Design and implementation of an airborne improved radio frequency measuring instrument based on FPGA

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Key words: Frequency measurement; FFT;FPGA; Xilinx Zynq 7010;ADC;oled

Abstract: According to short wave radio signal of a certain active airborne frequency measurement instrument part device still adopts pure hardware building mode and acquisition data scattered, leading to large volume, monitoring performance is limited, the real-time problem, low accuracy and can not upgrade the system corresponding to the complex environment. A new algorithm is proposed based on the FPGA parallel processing advantages. The algorithm is in the FFT frequency estimation based on serial iterative algorithm modified for parallel computing, and the feasibility of the algorithm is verified by simulation. Hardware part, the system integrates the CPU and FPGA into a chip, greatly reduces the equipment size and development time and uses high speed 14 bit A/D 125MHz data acquisition to improve the precision of frequency measurement. Many experiments show that each module design is reasonable, the system runs stably, Compared with the original instrument of frequency measurement accuracy is improved more than 1 times, the system response time is reduced to 0.1s~0.2s, and provide effective data for real-time monitoring and fault detection of radio frequency radio signal. The measuring instrument has been successfully applied to the corresponding forces equipment examination.

1 Introduction

Due to the strong anti-interference and easily transmitted frequency signal, it is a classical approach to convert test signal into frequency signal in the modern measuring instrument, so as to make the cost low and realize high precision, high resolution measurement as well as high anti-interference. At the same time, it also possesses good interface characteristics of digital system. Therefore, frequency measurement plays a more and more important role in science and technology research and practical application[1].

The active Airborne Short wave radio frequency measurement instrument still uses hardware components to build, due to part of the functional device. So it creates a large volume of equipment, high cost as well as complex and heavy maintenance work. What’s more, the equipment can not complete corresponding adjustment or upgrade on the basis of specific signal characteristics. The frequency measurement cycle of the active Airborne Short wave radio frequency measurement instrument is 1s. Under today’s complex and variable electromagnetic environment, it is impossible to meet the real-time requirements of frequency measurement.

In recent years, it is the use of new theory, new technology and new devices, especially rapid development of digital signal processing technology and increasing improvement of computer application technology that make the equipments of frequency measurement become more and more small, but possess increasingly high precision. Since the FPGA chip has the characteristics of good function, fast speed, high flexibility, short design cycle and so on, it has been widely used in modern electronic system. FPGA chip has been widely used in many fields, such as computer hardware, industrial control, intelligent instruments, household appliances, modern communication and soon; the development technology of FPGA has become the preferred solution of teaching practice, scientific research test, prototype debugging and small batch production of digital system.

Therefore, this thesis proposed a radio frequency measurement instrument which is based on the advantage of parallel processing based on FPGA chip using the modified FFT interpolation algorithm for frequency measurement. Compared with the original frequency measurement instrument, this system possesses the advantages of small volume and low cost. Moreover, it can carry out system adjustment and upgrade, according to special electromagnetic environment, specific signal characteristics. Meanwhile, in the aspect of real-time, the process of frequency measurement will be reduced to less than 0.2s, and the accuracy of frequency measurement is controlled within 4/10000.

2. The overall structure of the system

2.1 The overall structure of the system

The use of radio frequency measurement instrument is an effective way for signal monitoring and fault diagnosis of airborne radio equipment. The whole system includes signal receiving module, signal processing module, data display module and power supply module. Fig. 1 expresses the overall structure.

