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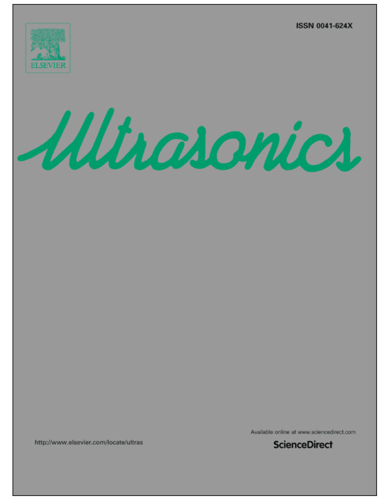

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Multipath ultrasonic gas flow-meter based on multiple reference waves

Hongliang Zhou[1]*,Tao Ji[1], Ruichen Wang[2], Xiaocheng Ge[2], Xiaoyu Tang[1] and Shizhen Tang[1]

[1] State Key Laboratory of Industrial Control Technology, College of Control Science and Engineering, Zhejiang University, Hangzhou, 310027, China

[2] School of Computing and Engineering, University of Huddersfield, UK

*zjuzhl@zju.edu.cn

Abstract—Several technologies can be used in ultrasonic gas flow-meters, such as transit-time, Doppler, cross-correlation and etc. In applications, the approach based on measuring transit-time has demonstrated its advantages and become more popular. Among those techniques which can be applied to determine time-of-flight (TOF) of ultrasonic waves, including threshold detection, cross correlation algorithm and other digital signal processing algorithms, cross correlation algorithm has more advantages when the received ultrasonic signal is severely disturbed by the noise. However, the reference wave for cross correlation computation has great influence on the precise measurement of TOF. In the applications of the multipath flow-meters, selection of the reference wave becomes even more complicated. Based on the analysis of the impact factors that will introduce noise and waveform distortion of ultrasonic waves, an averaging method is proposed to determine the reference wave in this paper. In the multipath ultrasonic gas flow-meter, the analysis of each path of ultrasound needs its own reference wave. In case study, a six-path ultrasonic gas flow-meter has been designed and tested with air flow through the pipeline. The results demonstrate that the flow rate accuracy and the repeatability of the TOF are significantly improved by using averaging reference wave, compared with that using random reference wave.

Keywords: Transit-time method; Cross correlation; Reference wave; Averaging method; Multipath ultrasonic flow-meter

1. Introduction

The measurement of gas flow rate in large-diameter gas pipelines has gained even more demands with the natural gas's wide use in china. The ultrasonic flow-meter (UFM) has many advantages over the traditional flow-meter in the field applications. Compared with other flow measurement techniques, the UFM does not contain any moving parts and will not cause the loss of pressure. It is easy to install and maintain. It can be applied in large-diameter pipelines with a rather high precision. Furthermore, the UFM allows bi-directional flow measurement [1].

UFM can be based on different principles, among which the transit-time method is one of the most widely adopted due to its numerous advantages [2-4]. In the transit-time UFM, at least one pair of transducers is applied with their centerlines inclined to the axis of gas pipeline at a designed angle. Transducers on the same acoustic path send and receive ultrasound alternately. Then the path velocity can be calculated by time of flight (TOF) of ultrasonic waves propagating in flow direction and reverse direction. The mean flow velocity over cross-section can be computed with path velocity according to certain integration algorithm. The upstream and downstream TOF can be calculated by following equations:

$$t_{up} = \frac{L}{c - v\cos\theta} \quad (1)$$

$$t_{down} = \frac{L}{c + v\cos\theta} \quad (2)$$

Where t_{up} and t_{down} are the TOF in upstream direction and downstream direction, respectively, L is the path length between the two transducers, v is the averaging flow velocity along the acoustic path, θ is the angle between acoustic path and the pipeline axis, and c is the speed of ultrasound in the profile, which can be calculated with the given temperature [5, 6], as shown in Eq. (3).

$$c = 331.45 \times \sqrt{\frac{T}{273.15}} \quad (3)$$

Where T is the thermodynamics temperature of the gas in the pipeline. The differential TOF of the acoustic path can be calculated by Eq. (4):

$$\Delta t = t_{up} - t_{down} = \frac{2Lv\cos\theta}{c^2 - v^2\cos^2\theta} \quad (4)$$

