Study on Method of Ultrasonic Gas Temperature Measure Based on FPGA

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Abstract. It is always a problem to measure instantaneous temperature of high-temperature and high-pressure gas. There is difficulty for the conventional method of measuring temperature to measure quickly and exactly, and the measuring precision is low, the ability of anti-jamming is bad, etc. So the article introduces a method of measuring burning gas temperature using ultrasonic based on Field-Programmable Gate Array (FPGA). The mathematic model of measuring temperature is built with the relation of velocity of ultrasonic transmitting and gas Kelvin in the ideal gas. The temperature can be figured out by measuring the difference of ultrasonic frequency \( \Delta f \). FPGA is introduced and a high-precision data acquisition system based on digital phase-shift technology is designed. The feasibility of proposed above is confirmed more by measuring pressure of burning gas timely. Experimental result demonstrates that the error is less than 12°C and the precision is heightened to 0.8%.

1. Introduction
For very high gas temperature and very quick temperature changing, the burning gas temperature measure of obturator, e.g. internal-combustion engine, diesel engine, etc., is always a problem. Because of good pointing direction, quick reactive velocity and non-contact measure, etc., the ultrasonic becomes a new measure method [1,2]. However, it is very difficult for conventional measuring circuits with ultrasonic, whose precision is restricted by SCM frequency, to achieve the purpose of measuring quickly and exactly, and exits many problems, low precision, bad anti-jamming, etc. Therefore, the article introduces a method based on FPGA to realize temperature measuring and the precision is improved greatly via data acquisition system designed by digital phase-shift technology. Synchronously, the feasibility of proposed above is confirmed by measuring pressure.

2. Measurement mathematic model
In ideal gas, the emitting velocity of ultrasonic is direct proportion to the square root of gas Kelvin [3], which is given by equation (1). It can be seen as adiabatic process when transiting burning gas.

\[
V = \left( \frac{\sqrt{RT}}{M} \right)^{1/2}
\]  

(1)

Where \( V \) represents the velocity of ultrasonic transmitting, \( r \) is the specific heat ratio (ratio of specific heat at constant pressure and specific heat at constant volume), \( R \) is the ideal gas constant, \( T \) is the Kelvin of gas, and \( M \) is the gas molecular weight.
When ultrasonic with some frequency emitting in gas medium, the frequency changes with gas temperature changing quickly. With the time changing, the disciplinarian of gas temperature, ultrasonic transmitting velocity and frequency is shown in figure 1, and a part of transmitting velocity curve is taken out and shown in figure 2. Supposing that \( \Delta t_1 \) is a period which ultrasonic emitter gives out at the time of \( t_1 \) and the distance of two ultrasonic sensors is \( L \), then equation (2) is gained.

\[
L = \int_{t_1}^{t_2} V dt = \int_{t_1}^{t_2} \frac{\Delta t_2}{2} V dt = \int_{t_1}^{t_2} \frac{\Delta t_2}{2} V dt
\]

As in figure 2, when \( \Delta t_1 \) and \( \Delta t_2 \) is infinitesimal, equation (3) comes into existence.

\[
V(t_1) \cdot \Delta t_1 = V(t_2) \cdot \Delta t_2
\]

Supposing that \( f_1 \) is ultrasonic frequency at the emitter, which is changeless, and \( f_2 \) is received frequency by receiver at the time of \( t_2 \). With the relation of time and frequency, equation (4) is gained.

\[
\frac{\Delta t_1}{\Delta t_2} = \frac{f_2}{f_1} \frac{V(t_2)}{V(t_1)}
\]

For \( t_1 \) and \( t_2 \) being close, the median \( t \) can be regarded as canonical value. The frequency of emitter is known, and \( f_1 \) is substituted with \( f_0 \), \( \Delta f = f_2 - f_1 = f_2 - f_0 \), then the mathematic expression of temperature measurement principle is written as:

\[
\frac{\Delta f}{f_0} = \frac{V(t_2) - V(t_1)}{V(t_1)} = \frac{L}{V^2} \frac{dV}{dt}
\]

As in equation (5), the relation of \( \Delta f \), \( dV/dt \) and \( V^2 \) is obtained. However, the distance between sensors should meet the following condition: the time spent by ultrasonic getting through, a space of \( L \), from emitter to receiver is far shorter than time interval of whole changing temperature, which makes frequency in figure 1 satisfy equation (5). Suppose \( T=T_0 \) at \( t=0 \), equation (6) is gained after integral.

\[
T = \left\{ \frac{\sqrt{\gamma RT_0}}{m} \right\}^{1/2} \frac{\Delta f}{f_0} dt
\]

3. Theory of measurement system

The system mostly consists of following: sending and receiving circuit, data acquisition system based on FPGA, controlling part to the sampling time, measuring pressure and data memorizing and processing by SCM. Figure 3 shows the structure block diagram of gas temperature measure theory.