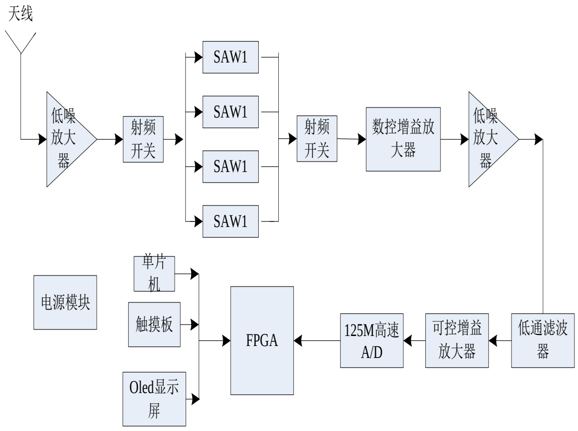

Fig. overall system block diagram

The overall system adopts Xilinx Zynq 7010 SoC as the main controller. It is a system which ntegrates Cortex-A9 MPCore with 28nm programmable logic and on the basis of processor. It can start the operating system when resetting the accessible programmable logic. The other modules are equivalent to application components which hang on the bus. This kind of design is simple and clear. In addition, it is more convenient to upgrade the system in future through adding functionality. The coupler divides measured signal received by the receiver into several roads in proportion, and makes data acquisition through high-speed AD with 14 bit. Then, the data acquired will be delivered to FPGA for frequency measurement operation.

2.2 The modified FFT interpolation frequency measurement principle

The existing airborne short wave radio signal is essentially modulated sine signal. China has already put forward many methods of frequency measurement on sine signal which is added to noise. FFT frequency estimation algorithm is widely applied for its characteristics of fast speed and convenience of real-time processing. However, FFT frequency estimation algorithm acquires discrete frequency value. If signal frequency does not coincide with FFT discrete frequency, the actual frequency of signal should be located between the two lines, due to the “Fence” effect [2]of FFT. It is clearly that use FFT frequency estimation algorithm only is difficult to meet the requirements of precision, thus various interpolation algorithm emerge as the times require.

2.2.1 Common interpolation algorithm

Rife algorithm. The literature[3] explains Rife algorithm. After this algorithm used for measured signal in a FFT operation, the maximum spectrum line is compared with two adjacent second spectra line, and then, uses interpolation to determine the true position of frequency. This algorithm is simple and it has a small amount of computation which is easy to realize, but this algorithm exists great error in the vicinity of FFT quantized frequency.

The modified Rife algorithm. Through removing the spectrum of the measured signal, the algorithm makes the signal frequency locate in the central region between two adjacent quantized frequency. Thus, it improves the frequency estimation precision, while the measurement time is not ideal.

Interpolation iterative algorithm based on Fourier coefficient. The literature[4] explains the interpolation iterative algorithm based on Fourier coefficient. Through preliminarily estimating the position of spectral peak in FFT operation, and then using iterative calculation to calculate the FFT coefficients front and rear the peak position, this algorithm can improve measurement precision as a result. However, it needs multiple serial iterative, which is not conductive to exert the advantage of FPGA parallel processing.

2.2.2 The modified algorithm principle

According to the frequency characteristics of a certain type of airborne radio signal, we combine the advantage of FPGA parallel processing, and consider to improve the accuracy of frequency measurement on the basis of the limited chip resources. As a result, we propose a new algorithm which uses signal FFT interpolation to conduct frequency estimation, so as to complete the test function of the whole system.

The sine signal with single frequency expresses as :

$$a(n) = Ae^{j[2\pi n f_0 / f_s + \theta]}, n = 0,1,\cdots, N-1 \qquad (1)$$

In this formula, A is range; f_0 is frequency; θ is initial phase; f_s is sampling frequency. Frequency estimation based on FFT is realized by being divided into two processes: coarse frequency measurement and precision frequency measurement. Coarse frequency measurement is completed by observing the point(m) of the maximum amplitude. Due to the limitation of observation time length T, the range of error is $\pm 1/(2T)$. Suppose σ to be the relative deviation of signal frequency and its corresponding frequency of the maximum FFT amplitude. Suppose $\hat{m}$ to be the true value of signal frequency, the relation of σ, m and $\hat{m}$ is expressed in the formula (2):

$$f_0 = \hat{m} \cdot f_s / N = (m+\sigma) f_s / N \qquad (2)$$

Through calculating FFT interpolation coefficient in $m+q$, we can get:

$$X_{m+p} = \sum_{n=0}^{N-1} a(n) e^{-j2\pi n \frac{m+q}{N}}, q \in [-1,1] \qquad (3)$$

