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Realization of a multipath ultrasonic gas flowmeter based on transit-time technique

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ABSTRACT

A microcomputer-based ultrasonic gas flowmeter with transit-time method is presented. Modules of the flowmeter are designed systematically, including the acoustic path arrangement, ultrasound emission and reception module, transit-time measurement module, the software and so on. Four 200 kHz transducers forming two acoustic paths are used to send and receive ultrasound simultaneously. The synchronization of the transducers can eliminate the influence caused by the inherent switch time in simple chord flowmeter. The distribution of the acoustic paths on the mechanical apparatus follows the Tailored integration, which could reduce the inherent error by 2–3% compared with the Gaussian integration commonly used in the ultrasonic flowmeter now. This work also develops timing modules to determine the flight time of the acoustic signal. The timing mechanism is different from the traditional method. The timing circuit here adopts high capability chip TDC-GP2, with the typical resolution of 50 ps. The software of Labview is used to receive data from the circuit and calculate the gas flow value. Finally, the two paths flowmeter has been calibrated and validated on the test facilities for air flow in Shaanxi Institute of Measurement & Testing.

1. Introduction

Compared with the traditional technologies (such as turbine, orifice, or vortex meters) , transit-time method ultrasonic flowmeter, possesses many merits [1]. This flowmeter has high accuracy and reproducibility. Moreover, containing no moving parts, it does not create extra pressure drop and allows bi-direction measurement. Finally this system can be conveniently maintained on-line without interrupting the fluid transport. Thus, the ultrasonic flowmeter has been more and more widely applied in the general field of process monitoring, measurement and control [2].

The transit-time ultrasonic flowmeter uses at least one pair of transducers with centerlines inclined at an angle to the axis of pipe containing the flow. Transducers on the same acoustic path send and receive ultrasound mutually. Then the path velocity is function of the different flight time of the sound transiting (TOF) in the flow direction and in the reverse direction. The flow velocity averaged over the entire cross-section can be computed with the path velocities according to certain integration. The principle is schematically illustrated in Fig. 1. The basic equations for a multipath flowmeter are given by following expressions:

$$v_i = \frac{L_i}{2\cos\theta}\left(\frac{1}{t_{i-\mathrm{up}}} - \frac{1}{t_{i-\mathrm{down}}}\right) \tag{1}$$

$$v = \sum_{i=1}^{n} \frac{L_i w_i}{2\cos\theta}\left(\frac{1}{t_{i-\mathrm{up}}} - \frac{1}{t_{i-\mathrm{down}}}\right) \tag{2}$$

Here, subscript i represents the path number, L_i denotes the distance between the two transducers achieved from the calibration process in Section 3.1, θ is the angle between the acoustic path and the pipe axis ensued from the meter construction. $t_{i-\mathrm{up}}$ and $t_{i-\mathrm{down}}$ are the flight times corresponding to an upstream sound propagation situation and a downstream sound propagation situation, respectively. v_i is the axial velocity average along the ith flight path. w_i is the matching weighting coefficient determined by the flowmeter integration.

The volume flow rate is then given by following equation:

$$Q_v = \pi R^2 \sum_{i=1}^{n} \frac{L_i w_i}{2\cos\theta}\left(\frac{1}{t_{i-\mathrm{up}}} - \frac{1}{t_{i-\mathrm{down}}}\right) \tag{3}$$

where Q_v is the volume flow rate and R is the internal radius of the pipe.

This paper designs a dual-path ultrasonic flowmeter adopting Tailored quadrature presented by Pannell et al. [3], and proposes a new timing circuit based on a high capability chip TDC-GP2. The timing resolution is about 50 ps. In addition other hardware and software is developed. Finally this system has been calibrated and tested on the standard air flow calibrating facilities in Shaanxi Institute of Measurement & Testing. Relevant experimental results are presented.

