characterized by simple structure, low cost, low noises, and high measurement resolution.

Key words: frequency measurement; the group period; phase coincidence fuzzy area; the measurement gate.

1. INTRODUCTION

The technological development in satellite navigation, metrology, communication, astronomy, and other fields has proposed high requirements for the speed and accuracy of frequency and time measurement [1,2]. At present, no major breakthrough has been made in the high-precision frequency measurement methods. Traditional measurement methods (such as multi-period synchronization, direct counting, analog interpolation, and cursor method) mainly rely on the microelectronics manufacturing process to improve measurement accuracy, but the room for improvement is very limited [3, 4]. The direct count method and the multi-period synchronization method are only suitable for low-frequency signals. As the accuracy is low, the counting error of the ±1 character cannot be solved. Analog interpolation uses the analog method to measure the time interval between the frequency signal and the actual gate signal. Compared with the first two methods, the analog interpolation can improve the resolution by three orders of magnitude, but it requires a longer time for conversion, the nonlinearities are difficult to control, and the count error of ±1 character still exists [5–9]. The design philosophy behind the vernier method is similar to that of a mechanical vernier caliper. The vernier oscillator can be used to accurately measure the mantissa outside the entire period. The HP5370B time interval counter based on the vernier method of Hewlett-Packard Company can measure the sub-frequency up to 20 ps. However, the hardware circuit is complex and expensive, and the conversion time is long, so the system integration and application are restrained [10–20]. The high-precision frequency measurement method based on the phase quantization of different-frequency signal groups uses the periodic law of the phase relationship between signals to solve the problems in the traditional frequency measurement method in principle. With the adoption of FPGA on-chip technology, the circuit structure is simplified and the measurement accuracy and stability are improved [1–4]. As the phase coincidence pulse of the standard frequency signals and the measured signals trigger the measurement gate, the gate signal is synchronized with the frequency standard and the measured signal, and the count error of ±1 character in the traditional method can be overcome. However, in the real measurement process, multiple phase coincidence pulses will appear in a group period and a fuzzy area can be formed, so the randomness of the actual measurement gate occurs and measurement accuracy can hardly be improved. The method based on the vernier reduces the width of the fuzzy area through the delay difference of the hardware delay line and makes the synchronization gate more accurate. However, the delay difference is determined by the signal frequency of the dielectric constant of the long wiring and other parameters, so the vernier method is not so reliable, and cannot ensure very precise and fast measurement in a wide frequency range [21–26]. To this end, this thesis proposes a differential synchronization detection method based on FPGA on-chip technology. This method quickly can reduce the width of the phase coincidence fuzzy area or extract the pulse at the edge of the phase coincidence fuzzy area, and trigger the synchronization gate signal to improve the accuracy and stability of frequency measurement through a program.

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2. MEASURING PRINCIPLE

2.1. Principles of quantized phase processing in different frequency groups

Internationally, the phase processing method is generally regarded as one with the highest resolution among frequency measurement methods. The traditional phase processing method is based on the same frequency phase. First, the frequency is normalized through frequency mixing, multiplication and synthesis, and phase comparison. An increase in cost and the introduction of distortion and noise make it difficult to improve measurement accuracy. The quantization phase processing method based on different frequencies signals is adopted to directly compare the two signals, study the phase changes between the compared signals and apply results to frequency measurement. In this way, the measurement resolution and frequency stability can be improved.

There are two stable signals, standard signal f_0, and measured signal f_x. The corresponding period is as follows:

$$T_0 = AT_{\max c}\,, \tag{1}$$

$$T_x = BT_{\max c}\,. \tag{2}$$

Two integers A and B are relatively prime, and $B < A$. $T_{\max c}$ is defined as the period of the greatest common factor of the two frequency signals.

$$T_{\min c} = BT_0 = AT_x = ABT_{\max c}. \tag{3}$$

According to formula (3), the least common multiple period $T_{\min c}$ of f_0 and f_x can be calculated. There is a full cycle of the standard frequency signal and a full cycle of the measured signal in $T_{\min c}$, and the time difference between the rising edge of each full cycle f_0 and the subsequent adjacent rising edge f_x is the phase difference f_{out} or $[PD_1, PD_2, PD_3, \ldots, PD_B]^T$ as shown in Fig. 1.