Put (1) and (2) into (3). Through calculation we can get :

$$X_{m+p} = e^{j\theta} \sum_{n=0}^{N-1} e^{j2\pi n \frac{\sigma-q}{N}} = e^{j\theta} \frac{1-e^{j2\pi(\sigma-q)}}{1-e^{j2\pi n \frac{\sigma-q}{N}}} \qquad (4) \qquad X_{m+p-1} = e^{j\theta} \frac{1-e^{j2\pi(\sigma-q+1)}}{1-e^{j2\pi \frac{\sigma-q+1}{N}}} = e^{j\theta} \frac{1-e^{j2\pi(\sigma-q)}}{1-e^{j2\pi \frac{\sigma-q+1}{N}}} \qquad (5)$$

Since the initial phase is generally not known, we can get :

$$\frac{X_{m+p}}{X_{m+p-1}} = \frac{1-e^{j2\pi \frac{\sigma-q+1}{N}}}{1-e^{j2\pi \frac{\sigma-q}{N}}} \qquad (6) \qquad e^{j2\pi} = \frac{X_{m+q} - X_{m+q-1}}{X_{m+p} e^{j2\pi(-\frac{q}{N})} - X_{m+q-1} e^{j2\pi(-\frac{q-1}{N})}} \qquad (7)$$

$$\sigma = \frac{q|X_{m+q}| - (q-1)|X_{m+q-1}|}{|X_{m+q}| - |X_{m+q-1}|} \qquad (8)$$

According to the characteristics of FPGA parallel processing, the calculation procedure is as followed :

Step one : Through the calculation of FFT amplitude spectrum sequence $\{X_n\}|_{1\le n\le N}$, we need to evaluate : $m = \arg\max_k \{X_k\}$.

Step two : Let $q = 0.5$, and calculate $X_{m+0.5}$ and $X_{m-0.5}$, then put them into formula (8), so we can get σ_1. Meanwhile, calculate $X_{m+0.75}$, $X_{m+0.25}$, $X_{m-0.75}$ and $X_{m-0.25}$.

Step three : According to formula (9), the value of σ_1 is different in different frequency q. We can get frequency estimation from formula (8) σ_2.

$$\begin{cases} q = 0, X_m, X_{m-1}, -0.25 \le \sigma_1 \\ q = 0.25, X_{m+0.25}, X_{m-0.75}, -0.10 \le \sigma_1 < -0.25 \\ q = 0.5, X_{m+0.5}, X_{m-0.5}, 0.10 \le \sigma_1 < -0.10 \\ q = 0.75, X_{m+0.75}, X_{m-0.25}, 0.10 \le \sigma_1 < 0.25 \\ q = 1, X_{m+1}, X_m, \sigma_1 < 0.25 \end{cases} \quad (9)$$

Step four : Frequency : $f = (m + \sigma_2) f_s / N$

During the process, step one is coarse frequency measurement, and step two as well as step three are precision frequency measurement. The frequency measurement value is the sum of coarse frequency measurement value and precision frequency measurement value. The flow chart of the algorithm is shown in Fig.2.

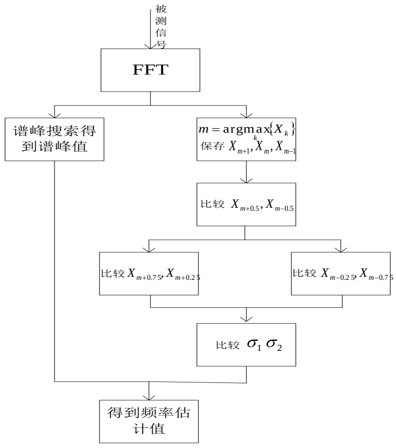

Fig.2. flow chart of the algorithm

3. The design of system software

The system software mainly consist of system initialization module, read the AD acquisition module, FFT interpolation algorithm processing module and OLED liquid crystal display module. System initialization module mainly completes the initialization of Zynq 1070 chip and OLED display screen. The flow chart of software is shown in Fig. 3.