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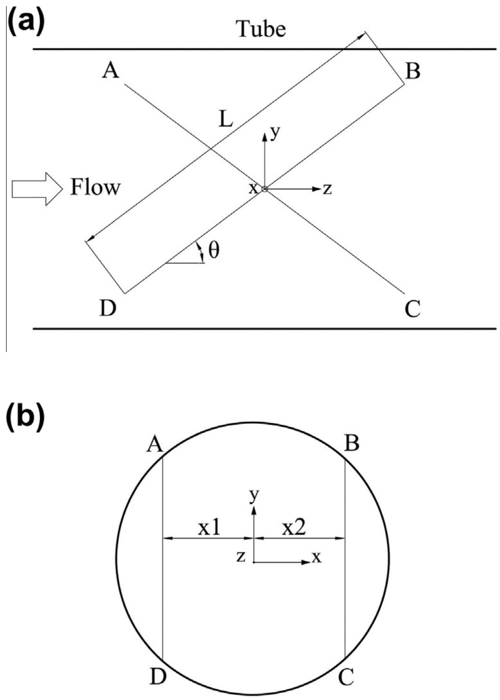

Fig. 1. Two pairs of transducers (A–D) are placed in the flowmeter body with the transducer centerlines inclined at an angle to the flow direction: (a) in the measuring plane and (b) in the projection on the tube cross section.

2. Design

The frame of ultrasonic flowmeter presented here is shown in Fig. 2. The system consists of flowmeter body, ultrasonic transducers, transmitter driving module, amplifier & filter module, comparator module, timing module, power module, control & data process module and storage & display module. Explanations of several modules are shown below.

2.1. Transducer and flowmeter body

Since the ultrasound sent and received from the transducer directly determines the flowmeter performance, ultrasonic transducer can be seen as the heart of the flowmeter. Several parameters need to be considered when selecting a suitable transducer for the flow measurement, including peak frequency, bandwidth, sensing range and maximum driving voltage. Peak frequency influences the sound attenuation and the signal to noise rate (SNR) [2]. Most flowmeter manufacturers typically choose the transducers in the frequency range from 40 kHz to 200 kHz.

The Airmar transducer (model AT200) chosen here has a peak frequency around 200 kHz. The active diameter is 16 mm, and the beam width is $14° \pm 2°$ at -3 dB. The sensing range is 0.1-3m. The allowed driving voltage cannot exceed 500 V peak to peak (V_{pp}).

The basic principles of the ultrasonic flowmeter show the integration for the transducers' placement on the meter body introduces inherent error. Most researchers had compared this error among different integration techniques [3–5]. Published quadrature tables are always based on the optimal integration of some defined form of the integrand. For example, the well-known Gaussian quadrature is based on polynomials, the N-point rule being, in fact, exact for integrating any polynomial of order $(2N-1)$ or less over finite domains [6]. As emphasized in Ref. [3], the integrand of the ultrasonic flowmeter is not inherently polynomial-like, so it is not very suitable for this Gaussian quadrature. Based on the study to fitted flow-velocity function form, in particular its asymptotic behavior at the end-points of the domain, Pannell et al. presented the Tailored integration in 1990. Fig. 3 shows the Tailored integration could reduce 2–3% of the relative error on volumetric flow compared with the Gaussian integration.

This work introduces four transducers as two parallel chord paths according to Tailored integration. The arrangement type is shown in Fig. 4. The internal diameter of the flowmeter body is 100 mm, and the angle between the acoustic path and the pipe axis is about 45°. The abscissa of the two paths is 23.9 mm and -23.9 mm. According weights are the same value 0.8695.

2.2. Ultrasound emission and reception

In most ultrasonic flowmeters, a transducer emits acoustic signal to the other transducer on the same path, and the latter transducer emits ultrasound to the former after a switch time. Time of Flight (TOF) upstream and downstream in the flow is measured at different times. Therefore, the final calculated flow value cannot reflect the real flow rate, especially the pulsating flow in the pipe. To eliminate the influence caused by the inherent switch time in simple chord flowmeter, the technique presented here allows all the transducers emit and receive the ultrasound simultaneously.

