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Equivalent Phase Allocation Method Based on Frequency Measurement without Dead Zone

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Abstract: In the field of precise time-frequency measurement and control, high resolution, time-dead zone and frequency measurement without dead zone are very important. In this paper, a frequency measurement method without dead zone is proposed, which locks the phase of the frequency signal output by the frequency synthesizer on the measured signal. By detecting the change of phase difference between the measured signal and the DDS output frequency signal, the DDS frequency control register and the phase shift control register are changed to realize the phase tracking. The frequency of the measured signals is calculated according to the phase change rule of the two signals. The experimental results in this paper show that the method achieves a measuring stability of 10^{-13}.

Keywords: Without dead zone, Frequency measurement, Phase tracking, DDS.

1. Introduction

As one of the seven international standard physical quantities, time is a component of many derived physical quantities and has the highest measurement accuracy among the current basic measurement units. In many fields such as aerospace, electric power and optical fiber communication, high precision time interval and frequency signal are needed. Precise time and frequency signal provide necessary reference signal for measurement and control. Precision time and frequency provide the necessary reference signals for measurement and control [1]. High precision time has good linearity and accuracy, which can more objectively reflect the motion law of the object. Therefore, in recent years, the world has attached great importance to the research of precision time and frequency measurement technology. At present high precision in any frequency measurement equipment, the measuring principle of many devices are dead zone of frequency measurement. For example, the 53230A frequency meter developed by Keysight has a 12-bit frequency measurement resolution, is a typical commercial frequency counter [2], but difficult to achieve without dead zone under high measuring resolution of frequency measurement, This seriously affects its application in the field of precision frequency measurement.

Because the phase information between two sampling periods is omitted in the frequency measurement method with dead zone, the measurement results cannot fully reflect the long-term frequency stability of the measured signal. When Aaron variance is used to characterize the measured results in the time domain, the stability curve changes as $1/\sqrt{\tau}$. However, when the phase ratio method is used for measurement, no phase information is omitted between the two measurements, and the stability curve of the measurement results changes with the rule of $1/\tau$. However, phase ratio is usually only used for the measurement of the same frequency standard, can not meet the needs of any frequency measurement. In this paper, a frequency measurement method without dead zone is proposed. Since no phase information is omitted in the frequency measurement method without dead zone, the measurement results can be equivalent to phase comparison, and the measurement range is large, which can measure any frequency signal between 1 and 80 MHz.

2. Frequency Stability

The indicators of the clock source mainly include accuracy and stability. Accuracy refers to the error between the real frequency of the oscillator and the nominal frequency. Generally, atomic clocks are used as clock sources in occasions that have higher requirements for frequency accuracy, and the clocks of various devices are locked on the atomic clocks through a phase-locked loop method to obtain higher accuracy. Stability refers to the ability of the frequency source to keep the frequency constant, and the Allan variance is usually used as an index to judge the stability. When studying the stability of crystal oscillators and atomic clocks, people found that the phase noise of these systems includes not only white noise, but also flicker noise. When using traditional statistical tools (such as standard deviation) to analyze this type of noise, the statistical results cannot be converged .In order to solve this problem, David Allan proposed the Allan variance in 1966. Nowadays, the Allan variance is used to characterize the frequency stability of clock sources in the time domain. In fact, not only oscillators, but any frequency source can use Allan variance to evaluate its frequency stability. Usually when using frequency data to calculate the Allan variance, the expression is:

$$\delta_y^2(\tau) = \frac{1}{2(M-1)} \sum_{i=1}^{M-1} [y_{i+1} - y_i]^2, \quad (1)$$

where τ is the sampling time, the calculation result of the Allan variance is a series of data with τ as the abscissa, M is the number of samples, and are the frequency values of the ith and (i+1)th measurements. Allan variance can reflect the stability of the frequency source over different sampling time lengths. If the sampling is without dead zone, that is, there is no omission between the two sampling data. The data can truly reflect the nature of the clock source, and the obtained Allan variance curve decreases with a slope of, that is, every ten times the sampling time increases, the Allan variance value also decreases by one-tenth. If the measurement method with dead zone is adopted, that is, there is no correlation or discontinuity between the data, the curve will decrease at a slope of, that is, the sampling time will increase by one hundred times, and the Allan variance will decrease by one-tenth. Phase comparison is an indirect frequency measurement method, which is generally carried out when the nominal values of the two frequency sources are the same. The phase comparison method can be used to measure the phase change relationship between the two signals. After the measurement result is converted into frequency stability, the change law of the stability curve follows. The interval frequency measurement method usually intercepts the phase change law within a period of time. The phase information between the two tests is lost, resulting in the change law of the stability curve to follow, while the frequency measurement method without interval collects all phase information. Can be equivalent to phase comparison.

