Design and realization of atmospheric pressure altitude measuring system with temperature compensation based on FPGA

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Abstract

Starting from the analysis of the measuring principle of atmospheric pressure altitude and the necessity of the pressure sensor temperature compensation, this paper presents the design and realization of an atmospheric pressure altitude measuring system with high performance which use FPGA as the data processor and with the pressure sensor temperature compensation design. Article discusses in detail the hardware circuit design of the measuring system, and the internal structure of FPGA software design. At last, the results of system test verify the feasibility and effectiveness of the atmospheric pressure altitude measuring system. Because of the FPGA's characteristics of high reliability, strong data processing ability, high speed and so on, and the effective combination of temperature compensation design, the atmospheric pressure altitude measuring system has the advantages of high measuring precision, high reliability, good real-time and low power consumption.

Keywords: atmospheric pressure altitude, FPGA, temperature compensation algorithm, measuring system

1 Introduction

Atmospheric pressure altitude data is an important flight parameters of aircraft, it can guarantee the safety of the flight and ensure the ground command and control personnel to properly guide the flight to complete mission. The development of modern microelectronics technology and computer technology greatly promotes the development of aviation testing technology, and makes the development of aviation testing equipment to high precision, strong anti-interference, small size, and low power consumption [1].

The FPGA (Field Programmable Gate Array) is a programmable processor, it has strong data processing ability, high reliability, high speed, flexible design, intelligent development tools advantages etc, and it is more and more popular in the field of high-speed hardware electronic circuit design [2]. With the characteristics of FPGA, this paper introduces the design and implementation of a kind of high precision and real-time pressure measuring system with pressure sensor temperature compensation method.

2 Measuring principle of atmospheric pressure altitude

According to international standard ISO25332, which was developed by the international organization for standardization, we can get the relation formula between the geopotential altitude H (often referred to as the standard atmospheric pressure altitude) and the atmospheric pressure PH in 2000m to 80000m altitude range, and this relationship is shown in Equation (1):

$$H = \frac{T_b}{\beta}\left[\left(\frac{P_H}{P_b}\right)^{-\beta R/g_n} - 1\right] + H_b. \tag{1}$$

In Equation (1), *R* is the air special gas constant and the value is $287.05287\,\mathrm{m}^2/\left(\mathrm{K}\cdot\mathrm{s}^2\right)$, g_n, is the free fall acceleration of gravity and the value is $9.80665\left(\mathrm{m/s}^2\right)$, β is the rate of vertical temperature change and the value is dT/dH; T_b, H_b and P_b are the lower limiting value of atmospheric temperature, standard atmospheric pressure altitude and atmospheric pressure in the corresponding altitude range that are used by international standard atmosphere [1], and their values are shown in Table 1.

TABLE 1 Atmospheric temperature, temperature gradient and altitude stratified

standard atmospheric pressure altitude H_b(km)	temperature T_b(K)	vertical temperature change β(K·km^{-1})	atmospheric pressure P_b(Pa)
-2.00	301.15	-6.50	127 774
0.00	288.15	-6.50	101 325
11.00	216.65	0.00	22 632

Making these parameters what are in Table 1 into the Equation (1), we can obtain the single value functions of atmospheric pressure and atmospheric pressure altitude in different altitude stratified [3], and these functions are shown in Equation (2) and Equation (3).

In the range of -2000 to 0m altitude

$$H = -46330.8\left[\left(\frac{P_H}{127774}\right)^{0.190263102} - 1\right] - 2000\,. \tag{2}$$

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In the range of 0 to 11000m altitude

$$H = -44330.8\left[\left(\frac{P_H}{101325}\right)^{0.190263102} - 1\right]. \tag{3}$$

3 Error analysis and compensation design

3.1 ERROR ANALYSIS

Piezoresistive pressure sensor is one of the most widely used sensors, but because the sensitivity of the semiconductor physics properties on temperature, the output of piezoresistive pressure sensor used in this measuring system will not only change with pressure but also change with the temperature. This phenomenon leads to the accuracy of the whole measuring system is reduced greatly, so a kind of software temperature compensation method for error correction used in FPGA processor is adopted to improve the accuracy of measuring system.

