High-Precision Measurement of Dual-Mixer Time Difference System Based on Software-Defined Radio

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Abstract: A novel high-precision digital dual-mixer time diffidence (DMTD) system is proposed based on the principle of the traditional DMTD method combined with the design concept of software-defined radio (SDR). In order to measure and monitor the frequency scale with high precision in real-time through the value of Allan deviation, the digital down-converter (DDC) is used to convert high-frequency signals into baseband signals. In the novel DMTD system, there are no sinusoidal-pulsed converter and zero-cross detector so that the influence of instrument noise can be reduced and more accurate measurement results can be obtained. Furthermore, the proposed system is simulated and the feasibility of system is also verified by using the SIMULINK. Applying the standard 20 MHz sinusoidal signals for testing, a measurement precision (standard deviation) of $8.14\times10^{-14}\left(\tau=1s\right)$ is obtained, which shows that the proposed DMTD measurement method is practical in SDR.

1. Introduction

High-precision time-frequency measurement technologies have a wide range of applications in aerospace, civil power systems, and communication systems. And their performance is mainly related to the noise generated in the system structure and application environment. The random frequency (phase) fluctuation caused by noise interference is caused frequency stability[1,2], which is the most important standard analysing measurement accuracy.

Dual-mixer time difference (DMTD) method[3,5], frequency difference multiplication method and beat method are the common frequency measurement techniques, especially the DMTD method is widely used for high-accuracy time-frequency measurement. For the traditional DMTD measurement method, the zero-crossing detection and the time interval counter are used to measure the beat signal. However, it is affected by noise and measurement errors at the zero-crossing point, which limits the improvement of measurement accuracy to a certain extent.

Based on the design concept of Software-defined radio (SDR) technology, this paper proposes a novel digital DMTD measuring system. The SDR is a technique that can be used to implement the specific functions - like measuring 20MHz signals - through basic software development. In the proposed DMTD system, the high-performance digital down converter (DDC)[6,7] is used to decreases the sampling rate of signals. In addition, there are also some other significant theories and technologies used in the system. Such as the digital orthogonal mixing, numerically controlled oscillator (NCO), efficient digital decimation filtering, phase detection, and Allan deviation. Furthermore, the system is implemented using the SIMULINK simulation platform. The system noise floor that reaches the order of 8.1×10^{-14} at an integration time of 1s can be obtained by analysing the performance of DMTD. It is indicated that the proposed digital DMTD measurement method is practicable and high-precision.

2. Measurement Principle

The development of SDR technology provides new ideas for digital frequency measurement. Based on this, a digital DMTD measurement system is proposed. The principle block diagram of DMTD measurement system is shown in Figure 1. First, the Device Under Test (DUT) signal and the reference (Ref) signal input into the system from two symmetrical channels, respectively. And each input signal is split and converted by the Analog-to-Digital Converter (ADC). After the two sampled signals are mixed with quadrature multiplication signals (sine and cosine) produced from the NCO and filtered by a set of low-pass decimation filters, the two beat signals Q and I are generated. Then, the phase information can be calculated by arctangent operation in the phase detector. Finally, Allan deviation is calculated by phase difference data to analyse the frequency stability.

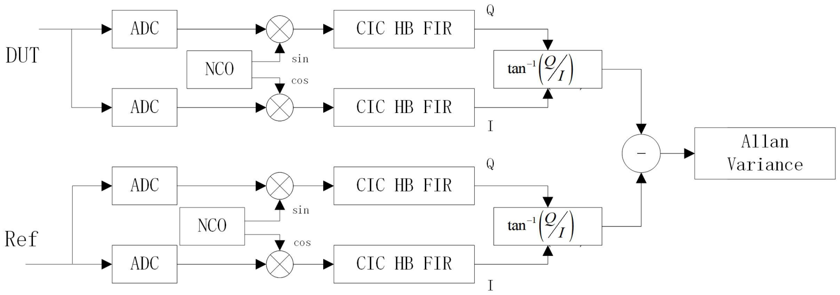

Figure 1: Principle block diagram of DMTD measurement system.

Since the block diagram is a symmetrical structure, the DUT signals is taken as an example to illustrate its mathematical model. Assuming a signal is:

$$x(t) = A\sin\left[2\pi f_c t + \varphi(t)\right] \qquad (1)$$

A represents the amplitude of signal, f_c is the signal carrier frequency, $\varphi(t)$ represents the phase change.