For frequency measurement equipment, it is usually used to measure its own reference clock, and the Allan variance obtained is used as the noise floor of the instrument. The measurement methods proposed in this article all use this method to evaluate the noise floor.

3. Principle of Phase Tracking

In this method, the principle used is basically the same as the digital PLL, The voltage controlled oscillator is replaced by a programmable frequency synthesizer, and the PI operation is replaced by the main controller. When the PLL is locked, the frequency of the frequency synthesizer is equal to the frequency of the measured signal [3]. However, the two frequencies can not be exactly the same, but a process of dynamic balance, so the voltage of the identification sign will constantly drift, and the true frequency of the measured signal can be obtained by measuring the phase of the identification sign and its basic principle is shown in Fig. 1.

Suppose the measured signal is f_x, the frequency generated by the frequency synthesizer is f_{syn}, and the difference frequency f_{beat} of the two signals is obtained after the phase discriminator, and f_{beat} is the identification signal. Let f_{syn} frequency be slightly higher than f_x, then:

$$f_{beat} = f_{syn} - f_x \quad (2)$$

Control f_{syn} to approach f_x so that the frequency of f_{beat} is low. The phase information of f_{beat} is transformed into voltage information, which is the phase discrimination voltage. Suppose the functional relationship between the phase of the identification signal and the phase detection voltage is:

$$\varphi = f(u) \quad (3)$$

Use an ADC to sample at fixed dead zones. Set the sampling dead zone as Δt and the voltage of two samples as u_1 and u_2 respectively, then:

$$\Delta\varphi = f(u_2) - f(u_1) \tag{4}$$

Since the phase is the integral of frequency, the frequency of the differential frequency signal is:

$$f_{beat} = \frac{\Delta\varphi}{\Delta t} \tag{5}$$

After the frequency f_{beat} of the signal is measured, the frequency of the measured signal can be calculated by Eq. (5).

In this method, high precision program-controlled frequency synthesizer is used to approximate the measured frequency and produce the frequency as close as possible to the measured frequency. If the two frequencies are exactly the same, it can be considered that the frequency generated by the frequency synthesizer is the measured signal, but the digitally controlled frequency source will be limited by its digital quantization bit, for any measured signal, it is impossible to use the digital frequency source to produce the exact same frequency. In fact, the PLL using the analog method is not exactly the same frequency, only that the locked oscillator frequency, or its frequency after the frequency divider is very close to the reference signal frequency [4]. Its real frequency fluctuates back and forth near the reference frequency. When the locking quality is good and the VCO signal closely follows the reference signal, the stability between the two is very good and the error frequency is very small. For a good PLL, the frequency stability between the output frequency and the reference signal can be better than 10^{-15} orders of magnitude.

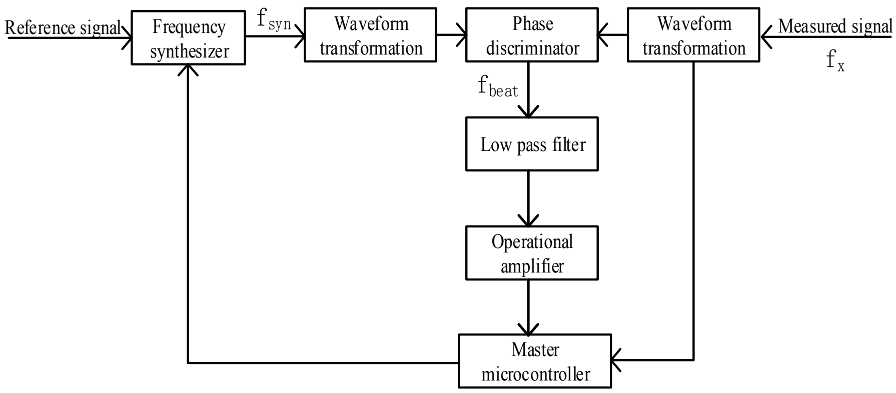

Fig. 1. Principle block diagram of frequency measurement method based on phase tracking.