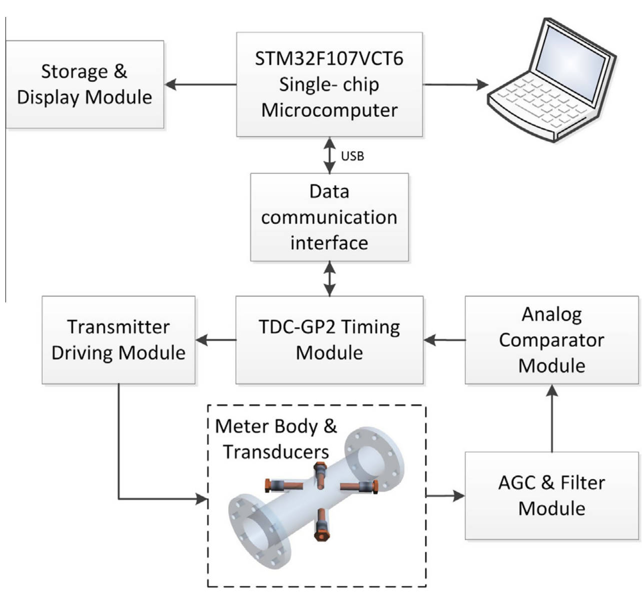

Fig. 2. Schematic diagram of the ultrasonic flowmeter system.

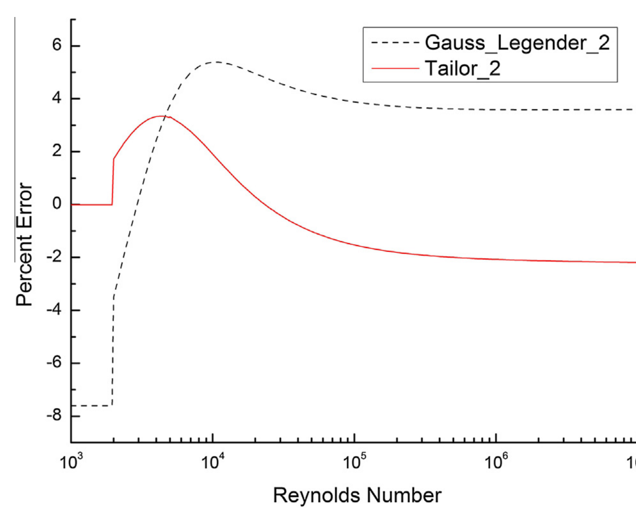

Fig. 3. Percentage error as a function of Reynolds number for 2-chord schemes.

Fig. 4. Two parallel-chord paths flowmeter body.

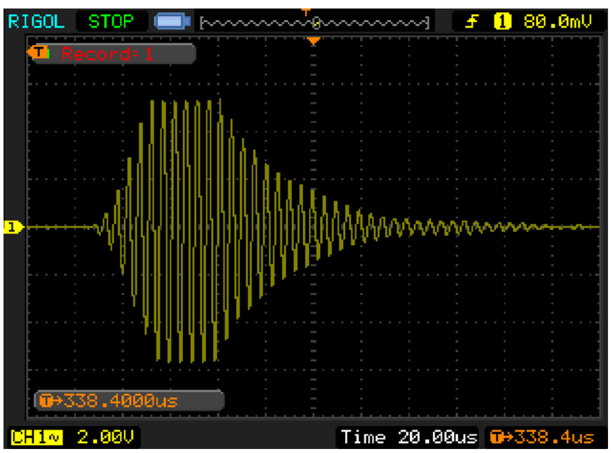

Fig. 5. Received signals after filtering and amplifying circuit.

As the measurement system start working, the chip TDC-GP2 (Acam Corporation) generates trains of transmitted signal in digital format. The 200 kHz signal is connected to the amplifier to supply an output signal. Then the transmitted signals excite all the transducers simultaneously. After few microseconds, four analogue switches connect the transducers to four identical receiving electronic circuits. The receiving circuits use band pass filter and automatic gain controlled (AGC) technique to improve the signal-to-noise ratio (SNR) and reduce error from attenuation effects. The associate filter has a band pass from 180 kHz to 220 kHz and a gain of around 24 dB. Fig. 5 shows the received signal 200 kHz ± 5 V. An analog comparator circuit is designed to transform the received signal from a sinusoid wave to a square wave, which is also known as a transistor–transistor logic (TTL) signal. The TDC-GP2 samples the signal for analysis at last.

2.3. TDC-GP2 timing module

Accurate determination of time-of-flight (TOF) is the key to the ultrasonic flowmeter. Different methods have been developed into the flowmeter design to improve the TOF measurement resolution, including detection threshold, various digital signal-processing algorithms, and envelope self-interference analysis [2,7–10]. This article finally chooses the double thresholding technique based on the timing chip TDC-GP2, which is different from the methods in existence.

The double thresholding detection utilizes a window to slide through the received signal one sample at a time. The sample exceeding the preset threshold level is numbered at each window position. If the number exceeds the second threshold number *m*, the received signal can be useful to estimate the TOF effectively which can eliminate the influence of the noise spike and improve the system robustness.