$$\begin{bmatrix} PD_1 \\ PD_2 \\ PD_3 \\ \vdots \\ PD_B \end{bmatrix} = \begin{bmatrix} n_1T_x - 1T_0 \\ n_2T_x - 2T_0 \\ n_3T_x - 3T_0 \\ \vdots \\ AT_x - BT_0 \end{bmatrix}$$

$$= \begin{bmatrix} n_1BT_{\max c} - 1AT_{\max c} \\ n_2BT_{\max c} - 2AT_{\max c} \\ n_3BT_{\max c} - 3AT_{\max c} \\ \vdots \\ ABT_{\max c} - BAT_{\max c} \end{bmatrix} = \begin{bmatrix} K_1 \\ K_2 \\ K_3 \\ \vdots \\ K_B \end{bmatrix} T_{\max c}\,, \tag{4}$$

$[K_1, K_2, K_3, \ldots, K_B]^T$ are zero or positive integer respectively. In a word, each phase difference is quantized by $T_{\max c}$. $T_{\max c}$ is the smallest and indivisible phase difference that is defined as phase quantization. At this time, $T_{\min c}$ is defined as a phase group that contains all phase differences.

When $T_0 \colon T_x \neq A : B$, it is assumed that the standard frequency signal has frequency deviation $\Delta f \neq 0$, $T_0' = T_0 \pm \Delta t$, $\Delta t > 0$. In the least common multiple periods, the step value of any adjacent phase difference is Δt, i.e. $PD_B^{(n)} - PD_{B-1}^{(n)} = \Delta t$, $B \geq 2$. The phase step value of any adjacent group quantization is $\Delta P = B\Delta t$: $|PD_B^{(n)} - PD_B^{(n-1)}| = \Delta P$, $n \geq 2$.

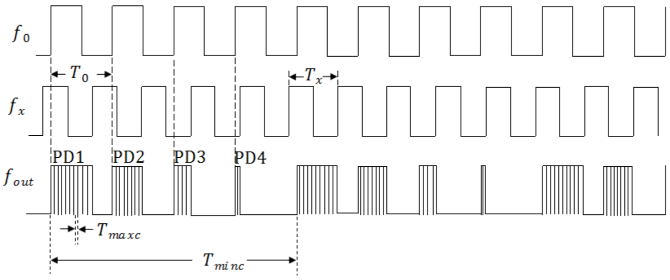

Fig. 1. Quantization processing of different frequency groups

When the step value of any group quantization phase is equal to the entire period of the measured signal f_x, $n\Delta P = T_x$. The phase difference and the group quantization phase will change over the full period and return to the initial state repeatedly. The period during which the quantized phase of any group undergoes a full-period change is called the group period T_{gp}.

2.2. Principle of the differential synchronization detection

According to the above analysis, if the group period is used as the measurement gate, the time interval between two phase coincidence points (T_{gp}) is often taken as the measurement gate in engineering, and the standard frequency signal. Calculating the measured signal calculated respectively within the gate time can overcome the counting error of ±1 character and help calculate the actual frequency of the measured signal. The phase coincidence point refers to a step value where the phase difference is the smallest in the group period. In fact, due to different frequency values, any two frequency signals will make their phase shift to each other. When two signals are formed into a narrow pulse for phase discrimination, there is a certain pulse width. Therefore, theoretically, two signals do not have a unique phase coincidence point: the phase coincidence point may be a cluster of pulses rather than a narrow pulse. In this cluster of pulses, the optimal phase coincidence occurs in highest amplitude and the rest phase coincidence points are known as false phase coincidence points. Therefore, the phase coincidence point has a certain fuzzy area where the narrow pulses are evenly distributed. There are many narrow pulses higher than the trigger level of the gate in the fuzzy area, so the random opening and closing of the measuring gate makes the actual gate time not exactly the same each time and the measurement accuracy is restrained $[PD_1, PD_2, PD_3, \ldots, PD_B]^T$ as shown in Fig. 2.

The fuzzy areas can not be eliminated, but the width of the fuzzy area can be decreased. The differential synchronization detection circuit is mainly aimed to decrease the width of the phase coincidence fuzzy area and to extract the pulse at the edge of the phase coincidence fuzzy area. The circuit can generate the edge characteristic pulse, which is taken as the counter switch signal, so as to enhance the stability of the gate signal and improve the measurement accuracy of gate time.