4. Frequency Synthesis Method Selection

There are three commonly used frequency synthesis methods:

The first is to complete frequency synthesis directly through mixers, frequency multipliers and frequency dividers. A very common method is to extract the harmonics of a square wave or pulse signal. A method of generating a 90 MHz signal from a 10 MHz signal is as follows: the reference 10 MHz sine signal is converted into a square wave signal. The frequency spectrum component of the square wave contains odd harmonics of the fundamental frequency signal, which contains 90 MHz frequency components. Use multi-stage band-pass filters and amplifiers to extract them, and then complete the frequency multiplication. If even harmonics are needed, the reference signal can be converted into pulses. This method can be used to complete frequency synthesis with good stability. However, when this method is used in the complex frequency conversion process, there are many components, high cost, complex circuit, and difficult debugging. In this solution, the signal under test is required. The frequency produces the same frequency, and its frequency synthesis is very complicated, so this method is not suitable for this scheme.

The second method is to use a phase-locked loop and a frequency divider. Using a wide-range voltage-controlled oscillator with a flexible reference signal divider, feedback signal divider and output divider can also generate many frequencies. Suppose the frequency division number of the reference signal frequency divider is, the frequency division number of the feedback signal frequency divider is, the output of the VCO is then output through the programmable frequency divider, and the frequency division number is, then the output signal and the reference signal Functional relationship:

$$f_{out} = f_{ref} \times \frac{N_{divider}}{R_{divider} \times VCO_{divider}} \tag{6}$$

Controlling the three frequency dividers can flexibly generate many frequencies, and the noise introduced in the frequency synthesis process can be very small. But for any measured signal, it is difficult to adjust the frequency step value to be small enough, and this scheme requires the frequency generated by the frequency synthesizer and the measured signal to be as small as possible, and it is best to reach below mHz, so the phase-locked loop The method is also not suitable for this program.

The third type is Direct Digital Synthesis. DDS uses high-speed DAC to directly generate sinusoidal waveforms, which can easily generate various frequency points and complete various tasks such as frequency modulation and phase modulation. Some DDS can be prepared in advance Good digitized waveform data generates waveforms, which is very flexible and has been widely used in various fields.

The DDS chip is mainly composed of an N-bit phase accumulator, a sine look-up table storage ROM, and a DAC. Some chips also integrate a voltage-controlled oscillator and a phase-locked loop. DDS controls the DAC to generate waveforms at a certain sampling rate. The data of the DAC comes from the ROM, and the sine look-up table is stored in the ROM. In Single-Tone mode, DDS generates a single frequency without introducing any modulation signal.

At this time, the phase accumulator accumulates according to the frequency control word (FTW, Frequency Turning Word). The larger the frequency conversion word, the larger the interval between the data obtained each time, that is, the larger the phase difference, the higher the output frequency. high. Send the corresponding amplitude data to the DAC, the ROM sends the data again and again, and the DDS generates a periodic signal. The signal is of ladder type, after adding a low-pass filter to filter out the sampling frequency, a sinusoidal signal can be obtained. Some DDS also has a phase shift function, which can realize functions such as phase modulation. The output frequency of DDS is determined by the sampling clock frequency, the number of bits of the phase accumulator N, and the frequency control word. For an N-bit frequency control word, it generally corresponds to an N-bit ROM. There are points stored in the ROM, then the phase of the nth point for:

$$\varphi(n) = \frac{2\pi n}{2^N} \tag{7}$$

The frequency control word indicates the point interval between two points taken. For a certain, the phase interval between two points taken is:

$$\Delta\varphi(n) = \frac{2\pi FTW}{2^N} \tag{8}$$

If the sampling clock frequency is, the phase sampled in one second is:

$$\varphi_{1s} = f_s * \Delta\varphi = f_s * \frac{2\pi FTW}{2^N} \tag{9}$$

Convert it to frequency to get:

$$f_O = \frac{FTW}{2^N} f_s \tag{10}$$

The number of bits N of the phase accumulator and the sampling clock together determine the frequency resolution of the DDS.

