

A Compound Detection System Based on Ultrasonic Flow Rate and Concentration

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Abstract: This paper proposes a new detection system for monitoring gas concentration and flow rate. Velocity difference of ultrasonic wave in bi-directional propagation in measured gas is recorded and utilized for computing the online gas concentration and flow rate. Meanwhile, the temperature compensation, return signal processing and error analysis algorithms are applied to improve the accuracy. The experimental results show that, compared with the single sensor measurement of gas flow rate or concentration, the proposed detection system with lower cost and higher accuracy can be applied in the occasion which needs simultaneous monitoring of gas concentration and flow rate. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Ultrasound, Time difference method, Propagation time, Concentration of oxygen, Gas flow rate, Temperature compensation.

1. Introduction

Ultrasonic measurement method has been widely utilized in ultrasonic flowmeter and ultrasonic gas concentration sensor. Ultrasonic gas flowmeter has been more and more widely applied in industry and medicine because of its high accuracy, good stability, wide range of application and many other advantages [1]. Ultrasonic gas concentration sensor with advantages such as the property of anti-interference, high accuracy, high ratio of performance to price has been widely used in practical production in different aspects, e.g. combustion efficiency control, industrial control, food industry, medical devices, automotive electronics and so on [2].

However, current ultrasonic flowmeter and ultrasonic gas concentration sensor at China and abroad are measured in separate instruments, which

can only measure gas flow or concentration separately. Besides, some of the sensors are made by electroplating or ceramic materials, which lead the need for frequent calibration, short product life, long reaction time, and high energy consumption [3]. Some sensors use temperature change of thermistor, which causes large measurement error [4]. Others have small ultrasonic string, which only holds a small amount of gas [5], and cannot be measured under low speed.

This paper presents a new ultrasonic gas detection system, which uses the temperature compensation, return signal processing, and error analysis to improve the accuracy of measurement. Compared with the traditional detection systems, the proposed detection system can simultaneously monitor the oxygen concentration and flow rate to satisfy the industrial application to test oxygen-generating machines. Besides, it is low cost, and accurate with

the property of high efficiency, energy-saving, and simple calibration process.

2. The Overall Design of the System

The principle block diagram of the detection system can be found in Fig. 1.

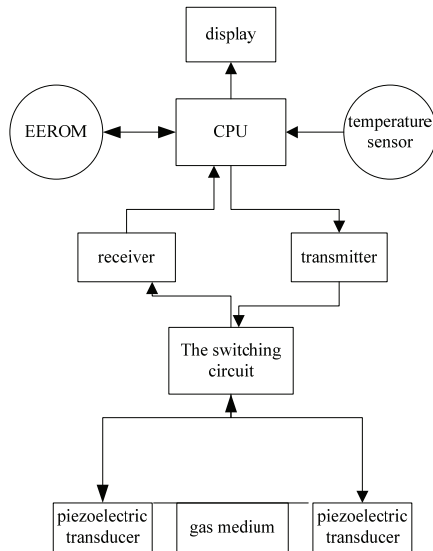


Fig. 1. Block diagram of detection system.

The detection system consists of an ultrasonic transducer, electronics and computing system. Ultrasonic transducer converts electrical energy into ultrasonic energy. Ultrasound emitted by transducer passes through the gas, and received by receiving transducer. The received ultrasonic signals are amplified by the electronic amplifier and converted into electronic signals representing the gas flow rate

and concentration. This design uses the principle that the propagation time difference of ultrasound in the gas upstream and downstream is related with the velocity and the concentration of measured gas. The calculation of flow rate and concentration of gas is based on the measured time difference.

3. Design of the Hardware

The design of the hardware is mainly composed of microprocessor circuit, signal adjusting circuit, the switching circuit, temperature compensation circuit, and liquid crystal display circuit.

3.1. Ultrasound Generator

The ultrasound transmitting and receiving require a device for energy bi-directional conversion between electric and ultrasonic signals, namely the transducer. Ultrasonic transducer (ultrasonic sensor) is an important part of the ultrasonic detection system. In the transmitting state, the transducer can realize the conversion from electric energy to mechanical energy, and then to sound out energy. On the other hand, it can also make the contravariant conversion. In order to research and apply ultrasound, many types of ultrasound generator have been invented. Currently the most popular ultrasonic generator is piezoelectric [6], which is used in this design.