The processing of signal in DDC is based on the principle of digital quadrature demodulation. The digital signal sequence after ADC sampling is $x(nT_s)$, T_s is the sampling interval, then the expression of the digital quadrature mixing output signal is:

$$y(nT_s) = x(nT_s)e^{j2\pi f_c T_s} = x(nT_s)\left\{\cos(2\pi f_c T_s) + j\sin(2\pi f_c T_s)\right\} \qquad (2)$$

The corresponding conversion can be obtained:

$$y(n)=x(n)e^{j2\pi f_c n}=x(n)\cos(2\pi f_c n)+jx(n)\sin(2\pi f_c n)=I(n)+jQ(n) \tag{3}$$

According (3), $I(\mathrm{n})=x(\mathrm{n})\cos(2\pi f_c \mathrm{n})$ calls In-phase component and $Q(\mathrm{n}) = x(\mathrm{n})\sin(2\pi f_c \mathrm{n})$ calls Quadrature component. Two local oscillator signals $\cos(2\pi f_c \mathrm{n})$ and $\sin(2\pi f_c \mathrm{n})$ are generated by the NCO, and f_c is also the local oscillator frequency of the NCO. Then using Cased Integrator-Comb (CIC) filter, Half Band (HB) filter and FIR filter to reduce the sampling rate and filter processing. The I-Q signals are calculated by phase detector:

$$y=\tan^{-1}\left[\frac{Q(n)}{I(n)}\right] \tag{4}$$

Because the signal processing of the upper and lower channels is the same, the phase information of the reference signal can be expressed as

$$y'=\tan^{-1}\left[\frac{Q'(n)}{I'(n)}\right] \tag{5}$$

According to (4) and (5), the phase difference can be obtained:

$$\Delta\theta=y-y' \tag{6}$$

Calculating Allen deviation by combining (6) and (7)

$$\sigma_y^{\,2}(\tau)=\frac{1}{2\tau^2(L-2m)}\sum_{k=1}^{L-2m}\left(\theta_{k+2m}-2\theta_{k+m}+\theta_k\right)^2 \tag{7}$$

where τ is the sample time of L samples of data, θ is the phase difference data.

Finally, the frequency stability evaluated by Allan deviation is calculated from the phase difference.

3. Simulation Results

The presented DMTD measurement technique in this paper relies on digital signal processing, requiring comprehensive know-how to build a precise simulation models in SIMULINK. The ideal signal source hopes to output a pure signal, but the frequency value of the signal will be affected due to the noise generated by the application environment and system structure. The effect of noise on the signal is usually represented by phase noise in the frequency domain. According to the power-law spectrum model, noise is superimposed on the phase information of the signal. The signal of DUT and reference are two signals with the same frequency but different noise, that is, the DUT signal needs to be added with noise for simulation.

The Allan deviation is the standard statistical analysis method used in the field of frequency and time metrology. As to the signal source, the frequency stability in time domain can be acquired by testing the phase difference or frequency difference, which is usually described by Allan deviation.

Performing the Allan deviation operation on the phase difference signal in the simulation experiment, the noise floor for $f_c = 20MHz$ are $\sigma_y(1s) = 8.1\times10^{-14}$. The result is shown in the Figure 2.

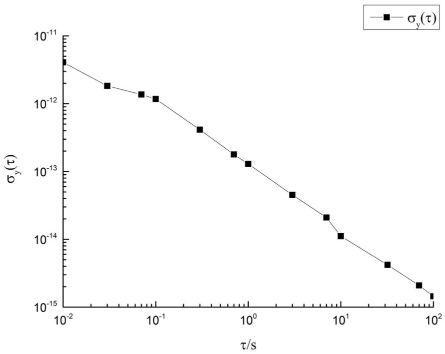

Figure 2: Allan deviation curve of simulation data.

4. Conclusions

This paper presented a DMTD system for high-precision frequency measurement based on the concept of SDR. As the signal is processed in a high-performance DDC, the accuracy of the system enhances. In addition, the measurement system based on SIMULINK platform has the characteristics of easy implementation and low cost. Although the error cannot be completely eliminated, the frequency stability of measured results for 20MHz input signals are around for an averaging time. All in all, the design and simulation of this system have achieved the expected results, which can lay a good theoretical foundation for the development of the equipment.

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