Nowadays most transit-time ultrasonic flowmeters design the timing module basing on the high speed counter of programmable logical controller (PLC) [7,9,11]. The idea of PLC method is to use a low frequency clock signal to achieve high-speed counting. The timing module presented in this work is different in the mechanism. As shown in Fig. 6, digital TDC-GP2 in the modules uses internal propagation delays of signals through inner gates to measure time intervals with very high precision as the propagation time between two gates is determinate. The measuring unit in the chip is actuated by a Start signal and stopped by a Stop signal. Every chip has two Stop channels referring to one start channel, therefore one TDC-GP2 is just enough for the TOF measurement of two transducers on the same path. This method makes the implementation of the timing circuits become easier than the PLC method.

In Fig. 7, block diagram of the timing module is schematically illustrated while another TDC-GP2 and two transducers are not displayed. A 3.2 MHz oscillator circuit is adopted here as the chip needs a 2–8 MHz high-speed clock for calibration. Another 32.768 kHz reference is used for the start-up control of the high-speed clock and the clock calibration. After the microcomputer (STM32F107VCT6) sends out the measure instruction, digital transmitting signals (S_T) are generated by the fire pulse generator in the TDC-GP2 to drive two transducers. Meanwhile the chip starts the internal timing unit to measure the flight time. Timing process is stopped when the received signal (S_R) from the analog circuits fulfills the double thresholding requirement. Based on the position of the ring oscillator and the coarse counter the time interval between START and STOP is calculated with a 20-Bit measurement range. The typical root-mean-square timing resolution is 50 ps.

2.4. Software block of the system

The software block diagram of the ultrasonic flowmeter system is shown in Fig. 8. After system initialization, the amplitude modulated ultrasonic waves generated by the TDC-GP2s are sent to drive the transducers. The STM32F107VCT6 starts the timing units simultaneously. After a certain delay time, the receive circuits are open to get the ultrasound from the transducers on the paths. The microcomputer will stop the timing process when the received signals satisfying the condition of double thresholding technique. Then the STM32F107VCT6 uploads the TOF data from the TDC-GP2s to the personal computer (PC) through USB communication.

Control software on PC was written on LabVIEW 8.6 (National Instruments, USA). This software can store and display the TOF data of the two acoustic paths in the meantime. Then the time data processed by the software using median filtering algorithm is converted to velocities along the acoustic path. In addition, the software is able to calculate the volume flow using all the path velocities according to the selected numerical integration. Software for the STM32F107VCT6 was written in C language (IAR, USA).

3. Experimental results

3.1. System calibration

As can be seen from Eq. (3), accurate flow measurement requires good precision for acoustic path length, the numerical

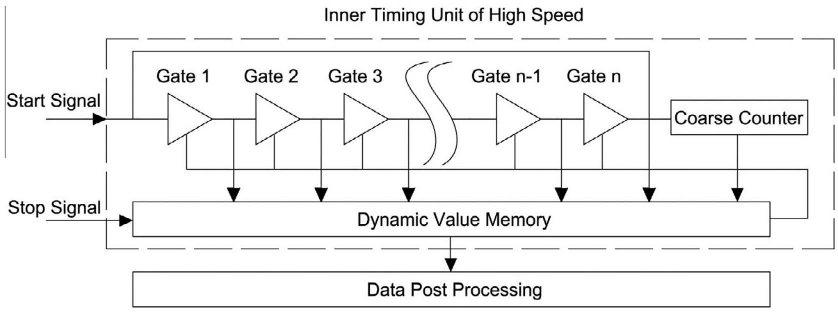

Fig. 6. The mechanism diagram of TDC-GP2 in the timing modules.