Since c^2 is much bigger than $v^2\cos^2\theta$ in normal atmospheric conditions (e.g. in natural gas or air), eq. (4) can be simplified as:

$$v \approx \frac{c^2 \Delta t}{2L\cos\theta} \quad (5)$$

Then the flow rate measured by a flow-meter with multiple acoustic paths can be obtained by applying following equation:

$$v_{\mathrm{m}} = \sum_{i=1}^{n} \frac{\omega_i c^2 \Delta t_i}{2L_i \cos\theta_i} \quad (6)$$

Where n is the number of acoustic paths, i represents the i-th acoustic path, ω_i is the coefficient of the i-th acoustic path determined by the integration algorithm, Δt_i is the differential TOF of the i-th acoustic path, and L_i is the path length of the i-th acoustic path, θ_i is the angle between acoustic path and the pipeline axis of the i-th acoustic path.

From Eq. (6), it can be seen that the accurate measurement of TOF is critical to the accuracy of UFM. Many technologies have been developed to obtain TOF, such as the threshold detection [5, 7], cross correlation [8], ZCT and TSS signal processing algorithms [9], envelope self-interference analysis [10] and etc. Due to the attenuation of ultrasonic wave caused by acoustic and thermodynamic properties of gas, the threshold detection method, which has one or more threshold values, cannot work well. Cross correlation method has the merit of suppressing the disturbance of the noise and has been widely applied in the determination of TOF [11]. To compute the TOF, the signal received needs to be cross correlated with the emitted signal, which can be designated as reference wave. So the reference wave plays a key role in the measurement of TOF. Few literatures have involved in discussing how to select reference wave. The common solution is to take the received signal at static state as the reference wave. [8] provided 'echo method' to determine the reference wave. However, it needs to capture a reflecting signal that is emitted and received by the same transducer and the signal is very weak.

In this paper, the attenuation of ultrasonic wave propagating in gas is analyzed. And a method to determine the reference wave by averaging multiple ultrasonic waves is proposed. It provides the multipath flow-meter a practical way to select the optimal reference wave. The method was tested and the experiment results are presented and analyzed.

2. Attenuation of ultrasonic wave and waveform distortion

As discussed above, the calculation of TOF is the key point to the flow rate measurement in the UFM. The quality of emitted and received ultrasonic signal has great impact on the calculation of TOF. Due to the acoustic and thermodynamic properties of the fluid, the ultrasonic wave will be seriously attenuated when travelling through the gas. Flow viscosity, heat exchange and relaxation phenomena are the potential reasons for attenuation and waveform distortion of the ultrasonic wave in gas. There also exist many factors which will affect the measurement of the flow rate. The noise will increase with the flow velocity and the attenuation will be much more severe when the flow velocity is high. Furthermore, each acoustic path in the flow-meter has one pair of transducers facing each other. One is located in the downstream of the UFM and the other is located in the upstream of the UFM. Existing researches have indicated that the ultrasonic signal received by downstream transducer contains more noise than that received by the upstream transducer.

2.1. Difference between the waveform received by upstream and downstream transducer

Some experiments were carried out to investigate the ultrasonic waveforms from the receiver transducer. And experiment results reveal that the ultrasonic waves are different when emitted by the same type of transducer.

In these experiments, two transducers of the same type with the center frequency of 200 kHz are deployed as upstream transducer and downstream transducer respectively. The experiment was done when the flow velocity is zero. The reference wave used for cross correlation is received by the downstream transducer. The results are shown in Table 1. S1, S2 and S3 are the ultrasonic waves received by the downstream transducer. S4, S5 and S6 are the ultrasonic waves received by the upstream transducer. The experiment results illustrate that ultrasonic waves received by different transducers of same type differ greatly while the ultrasonic waves received by the same transducer have more similarity. In the evaluation of differential TOF, the difference of the waveforms between upstream transducer and downstream transducer in the same acoustic path must be taken into account.

2.2. Impact of gas velocity and propagation direction on waveform distortion

Experiments were done to investigate the effect of flow velocity and propagation direction on the waveform distortion. Ultrasonic waves received by upstream transducer and downstream transducer at different gas velocity are acquired and analyzed. In this experiment, the exciting signal is five cycles of square-wave burst with peak-to-peak voltage of 24V. The results are shown in Fig 1.