$$f_{res} = \frac{f_s}{2^N} \tag{11}$$

The frequency resolution of DDS represents the minimum frequency difference between two different frequencies that it can output. When the frequency control word changes by 1, the frequency change of DDS is its frequency resolution. Generally, the frequency generated by DDS should not be greater than 40 % of its sampling rate. According to the Nyquist sampling theorem, the actual output frequency of DDS should not be greater than 50 % of the sampling rate. In fact, when is greater than, the output frequency of DDS is:

$$f_O = (1\text{-}\frac{FTW}{2^N})f_s \tag{12}$$

Based on this principle of frequency synthesis, DDS can quickly jump between different frequencies, the output frequency range is very wide, from its resolution to 40 % of the sampling clock, the frequency step is also very small, and can pass The programming mode is flexibly controlled, and it has been widely used in signal receivers and radar communication systems. Because its phase and amplitude are discontinuous after all, the noise of the signal produced by DDS mainly comes from phase truncation error and amplitude quantization error. In addition, there is the nonlinearity of the DAC, which all have an impact on the technical indicators of the DDS. These factors need to be considered comprehensively in high-precision application scenarios.

The frequency synthesizer sampled in this design is the direct digital frequency synthesis chip AD9952 of Analog Devices. The frequency control word of this chip is 32 bits, the maximum sampling rate can reach 400MSPS, the chip has its own phase-locked loop, and the maximum multiplier is 20. When using a 10 MHz signal as a reference, the internal clock can reach 200 MHz. If the signal is output at 40 % of the sampling rate, a signal of up to 80 MHz can be obtained. When working at a sampling rate of 200MSPS, its frequency resolution can be better than 50 mHz. At least three IO ports are required to control the chip, which saves IO resources. During PCB layout, the occupied area is small, the structure is simple, and the cost of the chip is relatively low.

5. Experimental Results and Analysis

This section describes the experimental investigation and analysis of the results in the frequency measurement method for realizing phase tracking.

In this experiment, use the rubidium clock's 10 MHz signal as a reference signal is used to track the phase of the measured signal using a direct frequency synthesizer (DDS) [5]. First, the frequency of the measured signal was measured to the order of Hz by the gate method, and the frequency of DDS was adjusted close to the measured signal, so that the frequency difference between the two was less than

10 Hz. Then double D flip-flop is used as phase discriminator to detect DDS signal and measured signal. Then an ADC analog-to-digital converter is used to measure the signal, and the frequency of the signal is calculated according to the voltage change speed of the signal, and then the DDS frequency is adjusted closer to the frequency of the measured signal to within 50 mHz. Then enter the precision measurement, use the operational amplifier to amplify the local voltage of the identification signal, and continue to use DDS phase compensation, so that the voltage of the identification signal is always within the sampling range of the ADC. The voltage sampling and DDS phase compensation are carried out with a period of one second. The phase change speed of the detected signal is calculated using the ADC sampling value measured for two adjacent times and the phase of DDS, that is, the frequency difference between the DDS signal and the measured signal. Then, the frequency of the measured signal can be calculated according to the frequency of DDS.

When testing its performance, we using a frequency measuring instrument to test the reference signal, the result obtained is the floor noise. During self-calibration, the 10 MHz signal is used as the test, and the power divider is used to divide the 10 MHz signal into two channels, one as the signal and the other as a reference. When the input reference signal is a square wave, the measurement results are shown in Fig. 2.

The measured second is 10^{-13}, which is equivalent to the floor noise of DDS. The noise of the tester itself may be better than the floor noise of the DDS. In order to further verify the testing capability of the tester for sine wave, the square wave was changed into sine wave for measurement, and the Allan variance curve obtained was shown in Fig. 3.

Using the signal source to generate any signal for measurement, the measurement is divided into two parts.

The first part is homologous measurement. The 10 MHz internal frequency standard signal output from the signal source is used as the reference frequency of the measuring instrument. The signal source is used to generate 4 MHz, 10 MHz, 20 MHz, 50 MHz and 80 MHz for measurement.

The second part is the measurement of different sources, using a crystal oscillator as a reference to measure another crystal oscillator, and then using this crystal oscillator to measure a rubidium atomic clock. The measured results are shown in Table 1.

It can be seen from Table 1 that in a wide frequency range, frequency measurement methods based on phase tracking can complete the measurement better.