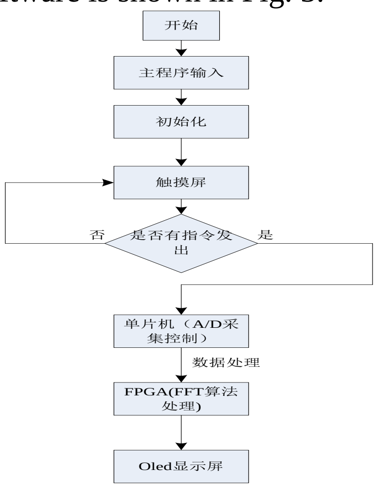

Fig.3. flow chart of the software

3.1. The modified FFT interpolation algorithm processing module

The whole frequency measurement part includes coarse frequency measurement and precision frequency measurement : first, we should conduct FFT operation on the measured signals and do spectrum peak research, so as to get the position of peak value; then we can get the frequency deviation σ_1 and σ_2 through FFT interpolation. The algorithm refines the band [m-1， m+1] where the measured frequency sine wave signal locates in into five sub bands. And according to the value σ_1, we can judge the location of the measured signal line, so as to make signal frequency locate in the central region of a certain sub band. Then we have to conduct frequency estimation. The algorithm begins with the translation of the measured signal, then we should conduct FFT on the translated signal. And we can calculate σ_1 and σ_2. In order to calculate the single X_{m+q}, we need only complex multiplication and addition for N times. The amount of calculation is relatively small, so the algorithm expressed in this thesis can simultaneously calculate several X_{m+q} and X_{m+q-1}, so as to improve the calculation rate.

If the three parameters which called signal phase, frequency and amplitude are all unknown, the lower limit for the variance [5] of frequency estimation is :

$$\operatorname{var}\{f\} = \frac{6 f_s^2}{(2\pi)^2 N\left(N^2 - 1\right) R_{SN}} \qquad (10)$$

In this formula, N is the number of samples.

The literature [6] proposes CRB of the parameter estimation variance. The limit provides a benchmark for any actual estimation variance which is compared with it. According to the parameter theory, the maximum likelihood estimation of any parameters are asymptotically unbiased and effective [7]. Thus, we can compare the estimation variance $\operatorname{var}\{f\}$ with CRB, so as to evaluate the performance of the algorithm. In the simulation experiment, let's suppose f_s =125MHz and N=512. The definition of signal-to-noise ratio is :

$$R = A^2 / 2\tau^2 \qquad (11)$$

In this formula, τ is the noise mean square error. Respectively do Monte Carlo on each frequency f_i for 500 times. And calculate the root mean square error of σ_1 and σ_2. The simulation results are shown in Fig. 1 and Fig. 2. Value R from -20dB to 0 dB, and respectively do Monte Carlo for 500 times. Calculate the normalized mean square error of the new algorithm results, and the simulation results are shown in Fig.4, Fig.5 and Fig.6.

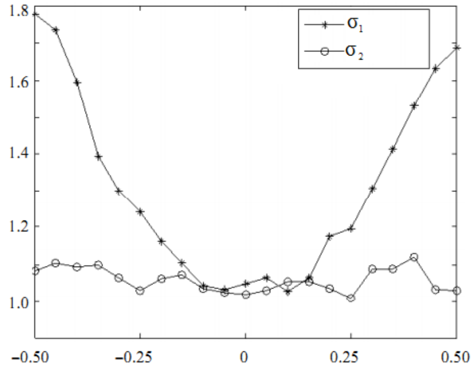

Fig. 4. The performance chart when R=0dB

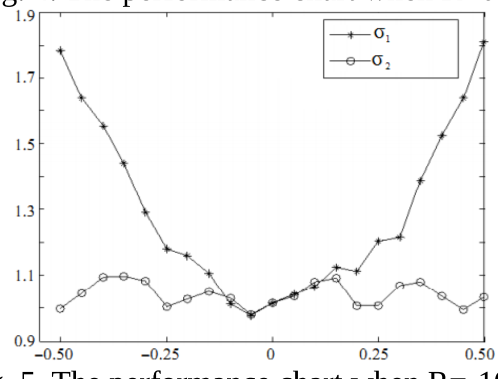

Fig. 5. The performance chart when R=-10dB

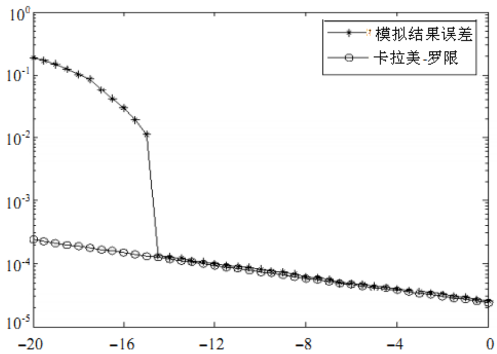

Fig. 6. The performance chart when the root mean square error of frequency estimation changing with R