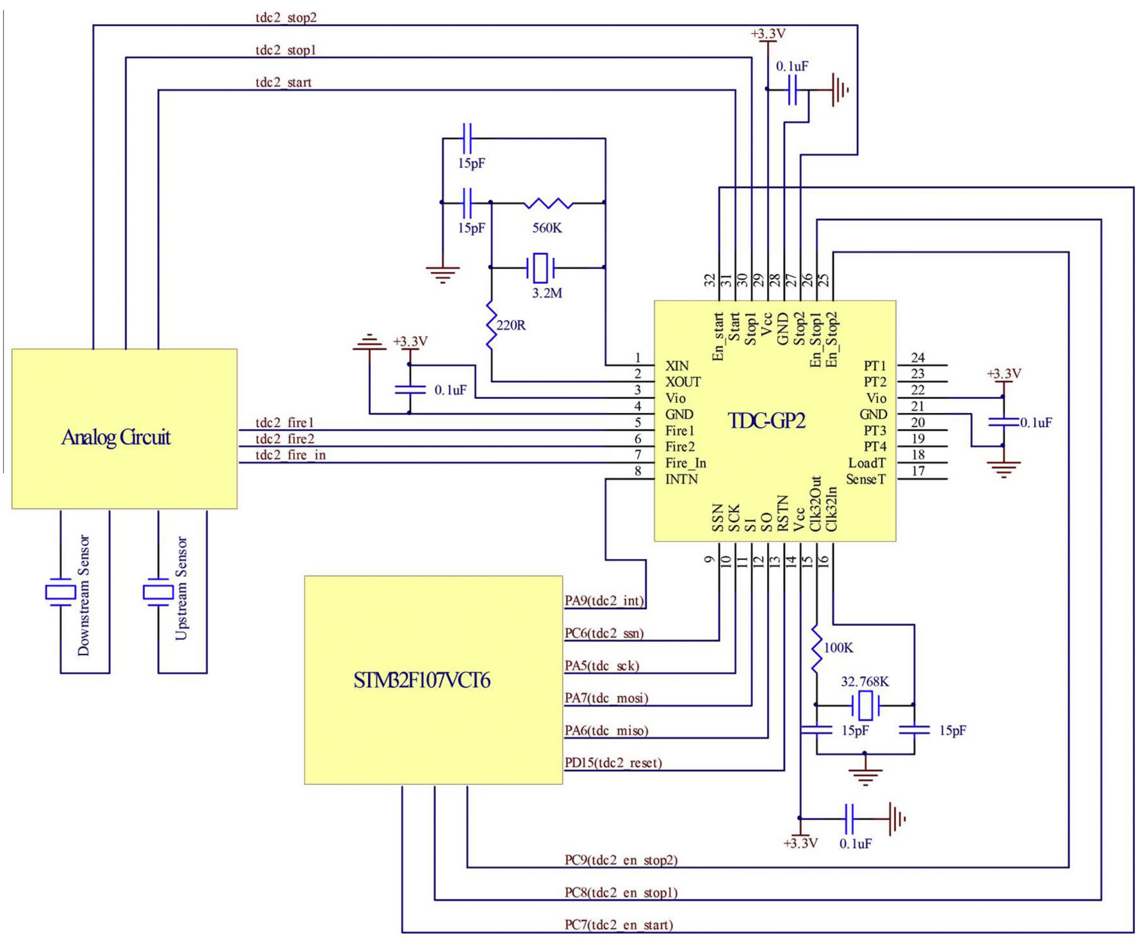

Fig. 7. Block diagram of the TDC-GP2 timing module.

integration, the angle between the acoustic path and the pipe axis, and accurate measurement of propagation time [12]. Considering the deviation caused by the manufacturing process and installation, volume flow can be corrected by following equations:

$$Q_v = K \times \pi R^2 \sum_{i=1}^{n} \frac{L_i w_i}{2\cos\theta}\left(\frac{1}{t_{i-\mathrm{up}}} - \frac{1}{t_{i-\mathrm{down}}}\right) + dev \tag{4}$$

where K is the correction factor related to the angle deviation and integration weight, *dev* is the system deviation. K and *dev* can be determined by the calibration experiments under different flow rates.

The distance L between the two transducers is the only parameter that is not determined. By calculating the sound velocity C theoretically in the air condition and measuring the flight time under the condition the flow rate is zero, the distance can be calculated by following equation:

$$\begin{aligned} L_i &= C\left(\frac{t_{i-\mathrm{up}}^{(0)} + t_{i-\mathrm{down}}^{(0)}}{2}\right) \\ C &= 331.45 \times \sqrt{\frac{T}{273.15}} \end{aligned} \tag{5}$$

where superscript is the flow rate value and T is the absolute temperature (in Kelvins) of the dry air. Table 1 gives out the values of the relevant parameters in the distance calibration as the $t_{i-\mathrm{up}}^{(0)}$ and $t_{i-\mathrm{down}}^{(0)}$ are averaged for 100 measured values.