Detection system flow chart is shown in Fig. 2. After digital signal processing such as amplification, filtering and shaping, the ultrasonic waves generated by the ultrasound generator are transmitted to the second transducer opposite. When the second transducer has detected the incident wave, the first transducer changes its role and works as a receiver to receive wave.

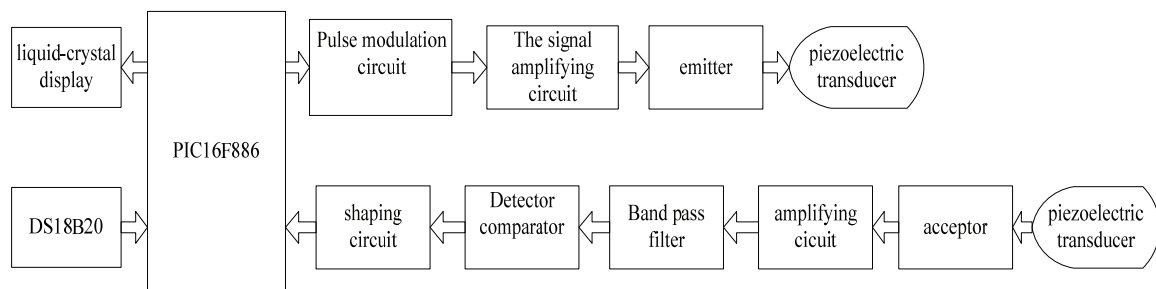


Fig. 2. Hardware structure of the proposed detection system.

3.2. Circuit of the System

Signal conditioning circuit used in the compound detection system is shown in Fig. 3(a). In order to improve the weak signal and reduce output impedance, the signal is amplified before comparison. Amplifier chip AD623 and comparator LM393 are used.

Relationship in the amplification circuit is shown in formula (1):

$$A = \frac{100 K}{R_G} + 1, \quad (1)$$

where $R_G=R_7=4.7K$, we obtain:

$$A = \frac{100\text{ K}}{4.7\text{ K}} + 1 = 22 \text{ ,} \quad (2)$$

In this manner, the detected signal is amplified for 22 times, i.e. the waveform with voltage from 0~115mV is changed into a 0~2.5 V waveform. The resonant circuit is used to reduce the volatility of sampled signal, and thus improve the sampling accuracy.

3.3. The Switching Circuit

This part is to complete the switching between transmitting and receiving on two ultrasonic. As shown in Fig. 3 (b), a three channel analog switch chip (74HC4053) is used to choose channels according to the different needs.

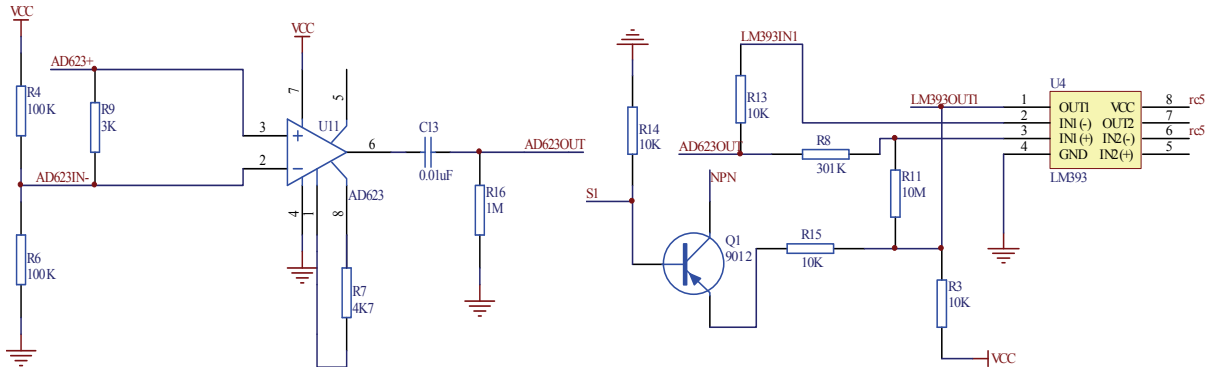


Fig. 3 (a). Signal amplification circuit.