Table 1 The cross correlation result

	S1	S2	S3	S4	S5	S6
Correlation coefficient	0.9449	0.928	0.9816	0.7849	0.5614	0.5564

Table 2 The cross correlation result

	S1	S2	S3	S4	S5	S6
Correlation coefficient	0.892	0.969	0.971	0.977	0.863	0.888

Fig.1a shows the typical waveform of an ultrasonic wave acquired from upstream transducer at zero velocity. Fig.1c and Fig.1e show the waveforms of the ultrasonic wave received by the downstream transducer and upstream transducer respectively when the gas velocity is 9.12m/s. And Fig 1b, 1d, and 1f show the spectrum distributions of corresponding received waves. The experiment results show that the principle component of the received ultrasonic waves is 199.92k Hz, which is nearly equal to the center frequency of the transducer. It can also be seen that the received ultrasonic waves contain many high frequency noises, which are caused by the propagation of ultrasonic waves and thermodynamic property of the gas in the pipeline.

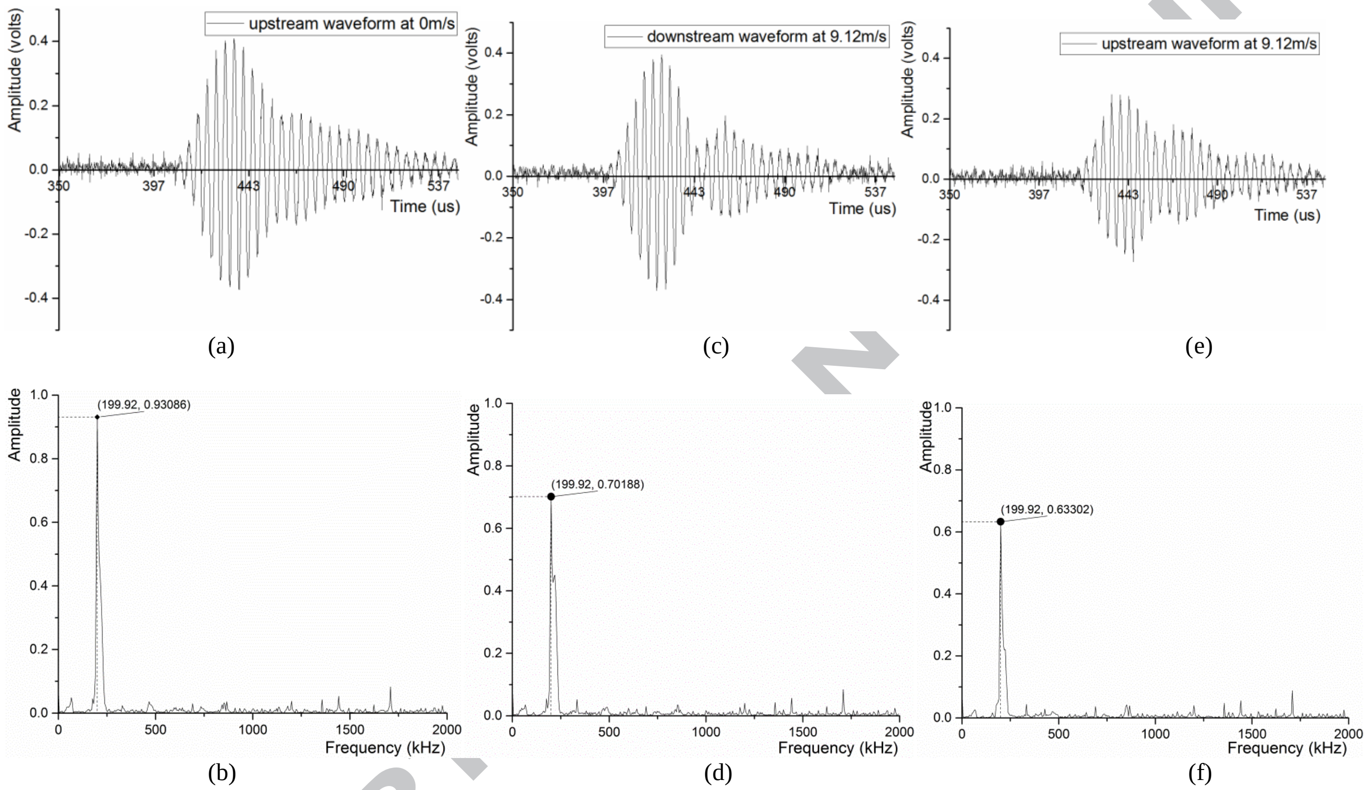

Fig.1 Waveforms received by transducers and their spectrum distribution

Besides, it can be seen that the noise increases with the gas velocity. The reasons for this phenomenon are complex. The flow field becomes complicated and more vortexes will be produced with the increase of gas velocity, which will affect the propagation of the ultrasonic wave in the pipeline. Simultaneously, the mechanical vibration will be more severe when the flow velocity increases and this will bring more noise. In the experiment, the amplitude of received signal at 199.92 kHz is about 0.931 at zero velocity, while the amplitude of that is about 0.702 at upstream transducer and 0.633 at downstream transducer when the gas velocity is 9.12m/s. The result indicates that the gas velocity has impact on the propagation of ultrasonic wave, and the upstream transducer receives more noises than the downstream transducer.