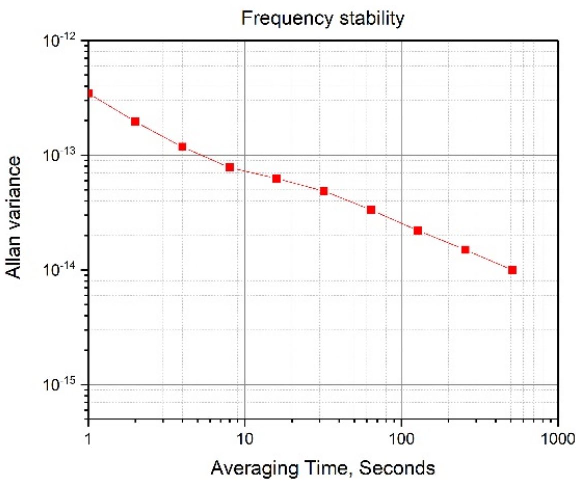

Fig. 2. Allen variance curve with floor noise of square wave measuring instrument.

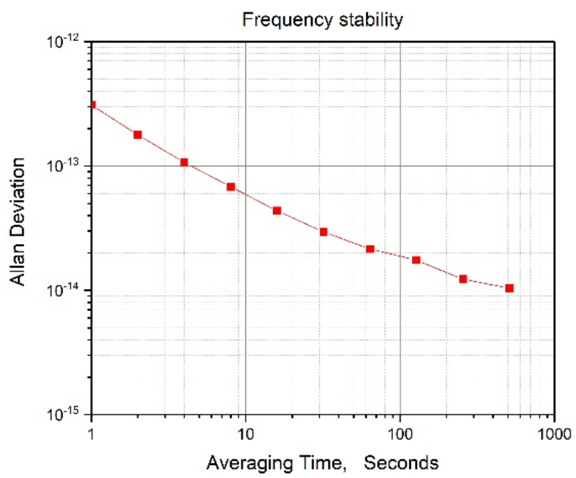

Fig. 3. Allen variance curve of the sinusoidal measuring instrument with floor noise.

Table 1. The phase tracking method was used to measure the signal stability at different frequencies.

f	τ		
	1 s	**8 s**	**128 s**
4 MHz	3.62×10^{-13}/s	7.12×10^{-14}/s	3.12×10^{-14}/s
10 MHz	3.11×10^{-13}/s	6.82×10^{-14}/s	1.75×10^{-14}/s
20 MHz	3.52×10^{-13}/s	6.65×10^{-14}/s	2.89×10^{-14}/s
50 MHz	3.41×10^{-13}/s	6.57×10^{-14}/s	3.02×10^{-14}/s
80 MHz	3.62×10^{-13}/s	6.45×10^{-14}/s	3.14×10^{-14}/s
Crystals-crystal	1.23×10^{-9}/s	7.42×10^{-10}/s	3.25×10^{-10}/s
Crystals- rubidium atomic clock	1.61×10^{-11}/s	7.53×10^{-12}/s	1.78×10^{-11}/s

The test result of frequency stability at 10 MHz is basically the same as that of direct self-test. It can be considered that the noise introduced by using signal source can be ignored.

In the crystals and crystal oscillator frequency ratio, the use of a crystal vibration for high stability crystal, its stability can reach 7.53×10^{-12}/s, as reference to measure another crystals and the crystals for the inside of a signal generator of crystals, tested its stability to 1.23×10^{-9}/s only, due to the stability of the high stability crystal vibration is much higher than this, so you can think internal clock signal source and poor stability. When the rubidium atomic clock is used as the frequency standard to measure the crystal oscillator with high stability, the stability of the crystal oscillator is measured as 1.61×10^{-11}/s. However, due to the poor long-term stability of the crystal oscillator, a significant increase can be observed when the sampling time is 128 s, which is caused by the crystal oscillator drift [7].

6. Conclusions

To sum up, in this paper, DDS produced by ADI and STM32 produced by STMicroelectronics are used as the control carrier, and the frequency stability can be achieved 10^{-13} by continuously measuring the frequency of the measured signals without dead zone. During the experiment, it is found that MC10116 is used as the waveform conversion circuit. When sinusoidal wave is converted into square wave, a lot of noise will be introduced, which will seriously affect the measurement results. After theoretical analysis and experiment, the scheme of using operational amplifier as waveform conversion circuit is redesigned.

This paper expounds the DDS without dead zone and high precision frequency measurement equipment, achieve no dead band frequency measurement, can be applied to a variety of applications, meet the demand of different measurement, however still exist some deficiencies on the accuracy of measurement, plans to use the higher conversion digit ADC, late can avoid using operational amplifier circuit, At the same time, it can improve the measurement accuracy and reduce the measurement steps, and avoid the error caused by the resistance drift of the amplifier circuit.

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