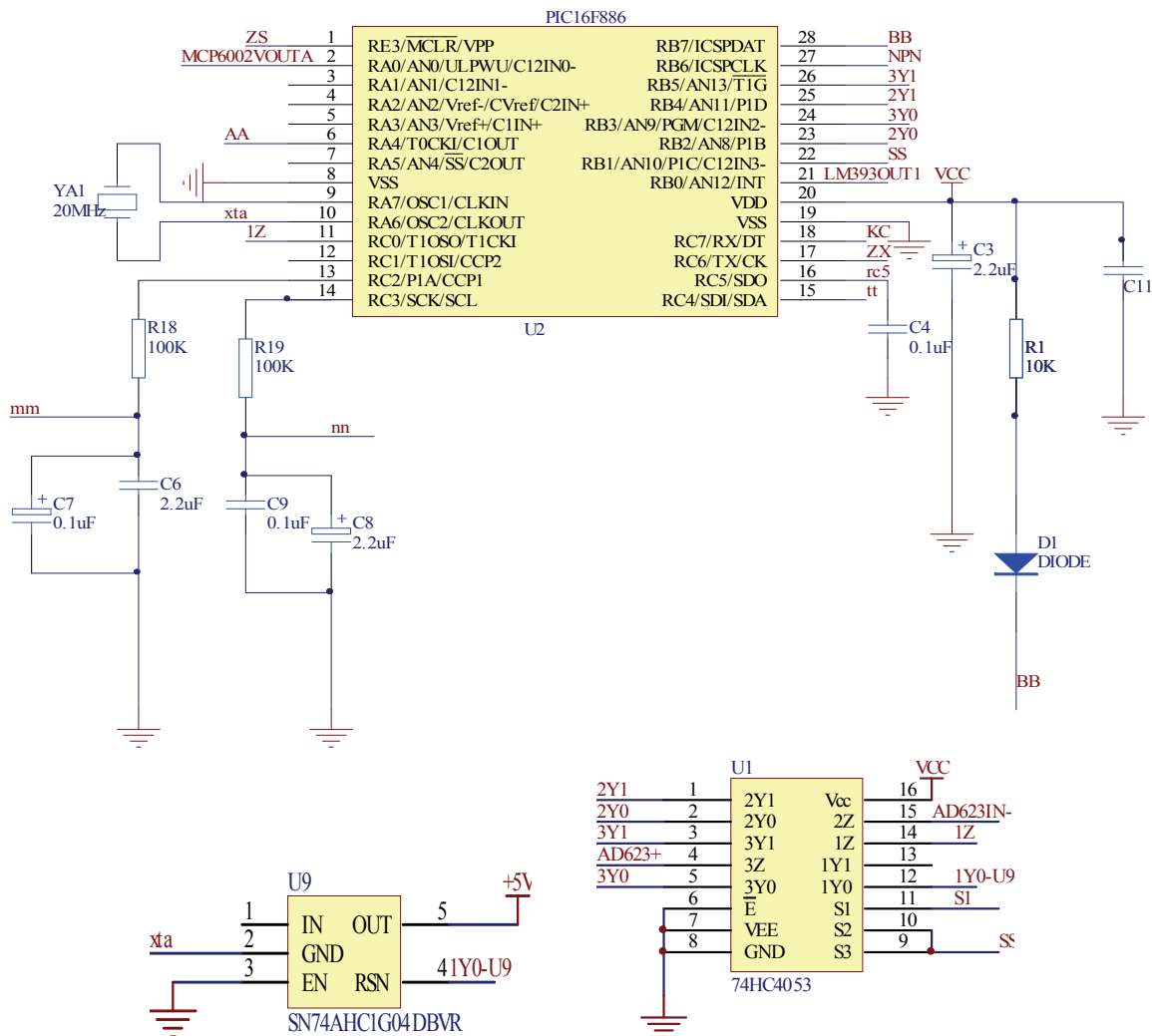


Fig. 3 (b). Switching control circuit.

4. Design of the Algorithm

The algorithm of calculating the ultrasonic propagation time is described in this section. At the start of the transmitting circuit, internal timer T0 in MCU is triggered. Counter T1 is used to record the ultrasonic propagation time between transmitting time and receiving time of the reflected wave. When ultrasonic reflected wave is received, receiving circuit outputs a negative jump to generate an interrupt request signal in INT0 or INT1 terminal. MCU responses this request and execute the external interrupt service subroutine to read the time difference, and to calculate the concentration and flow rate by using the formulas (3) and (4). Calculating system diagram is shown in Fig. 4. In the calibration process, MCU sets the known concentration gas as being with zero flow, and calculates & stores gas concentration offset and zero flow offset in EEPROM [7]. During normal operation, MCU reads the offset information and temperature compensation information stored in the EEPROM, and then calculates the compensated gas flow rate and concentration using this information.