3. TOF measurement based on averaging method

Ultrasonic gas flow-meter based on transit time method requires accurate TOF measurement. And cross correlation method has the merit of suppressing the disturbance of noise and has been widely used in UFM. The cross correlation function of signal $x(t)$ and $y(t)$ can be given as Eq. (7):

$$R_{xy}(t)=\int_{-\infty}^{+\infty} x(\tau)y(\tau-t)d\tau = x(t)*y(t) \qquad (7)$$

If $y(t)$ is a signal shifted of τ from signal $x(t)$, that means $y(t)=x(t+\tau)$, the cross correlation result will reach its maximum for $t=-\tau$. Then the delay between two similar signals can be determined by the t value for which the cross correlation result is maximum.

In discretized form, we can re-write Eq. (7) as:

$$R_{xy}(m)=\lim_{N\to\infty}\frac{1}{N}\sum_{k=1}^{N} x(k)y(k-m) \qquad (8)$$

In order to calculate the propagation time t_{i-up} and t_{i-down}, the received ultrasonic wave needs to be cross correlated with a reference wave. Results in Table 1 have shown that ultrasonic wave received by upstream transducer is obviously different from that received by downstream transducer. Due to the importance of the reference wave, a practical method to determine the reference wave is proposed in this paper. The method established the reference wave by evaluating the average of ultrasonic signals acquired by both upstream and downstream transducer at zero gas velocity. The number of ultrasonic waves acquired from upstream transducer and downstream transducer is the same. The basic function about average method is given in Eq. (9):

$$S_r = \frac{\sum_{i=1}^{n}\left(S_{up}^{i} + S_{down}^{i}\right)}{2n} \qquad (9)$$

Where S_r is the reference wave; S_{up}^{i} and S_{down}^{i} are the ultrasonic waves acquired from the upstream transducer and downstream transducer, respectively; n is the number of ultrasonic waves captured from upstream transducer or downstream transducer.

Fig.2.a shows the average waveform determined by Eq. (9). Four upstream waveforms and four downstream waveforms sampled at zero flow velocity are utilized to calculate the average waveform. And Fig.2.b shows the spectrum distribution of the average waveform. The results demonstrate that the average waveform also has a peak frequency at 199.92 kHz, which means the average waveform can be applied as the reference wave.