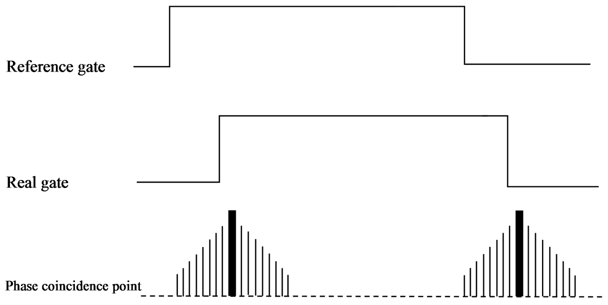

Fig. 2. Phase coincidence fuzzy area

In Fig. 3, the delay element is composed of D flip-flops, and all flip-flops in a delay element are synchronized with a master clock. The frequency of the main clock in different delay elements is different, and the difference between the period of the main clock is the detection resolution of the differential synchronization circuit. By adjusting the clock cycles of different delay elements, the researchers have obtained nanosecond or even picosecond circuit detection resolution. Due to the stability of the frequency relationship between the comparison signals, the fuzzy area of the phase coincidence points generated by the detection circuit is also stable and continuously moves on the time axis under the action of the delay elements. As delays of the two delay elements are different, the continuous moving distance of the phase coincidence point fuzzy area varies. After that, three groups of phase coincidence detection fuzzy areas in different positions were sent to the digital logic module to extract the edge pulses of the phase coincidence detection fuzzy area. The width of the characteristic pulse based on the fuzzy area is $\Delta t'$ – the difference between the clock cycles of the two delay elements. Under the prerequisite of ensuring accurate detection of the edge information of the fuzzy area at the phase coincidence points, the smallest $\Delta t'$ is preferred: the smaller the detection resolution of the circuit, the smaller the jitter of the gate signal, and the more accurate the gate time measurement.

3. FREQUENCY MEASUREMENT EXPERIMENT

In the experiment, 8607-B BVA quartz crystal oscillator is used as the common source for standard signal, clock sources of the delay elements, which are shown as master clock in Fig. 3. Keysight Technologies, Inc. E8663D PSG generates a series of measured signals. Measurement results are given in Table 1.

Table 1
Experimental data

Measured signal (MHz)	Standard signal (MHz)	Measured results (MHz)	Frequency stability (σ/s)
45.0000100	45	45.00000964	8.07626E–13
37.0000100	37	37.00000897	7.78378E–13
34.0000100	34	34.00000879	7.67489E–13
28.0000010	28	28.00000094	6.74564E–13
16.0000010	16	16.00000098	5.65461E–13
10.0000100	10	10.00000988	5.01275E–13
9.0000010	9	9.00000087	4.93836E–13
5.0000010	5	5.00000095	4.45181E–13
4.0000010	4	4.00000089	3.64207E–13
2.0000010	2	2.00000098	2.56E–13
1.0000010	1	1.00000094	1.74471E–13

