Design of Programmable Gain Amplifier Module in Dynamic Liquid Level Tester

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Abstract—Oil and gas wells need to perform dynamic liquid level detection during the development to prevent inaccurate detection during drilling and damage the oil and gas field. The Program Controlled Gain Amplifier (PGA) module designed in this paper is used in the dynamic liquid level test instrument. Using STM32F407ZGT6 as a microcontroller (MCU), the MCU, a multi-stage variable gain amplifier and a peak detection circuit form a closed loop control, forming an automatic gain control (AGC) circuit. First, the signal output by the peak detection circuit is collected by AD, and then the entire module is in a dynamic balance state through DA feedback. This AGC system can accurately control the gain and output signal. Finally, the ratio-average filtering algorithm is used to test the experimental data. Experimental results show that the module can achieve gain control of -20~60 dB in the frequency range of 1kHz~20MHz; the relative error of the output voltage is within 3%. This module achieves the performance indicators of broadband, high precision and high gain. Compared with the traditional module, its advantage is that it takes into account and optimizes the three performance indicators at the same time, and has better stability.

1. INTRODUCTION

In the process of oil and gas well moving liquid level detection, it is difficult to detect weak moving liquid level changes with conventional sensors\cite{1}. The electrical signal output from the sensor needs to be amplified before it can be sent to AD for data collection. The signal amplification process requires a high-precision, high-gain amplifier\cite{2-3}, Programmable Gain Amplifier (PGA) uses a program to precisely control its gain changes, adjust the signal dynamic range, and amplify weak analog signals with high precision. Therefore, using the multi-stage cascade method, the PGA module to be designed has the characteristics of bandwidth\cite{4}, high precision\cite{5} and high gain\cite{6}, and can be used with the Automatic Gain Control (AGC) circuit in the oil and gas well dynamic liquid level test instrument\cite{7-8}.
2. THEORETICAL BASIS
The PGA module designed this time is mainly designed based on the typical AGC loop. The AGC loop is a closed-loop feedback AGC system\[9\]. This system mainly includes VGA circuit, PD circuit, LF circuit and comparator. A typical AGC circuit is shown in Figure 1. The AGC loop gain setup time is related to the peak-to-peak value of the input signal, so the AGC loop should adjust the amplitude of Vout according to Vref to reduce the influence of Vin on the setup time of the entire AGC loop\[10\].

3. SYSTEM SCHEME DESIGN
This system is composed of a variable gain amplification (VGA) circuit, a fixed gain amplification (FGA) circuit, a peak detection (PD) circuit and a microcontroller (MCU). The overall block diagram of the system is as follows As shown in Figure 2. The MCU uses the STM32F407ZGT6 main control chip. This chip MCU uses its own ADC and DAC, which can optimize the circuit structure. The gain control of the PGA module is controlled by the upper computer. The PC end of the upper computer sends instructions, and the PGA module can receive the corresponding commands to control the output voltage value. The PD circuit is used for peak detection and converts the sinusoidal signal into a DC level signal.

4. HARDWARE CIRCUIT DESIGN
4.1. Variable Gain Amplifier Circuit
The main chip of the VGA circuit selects the wide-band, high-gain precision VGA chip AD603. The control modes of the two AD603s are both -10 ~ 30dB (90MHz) bandwidth mode, and the gain control pin is directly short-circuited to realize the synchronous setting of the gain.
4.2. Gain control circuit

In the automatic gain control method, in order to overcome the defect that most DACs can only output a positive voltage, a subtraction circuit is designed. The final control voltage of AD603 is calculated by a dual operational amplifier. The principle of the gain control circuit is shown in Figure 4. First, the external DA follows to the next stage, and then the voltage range of \(-500mV \sim 500mV\) is obtained through differential operation.

![Gain control circuit](image_url)

In the differential circuit of Figure 4, take \(R_{14}=20k\), \(R_{15}=10k\), \(R_{18}=10k\), \(R_{17}=820\), then the output voltage \(V_G\) is shown in formula (1).

\[
V_G = 5 \left(\frac{R_7}{R_7 + R_{12}} \right) \left(1 + \frac{R_5}{R_{41}}\right) - V_{DA} \times \frac{R_5}{R_{41}} = 0.567 \times \frac{V_{DA}}{2}
\]  

(1)

Let \(V_G=\pm500mV\), the external DA control voltage \(V_{DA}\) is:

\[
V_{DA(\text{min})} = (567 - 500) \times 2 = 134mV
\]

(2)

\[
V_{DA(\text{max})} = (567 + 500) \times 2 = 2134mV
\]