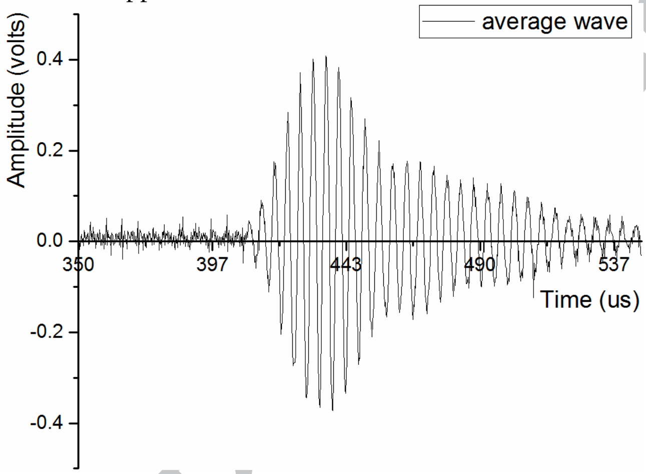

Fig.2.a Average waveform

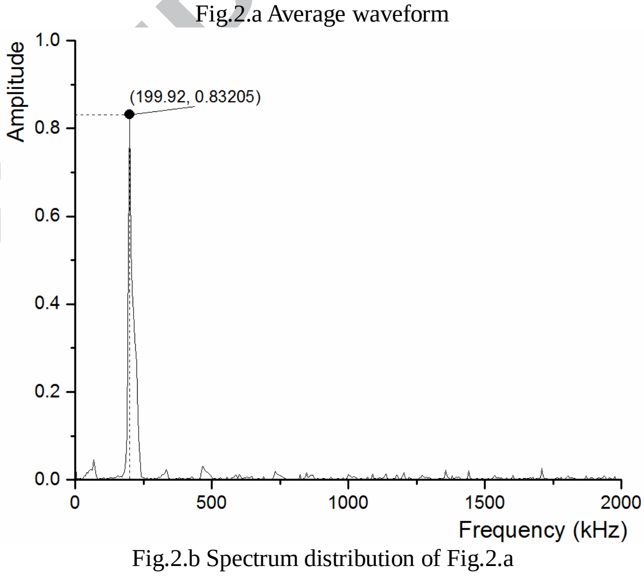

Fig.2.b Spectrum distribution of Fig.2.a

The results of cross correlation with reference wave based on averaging method are listed in Table 2. It can be seen that the cross-correlation coefficient has been greatly improved by using the averaging reference wave. It is reasonable that the averaging reference wave has more similarity with the waveform emitted by upstream and downstream transducer because the averaging reference wave contains both the waveform of upstream wave and downstream wave. Furthermore, averaging method can reduce the impact of white noise existed in the ultrasonic wave.

4. Multipath fusion in ultrasonic gas flow-meter

4.1. Integration algorithm of multipath UFM

Although the ultrasonic gas flow-meter has many advantages over the traditional flow-meter (e.g. turbine, vortex meters), single path UFM can’t meet the demand in terms of accuracy. Because of inhomogeneous gas velocity distribution in the pipeline [12], multipath ultrasonic gas flow-meter has been proposed [13]. Somehow, a multipath UFM is an extension of the single-path UFM. It uses more than one pair of transducer in the tube. Each acoustic path can be seen as a single path flow-meter which can evaluate the average velocity on the acoustic path. Then the velocities of multiple paths can be considered as input factors and be transformed into the average cross-section velocity using integration algorithm.

To improve the precision of the multipath UFM, many methods are proposed to optimize the position of transducer and the integral coefficients of the multipath flowmeter. These methods can improve the precision of flow measurement and can be realized at a low cost. The Gaussian quadrature method, which contains Gauss–Legendre quadrature, Gauss-Jacobi method and Optimized Weighted Integration for Circular Sections (OWICS) methods, are commonly utilized [14, 15]. However, each method has its own defects, for instance, the position of the multipath UFM and the integral factors should be determined in advance. Although the information can be easily found in [15], they are all based on an assumption that the flow field is ideal. In practice, the length of long-straight pipeline in the upstream or downstream of the multipath UFM may be restricted by the mounting location or space, which may cause the flow field in the section of measurement not fully developed or even distorted [16].

There is no perfect model that can be applied to all flow fields. Models based on artificial neural network (ANN) can eliminate the effect of the flow field and the position of the acoustic path and improve the flow measurement accuracy [17, 18]. The ANN based model works by building the mapping relationship between the velocity of each path and the average cross-section velocity and it can be trained by the velocity data in advance. Researches have proved that linear ANN model can adjust the integral factors dynamically for the dual path UFM in the complex flow field and improve the measurement precision of the UFM [17]. However, the improvement is limited due to the generalization ability of linear ANN. Genetic algorithm (GA) was used to replace the trial method to determine ANN architecture and improve the measurement accuracy of UFM [19].

4.2. The reference waves of multipath UFM

The aforementioned integration methods can reduce the error of the UFM and improve the measurement accuracy of flow velocity. The key point is the mapping relationship between the acoustic path velocity and the average cross-section velocity. The accurate measurement of the acoustic path velocity is a pre-condition of the average cross-section velocity. And in cross correlation method, the reference wave plays a critical role for measurement of the acoustic path velocity. The multipath UFM utilizes multiple acoustic paths, and the selection of reference waves of multipath UFM is more complicated than that of the single path UFM.

In this paper, each pair of the transducer will be provided a reference wave separately, which is determined by averaging method, to calculate the differential TOF of each acoustic path. The differential TOF of dividual acoustic path will be utilized for multipath fusion to evaluate the averaging cross-section velocity. The result shows that the TOF of each acoustic path determined by this method is more accurate and stable than that using a given reference wave or a single averaging reference wave. And the precision of the gas velocity is improved correspondingly.