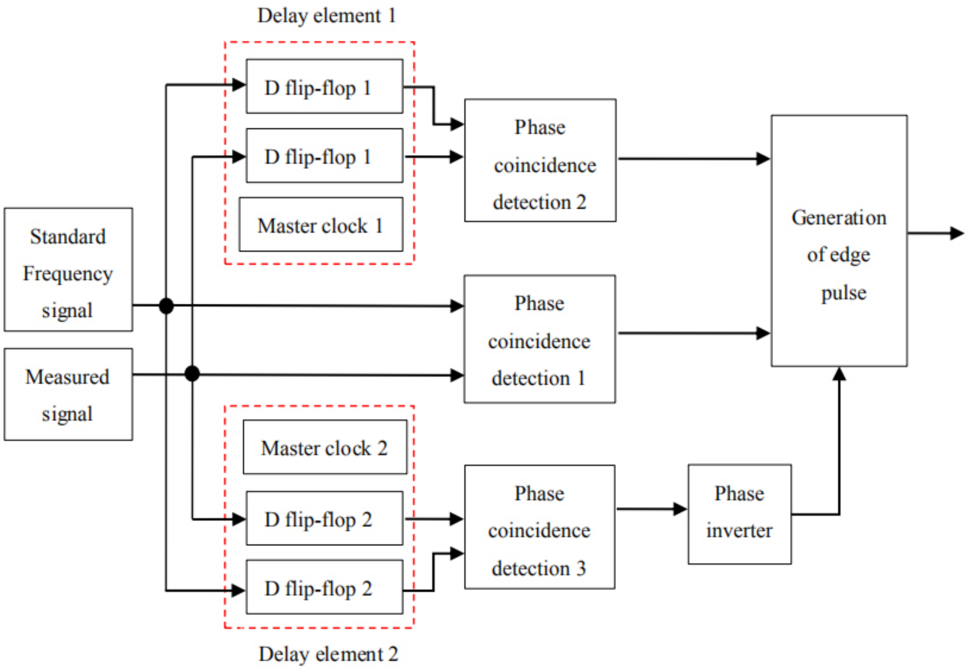

Fig. 3. Differential synchronization detection circuit

According to Table 1, frequency stability of E–13/s order of magnitude in the radio stability of the system can be achieved. Compared with the theoretical values E–11/S of the traditional frequency measurement method and E–12/S based on the vernier, the measurement accuracy of E–13/s order of magnitude is greatly improved. At the same time, the system has the same measurement level for ordinary integer frequency points and special decimal frequency points.

4. CONCLUSIONS

Based on the research of quantized phase processing in different frequency groups, this thesis proposes a differential synchronization detection method based on characteristic pulses at the edge of the fuzzy area. This plan improves the existing phase coincidence detection technology and narrows the width of the phase coincidence fuzzy area. In this way, the jitter of the pulse at the edge is reduced. The gate measurement accuracy and the system frequency stability are high. The use of differential synchronous detection technology eliminates system and hardware errors caused by the inconsistency of the detection devices, improves the circuit detection resolution, and realizes the precision of frequency measurement. The experimental results show that frequency stability can reach the order of E–13/s. In addition, compared with the traditional measurement method, it is characterized by simple structure, low cost, low noises, and high measurement resolution, so it can be applied to satellite navigation, scientific measurement, time-frequency transmission, precision frequency source, timing positioning, and other fields.

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REFERENCES

[1] X. Geng *et al*, "Different frequency synchronization theory and its frequency measurement practice teaching innovation based on Lissajous figure method," *J. Beijing Inst. Technol.*, vol. 27, no. 2, pp. 198–205, 2018, doi: 10.15918/j.jbit1004-0579.201827.0206.

[2] B.Q. Du *et al*, "High-precision frequency measurement system based on different frequency quantization phase comparison," *Measurement*, vol. 122, pp. 220–223, 2018, doi: 10.1016/j.measurement.2018.02.063.

[3] B. Du *et al*, "High-Resolution group quantization phase processing method in radio frequency measurement range," *Sci. Rep.*, vol. 6, no. 1, p. 29285, 2016, doi: 10.1038/srep29285.

[4] B.Q. Du *et al*, "Precise frequency linking method based on phase group synchronization," *Measurement*, vol. 62, pp. 222–229, 2015, doi: 10.1016/j.measurement.2014.11.016.

[5] Y. Xue, "High-Resolution Multi-Channel Frequency Standard Comparator Using Digital Frequency Measurement," *Sensors*, vol. 21, p. 5626, 2021, doi: 10.3390/s21165626.

[6] S.P. Maria and C. Enrique, "Time synchronization in Arduino-based wireless sensor networks," *IEEE Latin Am. Trans.*, vol. 23, no. 2, pp. 455–461, 2015, doi: 10.1109/TLA.2015.7055564.

[7] D. Georgakopoulos and S. Quigg, "Precision measurement system for the calibration of phasor measurement units," *IEEE Transactions on Instrumentation & Measurement*, no. 6, pp. 1–5, 2017, doi: 10.1109/TIM.2017.2653518.

[8] H. Wang and H.Y. Zeng, "Linear estimation of clock frequency offset for time synchronization based on overhearing in wireless sensor networks," *IEEE Commun. Lett.*, vol. 20, no. 2, pp. 288–291, 2016, doi: 10.1109/LCOMM.2015.2510645.

[9] H. Wang, L. Shao, M. Li, B. Wang, and P. Wang, "Estimation of clock skew for time synchronization based on two-way message exchange mechanism in industrial wireless sensor networks," *IEEE Trans. Ind. Inform.*, vol. 14, no. 11, pp. 4755–4765, 2018, doi: 10.1109/TII. 2018.2799595.

[10] V. Yatseev and O.V. Butov, "Phase-frequency time-gated reflectometry for absolute measurements," in *Proc. SPIE*, vol 11772 (Optical Sensors 2021), p. 1177215, 2021, doi: 10.1117/12.2589223.