(3)

Therefore, the voltage range of \(V_{DA}\) is 134mV \sim 2134mV. In theory, the relationship between the control voltage of the external DA input and the overall gain of the module is as (4):

\[
G(\text{dB}) = -40V_{DA} + 65.36
\]  

(4)

The unit of \(V_{DA}\) is V; Equation (4) is only a theoretical value calculation formula. Due to the influence of the resistance and capacitance accuracy, the accuracy of the DA part of the STM32F407ZGT6 and the accuracy of the test instrument, a certain deviation will occur.
4.3. Peak detection circuit
The core of the PD circuit is mainly a high-speed comparator and a detection circuit. The main chip of the comparator is TL3016. The comparator compares the input signal at the non-inverting end and the feedback signal at the reverse end. The principle of the peak detection circuit is shown in Figure 5. It is detected by diode and RC charge and discharge. When the diode is on, the signal charges C7 through R23; when the diode is off, the signal discharges R26 through C7. If the charging and discharging are detected properly, the system reaches the condition of negative feedback automatic adjustment, and the circuit will inevitably reach balance in the end. Figure 6 is the signal waveform output by the VGA circuit, and Figure 6 is the signal waveform output after the detection circuit. It can be clearly seen that after detection, it is the peak DC value.

5. SYSTEM SOFTWARE DESIGN
The system software part is mainly composed of the main program and some subprograms. It mainly completes the system initialization, the communication between the PGA module and the upper computer, data acquisition and processing, and the normal work of the software requires the coordination and control of various parts of the program. The software flow chart is shown in Figure 7. The system is initialized, the relevant parameters are configured, the PGA module communicates with the upper computer, the upper computer sends a fixed output voltage command, the serial port debugging assistant displays the current voltage value, and the output voltage in the ARM controls the gain of the PGA module. Then the gain is automatically adjusted to determine the size of the output voltage, and finally AD is collected, and the error analysis is judged. If the output is within the error accuracy range, the output result will be output. If the error accuracy is exceeded, the AGC loop system adjustment circuit will execute the loop subroutine.

The subroutines executed by the AGC adjustment circuit include ADC subroutine and DAC subroutine. DA output voltage controls the gain of VGA, and AD acquisition performs fine adjustments to approach the preset expected value successively. These two subroutines are the core part of the AGC circuit.
6. SYSTEM TEST AND RESULT ANALYSIS

There are mainly four types of test instruments as follows: function signal generator (KEYSIGHT 33500B Series), oscilloscope (KEYSIGHT InfiniiVision DSOX3012T), DC stabilized power supply (MATRIX DSP-3203TK-3), and Agilent Digit Multimeter (Agilent Digit Multimeter)[11-12]. The instruments used in the experiment have been calibrated to ensure normal operation and correct wiring.

The fixed output voltage amplitude of the PGA module takes 7 sets of data of 0.5V, 0.8V, 1V, 1.2V, 1.5V, 1.8V, and 2V as examples. The ratio-average filtering algorithm is used, and each set of data is measured 12 times at different frequencies., Remove the maximum and minimum values, and average the remaining 10 times to calculate the output voltage accuracy. Each input voltage signal can be amplified or attenuated. For example, when the output voltage amplitude is 2V, the input voltage amplitude changes between 0.1V and 2.2V. Calculate the accuracy of the output voltage at different frequencies, and the error analysis of the measured data is given in the form of the curve in Figure8.

It can be seen from the curve in Figure 8 that the accuracy of the fixed output voltage swings within a certain range, and the error curve has a larger range at higher frequencies. This is because the signal output is unstable when the signal generator outputs a larger frequency range. It is susceptible to the influence of noise to swing up and down; and the output measuring instrument will have an inaccurate measurement signal due to the high frequency, so the voltage accuracy will fluctuate greatly. As the frequency increases, the error gradually increases, but in the frequency range of 1kHz~20MHz, The voltage accuracy is basically maintained within 0.03.
7. CONCLUSION

Through the analysis of experimental data, it can be known that the automatic gain control mode of the PGA module has been realized, and the gain dynamic range of -20dB~60dB is realized in the frequency range of 1kHz~20MHz, and the relative error of the output voltage is within 0.03. The entire PGA module achieves the performance indicators of bandwidth, high gain and high precision, and has the advantages of module integration, good stability, convenient operation, and high cost performance. It can be used in the actual liquid level test process of oil and gas wells. The renewal of the well tester provides new ideas and lays a foundation for the improvement of future PGA modules.

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