5. Experiment system

The UFM system utilized in this paper is shown in Fig.3. It consists of Microcontroller Unit (MSP430F149), Time-to-Digital Converter (TDC-GP21), an amplifying circuit of driving module, switching circuit, flow-meter body, ultrasonic signal conditioning circuit, biasing circuit, Digital Signal Processor (DSP, TMS320F28335) and a host computer.

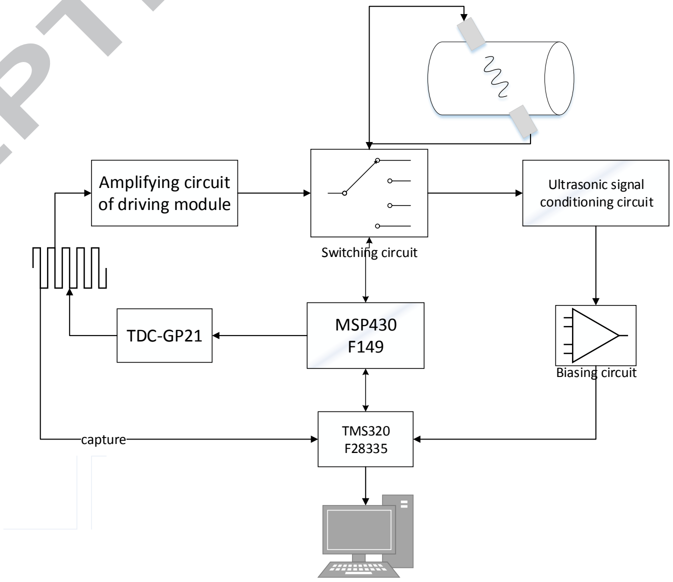

Fig.3 Multipath UFM system

The Microcontroller Unit based on MSP430f149 is used to control the switch of the upstream and downstream transducer and the acoustic path of the multipath UFM. Each transducer designed here works separately, which means that a transducer emits the ultrasonic wave at one time and the other transducer emit the ultrasonic wave after a switching time. And at one time, there will be only one transducer working as emitting transducer and another one working as a receiving transducer. This will guarantee that there exists only one ultrasonic wave in the pipeline at one time to avoid the interference between ultrasonic waves emitted from different transducers. The transducers, operating at a center frequency of 200 kHz, are driven by TDC-GP21, which emits five square wave pulses. The emitted square wave pulse is amplified to enhance the driving capacity. The experiment system uses cross correlation method to calculate the upstream and downstream transit time. To improve the precision and efficiency of the cross correlation algorithm, a DSP is used to complete the data processing. The

DSP receives the ultrasonic signal, which has been amplified and filtered by signal conditioning circuit, and completes the A/D conversion. Then cross correlation algorithm is adopted to calculate the TOF using the averaging reference wave. Finally the cross-section flow velocity can be obtained using the multipath integration algorithm.

Shown in Fig.4, the experiment system consists of experimental pipeline, centrifugal blower, gas conditioner, multipath UFM and a reference standard flow-meter. The diameter of the pipeline is 100mm. The tested flow is air. The centrifugal blower is used to provide variable flow rate fluid. The gas conditioner, located in the upstream of UFM, is used to maintain the airflow stable. The position of the six paths in UFM prototype is determined by Gauss-Legendre principle, as shown in Fig.5. A gas roots flow-meter with the accuracy of 1% is used as the reference standard flow-meter.

Fig.4. Experimental system

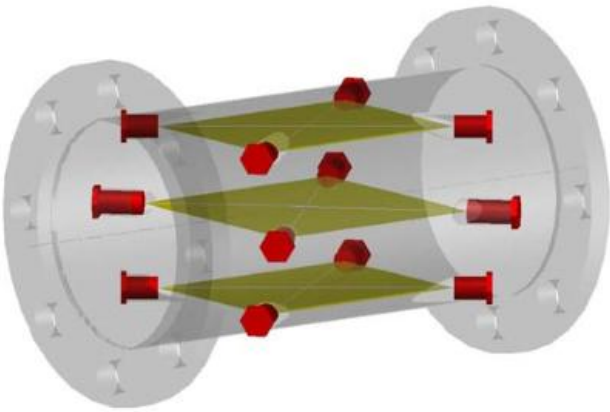

Fig.5 Flow-meter body with six paths based on Gauss-Legendre principle

6. Analysis of experiment results

Fig.6 shows the relationship between the upstream and downstream TOF and volumetric flow rate. The result indicates that TOF has approximately linear relationship with the flow rate when the flow field is fully developed. This is consistent with Eq. (2). Besides, the linearity of path 1 is better than path 2 and path 3. The sensitivity of path 1 is higher than other paths. Path 2 and path3 is nearly equal. The reason is that the volumetric flow rate on the diametrical path is bigger than that on the chordal path. Furthermore, when the UFM works in the low velocity, especially when the flow rate is less than 0.6m/s, the linear relationship is worsen. The reason for this could be that the flow field is not fully developed and the distribution of the flow velocity is very inhomogeneous on the acoustic path, which will finally influence the measurement result.