The idea of the temperature compensation method is to adjust the output values of pressure sensor at different environmental temperature to the output values at 25°C. The linear relationship between input p and output U of the pressure sensor at 25°C and t°C are shown in Equation (4) and Equation (5).

$$U_0 = a_0 + b_0 \times p, \tag{4}$$

$$U_t = a_t + b_t \times p, \tag{5}$$

a0, at, b0 and bt in Equation (4) and Equation (5) are zero position and sensitivity coefficient at normal temperature 25°C and t°C.

The output of pressure sensor with temperature compensation at t°C can be obtained by making the Equation (5) into the Equation (4) and it is shown in Equation (6).

$$U_t' = a_0 + \left(\frac{U_t - a_t}{b_t}\right) \times b_0. \tag{6}$$

System testing selects six groups of different atmospheric pressure value provided by the pressure pump for pressure sensor and six groups of different temperature value provided by high and low test temperature box for temperature sensor, the output values of pressure sensor without temperature compensation at different temperatures and pressures are shown in Table 2.

TABLE 2 Pressure sensor output values without compensation

Pressure/p_a	The output voltage/mV					
	-40°C	*-20°C*	*0°C*	*25°C*	*50°C*	*60°C*
49154.5	39.207	38.892	38.300	38.186	38.048	38.009
57728.3	46.023	45.661	44.975	44.849	44.688	44.645
67474.9	53.752	53.337	52.551	52.404	52.221	52.169
78513.1	62.526	62.049	61.146	60.981	60.771	60.711
90970.1	72.396	71.852	70.822	70.629	70.390	70.320
104981.0	83.529	82.908	81.727	81.512	81.238	81.158

It is obvious from Table 2 that the change magnitude of the pressure sensor output varies with temperature under the same pressure is large, and the maximum change amount under constant pressure output is 2.017 mV, to result in the decrease of sensor accuracy significantly [4].

3.2 COMPENSATION ALGORITHM DESIGN.

According to non-compensated pressure sensor data in Table 2, the linear relationship between the output *Ut* and the input pressure *p* of the sensor can be gotten by the linear interpolation algorithm using MATLAB software at different temperature, and these linear relationships are shown in Table 3.

TABLE 3 The relationships between input and output of sensor

Temperature	The linear relationship between sensor output and pressure
-40°C	$U_t = 0.19435 + 7.9379\times10^{-4}\times p$
-20°C	$U_t = 0.14724 + 7.8832\times10^{-4}\times p$
0°C	$U_t = 0.07012 + 7.7782\times10^{-4}\times p$
25°C	$U_0 = 0.04876 + 7.7596\times10^{-4}\times p$
50°C	$U_t = 0.02914 + 7.7354\times10^{-4}\times p$
60°C	$U_t = 0.02867 + 7.7278\times10^{-4}\times p$

According to the linear relationships between the output U_t and the input p of the pressure sensor at different temperature. The zero point data and sensitivity coefficient data of the pressure sensor at different temperature can be gotten, and then to use quadratic curve fitting formula with these data by MATLAB software to get zero point Equation (7) and sensitivity coefficient Equation (8).

$$a_t = 0.07143 - 2.17494\cdot10^{-3}\cdot t + 2.56347\cdot10^{-5}\cdot t^2 \tag{7}$$

$$b_t = 7.80122 - 2.6002\cdot710^{-3}\cdot t + 2.40446\cdot10^{-5}\cdot t^2 \tag{8}$$

Finally, the temperature compensation algorithm, which is shown in Equation (9), can be obtained by making the Equation (7) an Equation (8) into the Equation (6).

$$U_t' = 0.0487 + \frac{10000U_t - 0.256347t^2 + 21.7494t - 7143}{2.40446t^2 - 260.027t + 780122.0}\cdot 77.596 \tag{9}$$

4 Circuit design of measuring system

The circuit design of atmospheric pressure measuring system mainly consists of pressure sensor, temperature sensor, signal adjusting circuit, dual-channel A/D converter and FPGA processor, its working principle block diagram is shown in Figure 1.