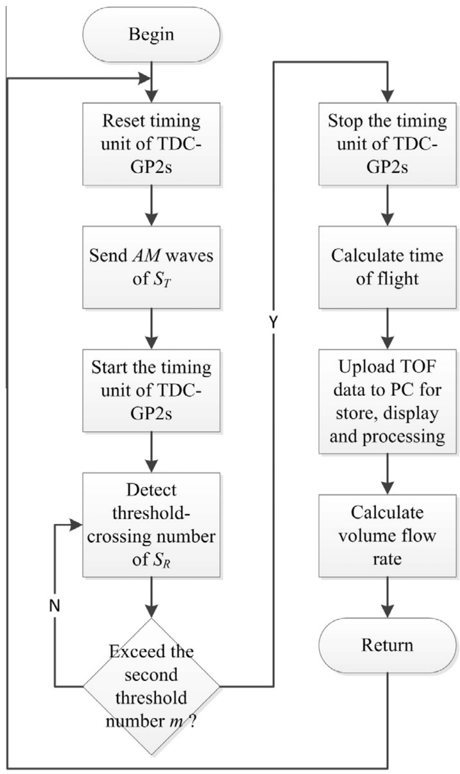

Fig. 8. The software block diagram of the ultrasonic flowmeter.

Table 1
Relevant parameter values in the distance calibration.

ith path	$t^{(0)}_{i-\mathrm{up}}$ (ns)	$t^{(0)}_{i-\mathrm{down}}$ (ns)	T (K)	C (m/s)	L_i (m)
1	316239.13	316239.42	293.15	343.37	0.109
2	312801.44	312801.82	293.15	343.37	0.107

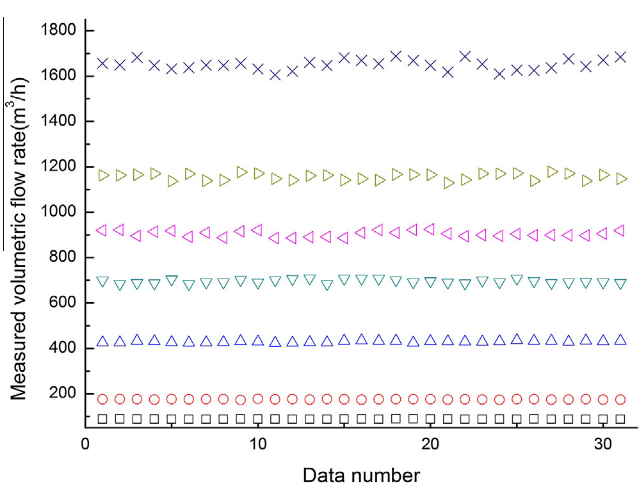

Fig. 9. Measured volumetric flow values in the calibration experiments.

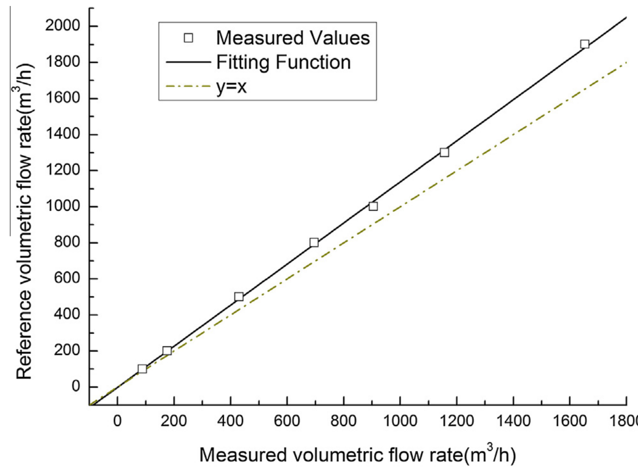

Fig. 10. The averaged volumetric flow rates and the linear fitting results.