[11] K. Shi, Y. Tang, X. Liu, S. Zhong, "Non-Fragile sampled-data robust synchronization of uncertain delayed chaotic lurie systems with randomly occurring controller gain fluctuation," *ISA Trans.*, vol. 66, pp. 185–199, 2017, doi: 10.1016/j.isatra.2016.11.002.

[12] N. Panigrahi and P. Mohan Khilar, "An evolutionary based topological optimization strategy for consensus based clock synchronization protocols in wireless sensor network," *Swarm Evol. Comput.*, vol. 22, pp. 66–85, 2015, doi: 10.1016/j.swevo.2015.02.001.

[13] J.R. Yang, "Measurement of amplitude and phase differences between two RF signals by using signal power detection," *IEEE Microw. Wirel. Compon. Lett.*, vol. 24, no. 3, pp. 206–208, 2014, doi: 10.1109/LMWC.2013.2293665.

[14] S.J. Yang and Y.Y. Wang, "Frequency synchronization for interleaved OFDMA uplink systems," *J. Frankl. Inst.*, vol. 356, no. 15, pp. 8855–8869, 2019, doi: 10.1016/j.jfranklin.2019.08.027.

[15] K. Shi *et al*, "Nonfragile asynchronous control for uncertain chaotic Lurie network systems with Bernoulli stochastic process," *Int. J. Robust Nonlinear Control* vol. 28, pp. 1693–1714, 2018, doi: 10.1002/rnc.3980.

[16] C. Zhao and J. Li, "Equilibrium selection under the bayes-based strategy updating rules," *Symmetry*, vol. 12, no. 5, pp. 739, 2020, doi: 10.3390/sym12050739.

[17] S. Gong and J. Fu, "Noether's theorems for the relative motion systems on time scales," *Appl. Math. Nonlinear Sci.*, vol. 3, pp. 513–526, 2018, doi: 10.2478/AMNS.2018.2.00040.

[18] S.S. Zhou *et al*, "Status of satellite orbit determination and time synchronization technology for global navigation satellite systems," *Chin. Astron. Astrophys.*, vol. 43, no. 4, pp. 479–492, 2019, doi: 10.1016/j.chinastron.2019.11.003.

[19] M. Coban and S.S. Tezcan, "Detection and classification of short circuit faults on transmission line using current signal," *Bull. Pol. Acad. Sci. Tech. Sci.*, vol. 69, p. e137630, 2021, doi: 10.24425/bpasts.2021.137630.

[20] A. Yan *et al*, "Cost-effective and highly reliable circuit components design for safety-critical applications," *IEEE Trans. Aerosp. Electron. Syst.*, p. 1, 2021, doi: 10.1109/TAES.2021.3103586.

[21] K.X. Ren *et al*, "A time and frequency synchronization method for CO-OFDM based on CMA equalizers," *Opt. Commun.*, vol. 416, pp. 166–171, 2018, doi: 10.1016/j.optcom.2018.02.007.

[22] D. Hernandez-Balbuena *et al*, "Constraints definition and application optimization based on geometric analysis of the frequency measurement method by pulse coincidence," *Measurement*, vol. 126, pp. 184–193, 2018, doi: 10.1016/j.measurement.2018.05.025.

[23] Y. Wu and J.L. Fu, "Noether's theorems of variable mass systems on time scales," *Appl. Math. Nonlinear Sci*, vol. 3, pp. 229–240, 2018, doi: 10.21042/AMNS.2018.1.00017.

[24] F.N. Murrieta-Rico *et al*, "Optimization of pulse width for frequency measurement by the method of rational approximations principle," *Measurement*, vol. 125, pp. 463–470, 2018, doi: 10.1016/j.measurement.2018.05.008.

[25] G.X. Yang and H. Liang, "Adaptive frequency measurement in magnetic resonance coupling based WPT system," *Measurement*, 2018, vol. 130, pp. 318–326, doi: 10.1016/j.measurement.2018.08.025.

[26] Y. Du, B. Qin, C. Zhao, Y. Zhu, J. Cao, and Y. Ji, "A novel spatio-temporal synchronization method of roadside asynchronous MMW radar-camera for sensor fusion," *IEEE Trans. Intell. Transp. Syst.*, pp. 1–12, 2021, doi: 10.1109/TITS.2021.3119079.