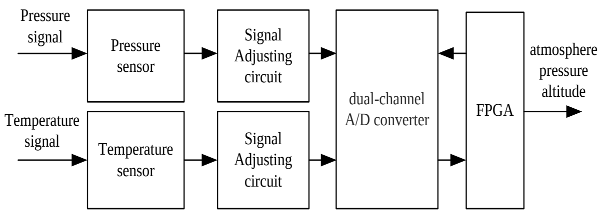

FIGURE 1 Principle diagram of system circuit

The output voltage signals of the pressure sensor and temperature sensor will be transmitted to the A/D converter through signal amplification, filtering and zero regulation of the signal regulation circuit. Then the A/D converter will convert pressure and temperature analog signals into digital pressure value and temperature value, finally the FPGA processor will read the digital pressure and temperature value from the A/D converter, and output the atmospheric pressure altitude value by the calculation of the temperature compensation algorithm and atmospheric pressure altitude formula [5, 6].

4.1 SENSOR CIRCUIT

The pressure sensor used in this measuring system circuit is an absolute pressure sensors of NPC-1210-015A type made by GE NovaSensor company, it has the measuring range of 0Pa to 103425Pa, and the output voltage of the pressure sensor is in the range of 38.009 mV to 83.529 mV when the pressure sensor is tested in the pressure range of 49154.5Pa to 104981Pa.

The temperature sensor is AD590 made by AD Company, its measuring temperature range is the range of 55°C to150°C and the temperature coefficient is 1uA/K. The output current of the temperature sensor is in the range of 233.2uA to 333.2uA when the temperature sensor is tested in the temperature range of -40°C to 60°C If the output circuit of the temperature sensor connects an external 10k resistor, the sensor output voltage is the range of 2.332V to 3.332V.

4.2 SIGNAL ADJUSTING CIRCUIT

The signal adjusting circuit of the measuring system mainly completes the work of signal amplification, filtering and zero regulation of the sensor's output analog voltage signal.

The amplifier circuit is designed by AD620 made by AD Company which is low power consumption, low noise and high precision instrumentation, its use is very convenient that just connect a resistance R_G between pins 1 and pins 8 on a chip to adjust the amplification factor of amplifier, the Equation of amplification factor is shown in Equation (10).

$$G=49.4\ k\Omega/R_G+1. \quad (10)$$

Due to the reference voltage of the A/D converter is set to 1v, so the sensor output voltage range need to adjust the sensor voltage range of 0v to 1v, the value of resistance R_G can be calculated by Equation (10), the R_G resistance selection of 2.355kΩ resistance, magnification is about 21.968 times. In order to get more accurate output voltage range, one trimming resistor can be connected in parallel with R_G resistance.

Zeroing circuit in the system is implemented by anti-adder that is constituted by MAXIM OP07 operational amplifier. The role of zeroing circuit is to adjust the output voltage signal of pressure sensor and temperature sensor what are amplified to the 0 to 1V range in system testing scope [7, 8].

4.3 A/D CONVERTER

A/D converter used in the system circuit is AD7705 made by AD Company; it is a 16-bit dual-channel Sigma - Delta converter with 500Hz maximum sampling frequency and a three line serial communication port. AD7705 can work on two voltage range of 2.7V to 3.3V and 3.3V to 5.25V, in order to match with the working voltage of FPGA chip, the design choose 3V working voltage, and the reference voltage of AD7705 is VREF - 0V and VREF +1V.

The working status of AD7705 is set mainly by its 4 internal function registers which are communication registers, setting registers, clock registers and data registers. The communication register is used to select the register type will be working, the setting registers is used to set the AD7705 operating polarity and buffers, the clock register is used to select the AD7705 operating the master clock frequency and the sampling frequency, the data register is used to store finished converting 16 bit binary data, read these features and conversion data register settings are done through the FPGA control [3]. The connection diagram of AD7705 and FPGA chip is shown in Figure 2.

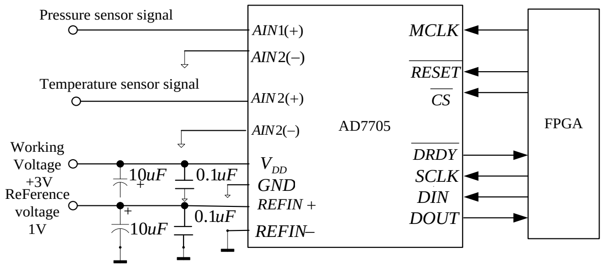

FIGURE 2 Connection diagram of AD7705

4.4 FPGA CIRCUIT

The type of the FPGA chip used in measuring system is Strax EP1S25F780C5 processor made by Altera Company, with an external crystal oscillator of 80MHz. FPGA is a core part of system control and data processing, to complete the work of reading the data from the A/D converter, implementing temperature compensation algorithm and calculating atmosphere pressure altitude.