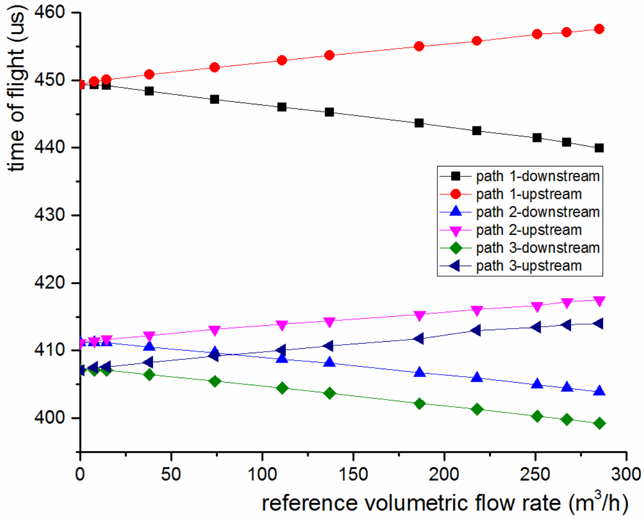

Fig.6. Relationship between TOF and the volumetric flow rate

Fig.7 shows the comparison of standard deviation of TOF based on random reference wave and averaging reference wave. And Fig.8 shows the relative error of the measured flow rate in single path UFM. Overall it can be seen that the averaging reference wave method can improve the computing accuracy of TOF in the UFM, which primarily because the averaging method can reduce the impact of the white noise. Meanwhile, the averaging reference wave is the compromise of upstream wave and downstream wave. As a result, the transit time calculation accuracy of upstream and downstream can be improved by cross correlation.

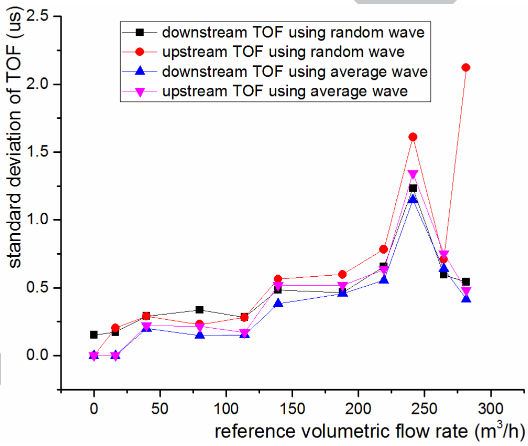

Fig.7. The standard deviation of the TOF

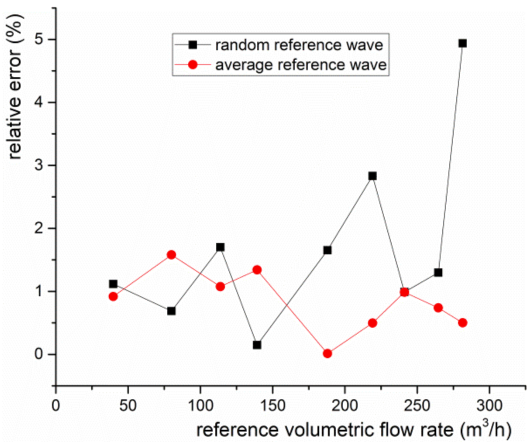

Fig.8. Relative error of measured flow rate

Fig.9 to Fig.11 shows the standard deviation of TOF in multipath UFM. The computation of TOF is based on reference wave selected by different ways. In these figures, path 1 represents the diametrical path. Path 2 and path 3 are the chordal paths. In Fig.9, all acoustic paths use the same reference wave, a randomly selected waveform emitted by the upstream transducer of path 1. The result indicates that the accuracy of path 1 is rather acceptable while the errors of the other two paths are much bigger. In Fig.10, all acoustic paths use the same reference wave, an averaging waveform of path 1. The result is similar. In Fig.11, each path uses its own reference wave which is determined by using averaging method. Compared with the results in Fig.9 and Fig.10, the repeatability is greatly improved. It can also be seen that the standard deviation of upstream TOF is bigger than that of downstream TOF. This can be explained that upstream waveform contains much more noise than the downstream waveform. Fig.12 show the relative error of volumetric flow rate based on different reference waves with the integration algorithm of Gauss–Legendre quadrature method. The accuracy can be further improved by multiple averaging reference waves, since the characteristic of transducers in different acoustic path differs a lot with each other.