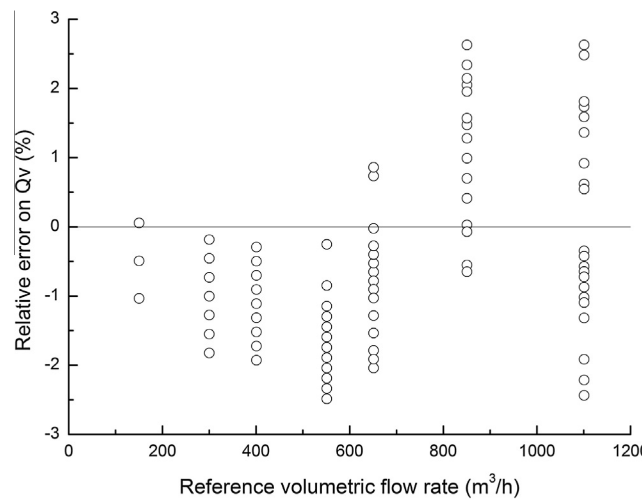

Fig. 11. Relative errors on volumetric flow vs reference flow rate in the validation experiments.

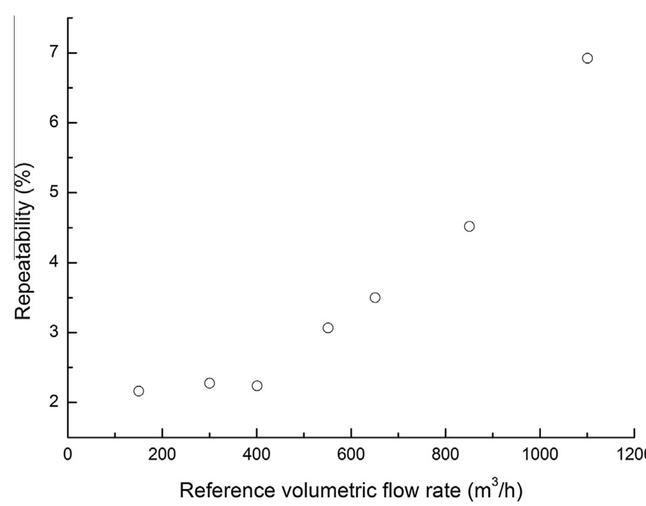

Fig. 12. Measurement repeatability of the flowmeter.

3.2. Calibration and test on baseline configuration

This work has conducted a series of calibration experiments of the developed ultrasonic flowmeter under the ideal flow condition on the test facilities for air flow in Shaanxi Institute of Measurement & Testing. The ultrasonic flowmeter was installed between two straight pipes. The upstream pipe is 3000 mm long and the downstream pipe is 2000 mm long. The reference volumetric flow rate is provided by a sonic nozzle flowmeter with the accuracy of 0.1%.

Fig. 9 presents the experimental results of the flow rate without calibration in the flow range from 100 to 1900 m^3/h at 1 bar. Linear fitting for the averaged flow data to the measured–actual flow curve was carried out. The fitting results are shown in Fig. 10. K and dev are derived to be 1.13923 and -1.34276, the standard errors of which are 0.031 and 11.98. The measured flux is smaller than the standard value, which can be explained by the manufacturing error and the existence of delay time.

Finally, the validation experiments were carried out under different flow rates and 21 measured values at each reference flow rate were got. Fig. 11 shows the experimental results. The flowmeter supplies a relative error from -3% to 3% in the experimental flow range. The stability of the measurements was worked out according to the standard deviation formula computed by several measurements which are presented in Fig. 12. The ultrasonic meter supplies stability from 2.2% to 6.9%. As the flow increases, the repeatability of the flowmeter gets worse because of the increase in turbulence generated upstream of the standard sonic nozzle location and decrease of the SNR.

4. Conclusions

This approach lists several function modules' design of an ultrasonic flow meter based on TOF technique. Using ultrasonic wave to measure the gas flow rate, the flowmeter will encounter some system errors, which are determined by the numerical integration and accurate TOF measurement. In this article, we designed the flowmeter body and placed the transducers according to the Tailored integration to decrease the inherent error. The error of the TOF measurement is mainly due to the amplitude attenuation and the inertia delay of the received signals. This approach applied the automatic gain controlled technique to reduce the influence of the inertia delay. In addition a novel timing circuit with resolution of 50 ps used the chip TDC-GP2 was presented. Finally, the system was calibrated and validated with tests carried out under the ideal flow condition on the test facilities for air flow in Shaanxi Institute of Measurement & Testing. The results obtained at different flow rates indicate the proposed flowmeter can achieve real-time and accurate flow rate detection.

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