5 Design of FPGA processor

The FPGA processor is designed by VHDL hardware description language using the QuartusII integrated development environment, the function structure of FPGA includes frequency dividing module, data reading and writing module, compensation calculating module and altitude calculating module.

5.1 FREQUENCY DIVIDING MODULE

The frequency dividing module plays a role of providing the clock signals that are required in FPGA control, A/D converter working and the serial port communication from main clock signal, which is 80MHz. The internal structure of the frequency dividing module is shown in Figure 3.

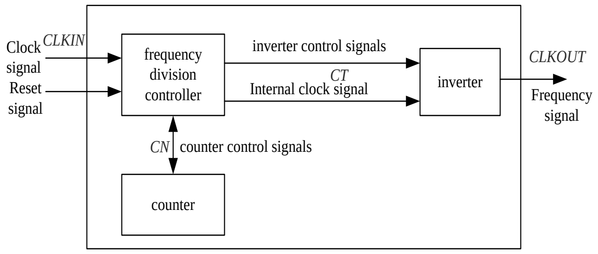

FIGURE 3 Inside block diagram of the frequency dividing module

As the system resets, the frequency division controller clears the counter through counter control signal *CN*, and then the counter starts counting according to the Rising edge of master clock *CLKIN* signal. When the counter reaches the frequency counts, a reverser control signal *CT* is sent to reverser by frequency division controller, and make the output clock signal *CLKOUT* reverse, at the same time counter will reset, so repeatedly.

5.2 DATA READING AND WRITING MODULE

Data reading and writing module mainly controls the working status of the A/D converter through the $\overline{CS}$ and $\overline{RESET}$ pins of AD7705, and sets the running status of A/D converter through the serial communication port, and ensures the FPGA reading the converted digital pressure value and temperature value fast and accurately. The internal structure of data reading and writing module is shown in Figure 4.

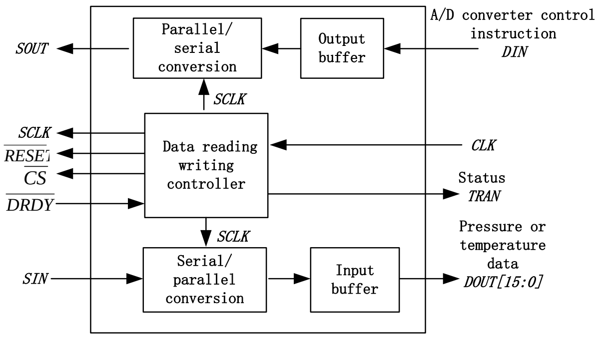

FIGURE 4 Inside block diagram of data reading and writing module

After the system resets, data reading and writing controller makes the A/D converter into working status through setting the $\overline{CS}$ and $\overline{RESET}$ signals, sends the operating status register command which has made parallel/serial conversion to A/D converter. Then monitors the status of pin *DRDY* in A/D converter, when *DRDY* status is valid, data can be read from the data register of A/D converter, and converts the serial data into parallel data [9].

5.3 COMPENSATION CALCULATING MODULE

Compensation calculating module is used to calculate the digital pressure value compensated according to the pressure sensor temperature compensation algorithm. The internal structure of compensation calculating module is shown in Figure 5.

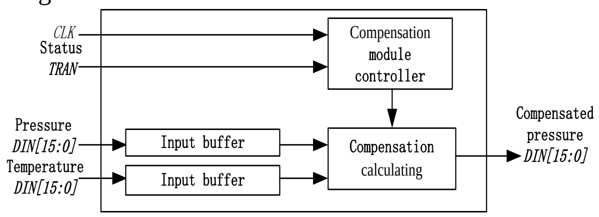

FIGURE 5 Inside block diagram of compensation calculating module

Calculating module controller monitors the value of *TRAN* at the trigger edge of the clock *CLK*, and reads pressure and temperature data when the value of *TRAN* is valid and calculates the pressure value with the temperature compensation algorithm.