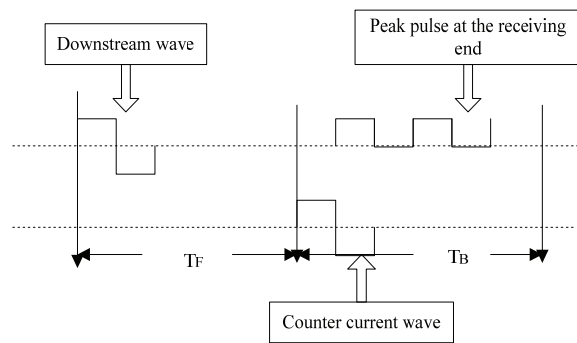


Fig. 4. Calculating system block diagram.

Oxygen concentration formula is

$$P = C_1 * T + C_2 * O_1 + C_3(T_{FB}), \quad (3)$$

Oxygen flow formula is

$$Q = ABS(C_4(T_F - T_B)) + C_5 * O_2, \quad (4)$$

where C_1, C_2, C_3, C_4, C_5 are constant formed in ultrasound, T is the temperature of the gas. T_{FB} is the round trip time of ultrasound in sensor cavity, T_F is the transmission time between two sensor in the forward direction. T_B is the transmission time between two sensor in the backward direction. O_1, O_2 are the determined the calibration offset value.

Ultrasound is a kind of sound wave with propagation velocity related with density of the gas. In larger density gas, velocity of ultrasound is higher. In the meantime, gas density is affected by temperature. Therefore, gas temperature change can determine the change in ultrasound velocity. Because oxygen concentration is influenced by gas density, oxygen concentration in the ultrasonic generator is directly influenced by temperature [8]. As shown in the formula (6), when the temperature is 0 degree, ultrasonic wave velocity in the oxygen as $V=316$ m/s; when the temperature is 27 degrees, $V=332$ m/s; when the temperature is 37, $V=338$ m/s with the variation of 6 m/s. When in 37 degree, but using velocity in 27 degrees, we will obtain oxygen concentration measurement with big errors. Therefore, in order to realize the high accuracy measurement, temperature compensation must be used.

From the formula of temperature compensation:

$$C = 316 \sqrt{\frac{T + 273.16}{273.16}}, \quad (5)$$

The approximate calculation formula is deformed by the Taylor formula:

$$V = 316 + 0.6067T - 0.0005T^2, \quad (6)$$

We have

$$V = 316 + 0.607 \times T(^{\circ}C), \quad (7)$$

$$V = C_3(T_{FB}) + C,$$

where V is the speed of sound wave, C is the constant, V and T_{FB} are with a linear relationship.

Hardware circuit is shown in Fig. 5.

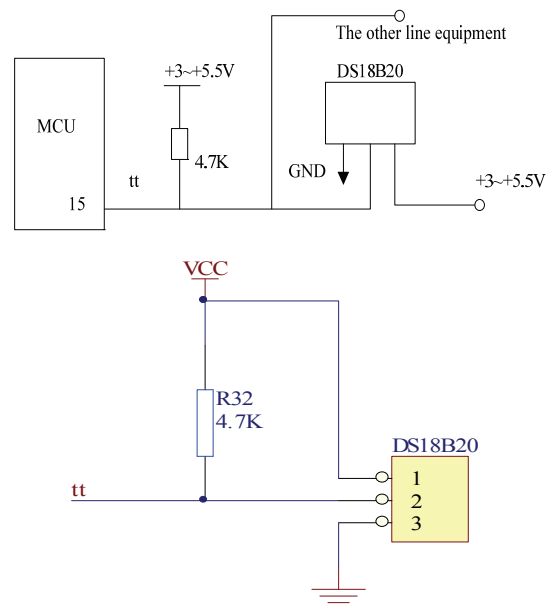


Fig. 5. DS18B20 temperature compensation hardware circuit diagram.