First of all, all counters are cleared by SCM. At the moment of being burnt, the signal gave out by P1.0 makes AND start up. Then the pulse that the vibrator gives out inspires emitter with frequency 40KHz. Two counters are synchronously started up. The number counted is the frequency of signal to be measured. The first counter counts the starting frequency \( f_0 \) while the other counts \( f \) in burning. When \( f \) is greater than \( f_0 \), the output of RS trigger is High, and the data acquisition system is started up. Then the system stops working at the next 1ms. SCM gives out Reset to prepare for the next count beginning with Zero. When \( f \) is not greater than \( f_0 \), the output of RS trigger is Low, then the data
acquisition system is shut and count process is over. Synchronously, SCM starts up A/D to measure pressure in firebox. Because gross sampling time is much shorter, about only 30ms, data processing will be done after all data acquisition being finished.

Figure 3. Structure block diagram of gas temperature measure theory.

4. System structure

4.1. Fixing of ultrasonic sensor
In system two ultrasonic sensors are used, of which the fixing distance being correctly selected is very crucial. The distance should meet following conditions: the time spent by ultrasonic getting through gas medium, a space of $L$, is far less than the time interval of whole changing temperature, which makes not only the gas be seen approximately as ideal state, but also the system accomplish data acquisition and storage once. The requests can be met when $L$ is selected as 50mm.

4.2. Design of pressure sensor
As the object to be measured is high temperature gas, it should be firstly considered that pressure sensor endures very high temperature. The article adopts Silicon on Insulator (SoI) technology and silicon dioxide of embedding layer is shaped by injecting high-energy oxygen ion in order to insulate leak-current formed by temperature hoist between top silicon-layer and body-silicon [4]. After cooling, the pressure sensor can operate under 350°C and bear transient impact.

4.3. Design of data acquisition system
There is difficulty in sampling and memorizing of data because the interval of burning gas temperature change time is much shorter, about only 30ms. In article, we design a high-resolving power data acquisition system based on digital phase-shift and FPGA to realize data acquisition.

4.3.1. Digital phase-shift technology. The phase-shift is that two signals with the same frequency and one is referenced signal and the other forth-comes or lags for it to form phase difference. As shown in figure 4, the digital phase-shift technology usually adopts delaying method. CKL90, CKL180, CKL270, their phase difference being 90° in turn, are respectively obtained by original pulse CKL0. Then four clock pulses respectively drive four same counters synchronously. Supposing that the clock frequency is $f$, period is $T$ and $m_1, m_2, m_3, m_4$ represent result of four counters, respectively. So the final pulse width is calculated as:

$$\omega = \frac{(m_1 + m_2 + m_3 + m_4)}{4} \times T$$

Equation (7) shows that signal to be measured is counted with the equivalent clock frequency 4$f$ but the original clock frequency being $f$ and measure precision is improved four times to quondam one.
4.3.2. Counter Design. The 20 bits counter with high-speed pulse is designed using XC4003E, whose structure is shown in figure 5. CK+ and CK-, their phases being reverse, are respectively obtained by CK via comparator, which enter into FPGA, where CK1, CK2, CK3 and CK4, their phases difference being 90° in turn, are respectively formed. There are four kinds value combined: 0110, 0101, 1001and 1010, and others are non-effective. Counter C, whose result is High 16 bits, is started up by CK1. The TOA makes four triggers turn, and the current state of four clock signals is respectively recorded, which, adding flag bit, forms Low 4 bits. Then the latch is triggered to read counter C. All count results are summed by an adder, of which the data output is read into SCM.

![Figure 4. Principle of digital phase-shift.](image)

![Figure 5. Structure of counter.](image)

5. Experimental test result and error analysis
An experiment to measure temperature in firebox of engine is made. During data acquisition system working, the sampling frequency is integrated with digital by SCM. The changing curves of gas temperature and sampling pressure are described in figure 6, which denote that two curves keep almost same in condition of lower temperature and pressure. However, the main error is following:

![Figure 6. Experimental testing curve.](image)

(a) Curve of gas temperature  
(b) Curve of gas pressure ratio

(1) Count error of count system
As maximal counter error is one pulse, the clock frequency of counter should be heightened if possible. RS trigger can be used to make the count time of system and changing time of frequency to keep synchronous. In addition, FPGA should be optimized by selecting elements reasonably [5].

(2) Measure environment error
There are a lot of mechanical and electric noises at measure locale, which make measure precision greatly fall. So these factors must be as eliminated as possible during designing hardware circuit.

(3) Pressure measurement error
For pressure measure system, there is great effect on ultimate result when pressure is very big, so A/D chip should be selected appropriately.
6. Conclusion

This article presents a new method of gas temperature measurement based on FPGA. The system precision heightens to 0.8% in measuring high-temperature gas in firebox of engine. Experimental results demonstrate that temperature measured by proposed above is basically same with that estimated in ideal state. Therefore, the available scheme is presented for temperature study in atrocious environment of high-temperature, high-pressure or high-speed airflow. Furthermore, the system can widely used to measure temperature on aviation, plasma room and nuclear reactor, etc.

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