5.4 ALTITUDE CALCULATING MODULE

The function of altitude calculating module is to calculate the atmospheric pressure altitude value according to the Equation (2) and Equation (3). In order to simplify the calculation for improving calculating efficiency, the linear interpolation method is adopted to make approximate treatment for atmospheric pressure altitude Equation. According to the error formula of the linear interpolation method, which is shown in Equation (11), and the precision requirements of the system design, we can calculate the maximum step length of the interpolation and the minimum interpolation section number in measuring range.

$$|\mathrm{R}(\mathrm{x})| = \left|\frac{\mathrm{f}''(\delta)}{(2)!}\omega(\mathrm{x})\right| \le \delta. \tag{11}$$

At each interpolation interval, we can use Equation (12) to make approximate calculation, and the interpolation parameters y_i, k_i, x_i in Equation (12) can be calculated in advance and stored in memory.

$$\mathrm{y} = \mathrm{y_i} + \mathrm{k_i}(\mathrm{x} - \mathrm{x_i}). \tag{12}$$

The internal structure of altitude calculating module is shown in Figure 6.

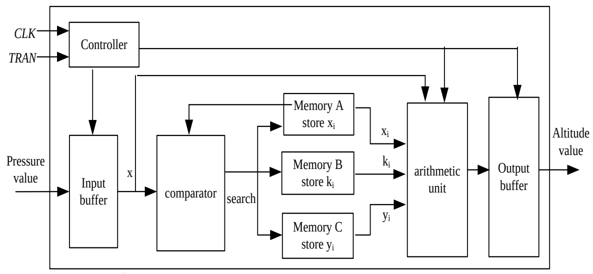

FIGURE 6 Inside block diagram of altitude calculating module

When TRAN value is valid, the controller will read the pressure value, which is compensated into input buffer. First of all, by comparing the pressure value decide the interpolation interval, and then the corresponding interpolation parameters can be got from the FPGA memory, finally to calculate the atmospheric pressure altitude value according to the Equation (10). In order to improve the search efficiency and the computational efficiency, the binary search algorithm can be adopted when to search interpolation interval.

6 FPGA simulation and system testing

6.1 FPGA SIMULATION

After accomplishing program edit of FPGA using VHDL language, the functional simulation can be performed by Modelsim SE 6.0 software to verify the circuit function whether to meet the design requirements. The functional simulation picture of data reading and writing module is shown in Figure 7.

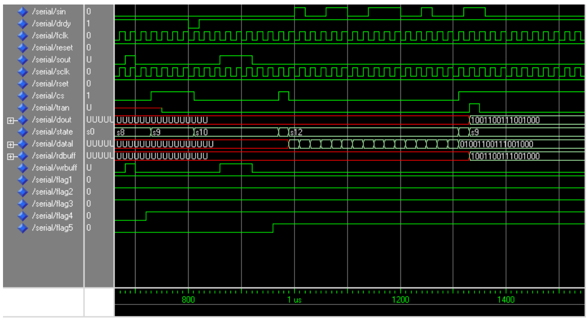

FIGURE 7 Functional simulation map of data read module

If every functional simulation of the FPGA's functional blocks is correct, the integrated design can be performed by QuartusII software to get the connection diagram of the basic logic units. The logic connection diagram of compensation algorithm is shown in Figure 8.

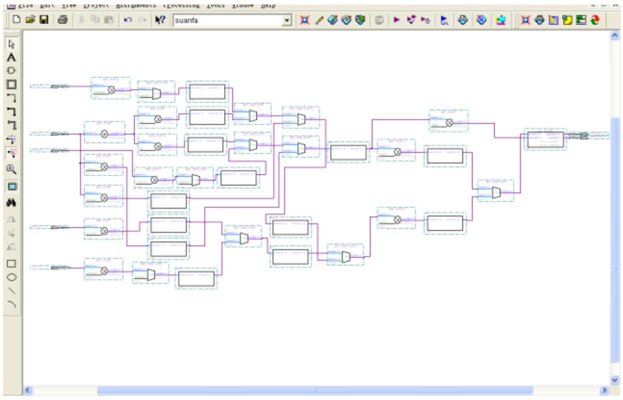

FIGURE 8 Logical connection diagram of compensation algorithm

FPGA's timing simulation is implemented after the completion of the placement and routing design in the FPGA, this kind of simulation contains the most comprehensive and accurate delay information, and reflect effecttively the actual working state of the FPGA chip [10, 11]. The simulation diagram of compensation algorithm is shown in Figure 9.