Related reliable software has been designed while the circuit design is relatively simple. The software design includes two parts: measurement of temperature and correction of results. MCU reads measured temperature from chip DS18B20, corrects the velocity and calculates oxygen concentration. The numerical filtering sorts every 8 sets of data, removes the maximum and minimum values, and sends the middle 6 data to MCU with temperature values. The results are computed based on round trip time and displayed [9].

5. Software Design of Ultrasonic Oxygen Concentration Sensor

The software is mainly designed using C language with modular structure. It mainly consists of two parts: the main program and interrupt service subroutine. From Fig. 6, the main program completes the initialization, transmitting and receiving of ultrasonic wave. The initialization includes: clock module initialization, analog-to-digital conversion ADC initialization, serial initialization, and I/O port initialization. Timing interrupt service subroutine completes bi-directional ultrasonic wave transmission in turn, while the external interrupt service subroutine reads the value of completion time, calculation of flow rate and concentration, as well as output of the results.

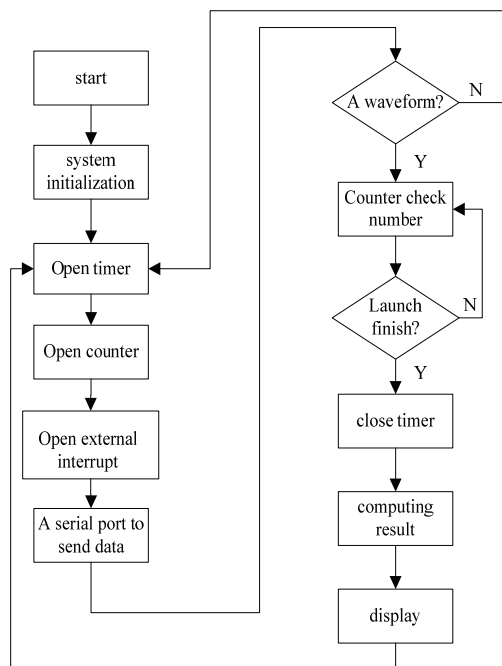


Fig. 6. The flow chart of the software.

6. Results Verification

A gas analyzer Certifier FA Plus with accuracy of up to 2 % is used for calibration. It records the actual oxygen concentration and flow rate to compare with

the calculated values obtained by the proposed system. Results are shown in Table 1 and Table 2.

Table 1. The concentration of oxygen verification table.

No.	Measurement (%)	Reference (%)	Error (%)
1.	90.0	91.2	1.30
2.	90.5	91.8	1.43
3.	91.0	92.7	1.83
4.	91.5	92.5	1.01
5.	92.0	91.2	-0.8
6.	92.5	91.1	-1.5
7.	93.0	93.6	0.61
8.	93.5	94.8	1.4
9.	94.0	92.4	-1.7
10.	94.5	94.9	0.5
11.	95.0	93.3	-1.8
12.	95.5	94.2	-1.36

Table 2. The flow of oxygen verification table.

No.	Measurement (%)	Reference (%)	Error (%)
1.	0.50	0.48	-4.0
2.	0.55	0.57	3.6
3.	0.85	0.82	-3.6
4.	1.00	1.01	1.0
5.	1.55	1.52	-2.0
6.	1.85	1.91	3.2
7.	2.00	2.00	0
8.	2.55	2.57	0.8
9.	2.85	2.80	-1.8
10	3.00	3.00	0
11.	3.55	3.43	-3.5
12.	3.85	4.98	3.6
13.	4.00	4.12	3.0
14.	4.55	4.69	3.1
15.	4.85	4.70	-3.2
16.	5.00	5.02	0.4

In order to ensure the accuracy of the sensor, regular maintenance and calibration are needed. We usually use the ultrasonic gas sensor with high precision for calibration. According to the measured data, the relative error is obtained to correct coefficients in temperature compensation. The measurement error is reduced to the lowest value. From Table 1 and Table 2, the oxygen concentration of this design is within 2 %, and oxygen flow rate error is within 5 %, which meets the measurement requirements of oxygen-making machines [10].

7. Conclusion

The ultrasonic detection system has the following advantage: the system combines test environment generating devices, data acquisition, data collection, analysis, and display in a single equipment, which reduces the measurement error and cost, improves the work efficiency, and fully satisfies the requirements on scientific research and industrial production of gas

sensor. In this system, the design of the temperature sensor for temperature compensation can improve the accuracy of measurement, which has great superiority.

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