The simulation results show that σ^2 will not fluctuate with the frequency distribution of the measured signals; when R>-14dB, the frequency measurement value variance of the new algorithm in the whole frequency band is close to CRB, which possesses the characteristic of stability.

3.2 OLED display module

According to the requirement of design size, we can adopt OLED in 3.12 inch. The display has the display area of 256*64 lattice. Each point is able to emit light by itself. Thus, it does not have the restriction of backlight, which brings convenience for the equipment to be used in daytime. The visual angle is more than 160 degrees, which makes low power consumption. The results are shown in Fig.7.

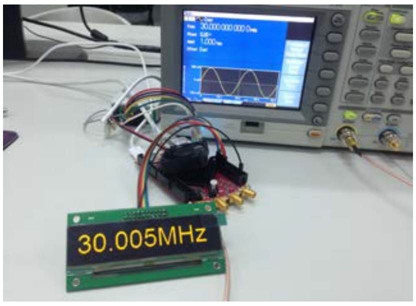

Fig. 7. Display of OLED results

Part of the procedure is as followed :

```
init_platform();
    Initial_ssd1325();
    GUI_SetColor(15,0);
    GUI_ClearSCR();
    GUI_PutString8_8(28,24,"Aviation University of Air FORCE");
    GUI_Exec();
    delay(10000);
while(1)
{
      int j;
     f=0;
     sum2=0;
     for(j=0;j<100;j++)
     Xil_Out32(0x40100004, 0x1);
         Xil_Out32(0x40100000, 0x1);
    ……
```

4. The analysis of system performance

The accuracy of signal frequency measurement and calculation time of the system response are mainly test target of the whole system experiment. Through selecting six groups of measured frequency values, we can compare them with the value of the original radio frequency measurement instrument. The concrete data are shown in table 1.

Table 1. the data of comparison with the measured value of the original radio frequency measurement instrument

Designed frequency	The measured value of the original frequency	The measured value of the designed frequency	Result of comparison	Percentage error
50.000 MHz	Can not be measured	49．988MHz		0.024%
30.000 MHz	30.024MHz	30．005MHz	-0.019 MHz	0.017%
25.000 MHz	25.022MHz	25．009MHz	-0.013 MHz	0.036%
20.000 MHz	20.015MHz	20．005MHz	-0.010 MHz	0.025%
15.000 MHz	15.012MHz	15．005MHz	-0.008 MHz	0.016%
10.000 MHz	30.008MHz	10．001MHz	-0.007 MHz	0.010%

The experimental results show that the system not only over doubled on the accuracy, but also broaden the frequency measurement range of frequency measurement instrument. In the process of the experiment, we find the response time of the system is 0.1s to 0.2s. It increases significantly compared with the original response time 1s, which meets the design requirements.

5. Conclusion

The Airborne radio frequency measurement instrument which is based on FPGA adopts Xilinx Zynq 7010 SoC as the main controller, and it is connected with other modules through the bus. The design method of the software greatly reduces the development time, and brings advantages to the upgrade and maintenance of the equipment in the future. The frequency estimation algorithm based on FFT interpolation of FPGA makes full use of FPGA parallel processing ability and improve the accuracy of measurement at the same time. It controls the accuracy of measurement within four over ten thousand. The results of trail show that the frequency measurement instrument has simple operation, high accuracy of measurement, elegant and generous display and it can realize real-time measurement. Moreover, it is able to adjust system upgrade according to the characteristics of the signal, and the measured data play a significant role in equipment monitoring and detection.

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