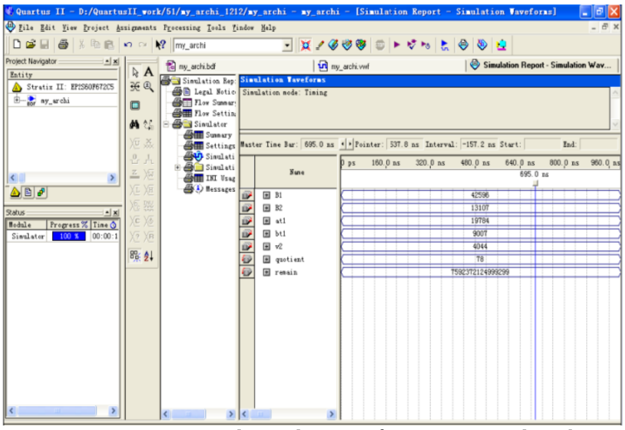

FIGURE 9 Timing simulation diagram of compensation algorithm

6.2 SYSTEM TESTING

After the FPGA simulation, the configuration file generated by source code program can be downloaded to the FPGA chip, and then connect FPGA chip to the whole measuring system. The measuring system is tested with the six groups of atmospheric pressure and three kinds of temperature, and the results of testing are shown in Table 4.

Table 4 The results of measuring system with compensation

atmospheric pressure (p_a)	**theory altitude (m)**	**measuring altitude (m)**		
		-20°C	*25°C*	*50°C*
49154.5	5700	5701.6	5700	5700.7
57728.3	4500	4497.9	4498.8	4501.1
67474.9	3300	3300.7	3300.5	3301.8
78513.1	2100	2097.7	2098.6	2102.6
90970.1	900	897.8	898.9	900.9
104981.0	-300	-297.5	-299.4	-298.6

As can be seen from Table 4, the maximum error of measuring system tested at different atmospheric pressure and temperature is 2.6m, and it is proven that this measuring system has the very high precision. Factors lead to error are the following:

1) Calculation error of FPGA data calculation.

2) The precision of reference voltage used in A/D converter.

3) Inherent quantization error of A/D converter.

4) External error of system test, such as the accuracy of the test equipment, human error, etc.

7 Conclusions

In this paper, a kind of atmospheric pressure measuring system is designed and implemented with temperature compensation design based on FPGA processor. Because FPGA has the advantageous characteristics of high reliability, high speed, strong processing capacity, small volume, low power consumption and so on, so this measuring system has a better performance in terms of stability, real-time, power consumption and so on, and the data processing time is only about 9us. The combination with the temperature compensation design in system also improves greatly the precision of the measuring system on the whole.

References

[1] Fan S C, Lv J F, Zhang Q R 2005 Aviation Test System *BeiHang University Press Beijing* 234-40 (*in Chinese*)

[2] Li H Z 2011 FPGA/ASIC High Performance Digital System Design *Electronic Industry Press Beijing* (*in Chinese*)

[3] Yan J M, Zhang H T 2007 Chinese Journal of Sensors and Actuators **20**(3) 707-10 (*in Chinese*)

[4] Zhang H T, Xue J X 2013 Applications of Electronic Technique **39**(4) 65-7 (*in Chinese*)

[5] Liang S Z, Guo X M, Yu X T 2013 *Chinese Journal of Sensors and Actuators* **26**(5) 654-9 (*in Chinese*)

[6] Wang J C, Wang F P, Hou R F 2011 *Transducer and Microsystem Technologies* **30**(12) 123-5

[7] He J T, Liu X Y 2009 Intelligent Sensor Principle, Design and Application *Electronic Industry Press Beijing* (*in Chinese*)

[8] Creed H 2009 Intelligent Sensor Design *People's Posts and Telecom Press Beijing*

[9] Cheng Z L 2011 *Applications of Electronic Technique* **37**(4) 7-9

[10] Zhou R J, Tu Y, Zhang L M 2007 FPGA/CPLD Digital System Design Example Based on Quartus II *Electronic Industry Press Beijing* (*in Chinese*)

[11] Xu X, Yu H Q 2005 Embedded System Design Based on FPGA *Mechanical Industry Press Beijing* (*in Chinese*)

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