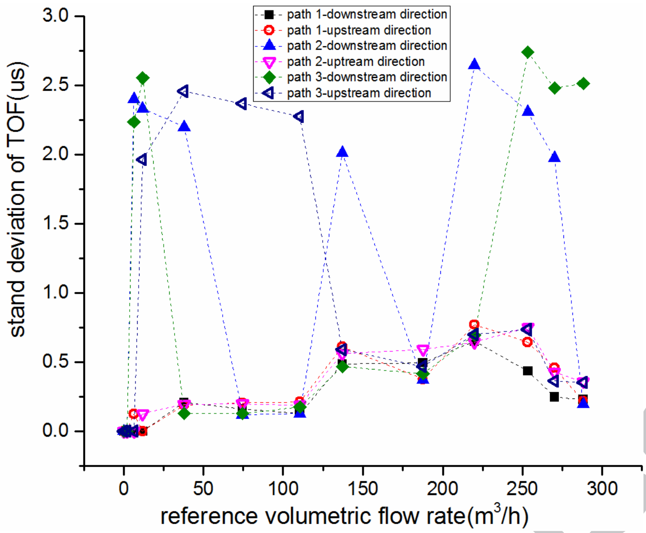

Fig.9. Standard deviation of TOF in multipath UFM based on one random reference wave

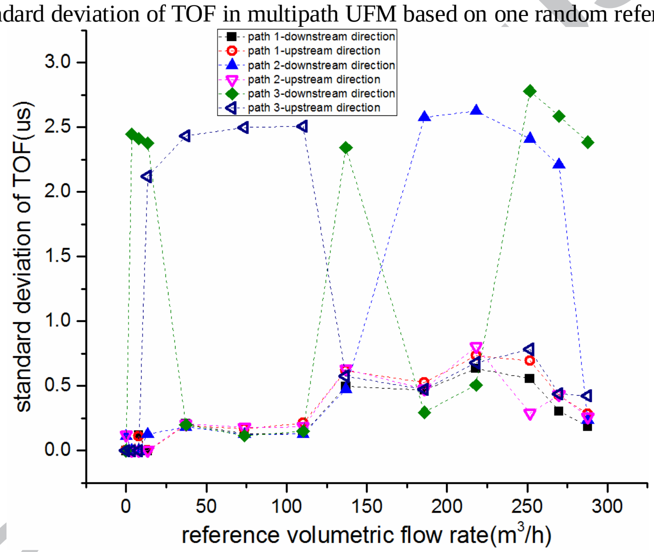

Fig.10. Standard deviation of TOF in multipath UFM based on one averaging reference wave

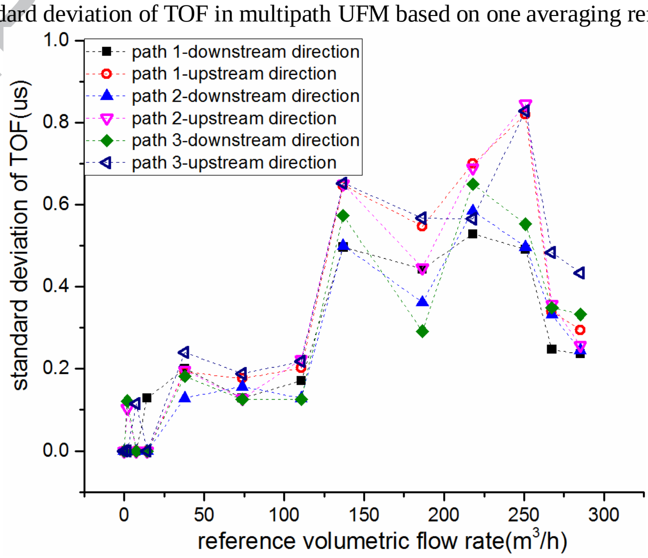

Fig.11. Standard deviation of TOF in multipath UFM based on multiple averaging reference wave

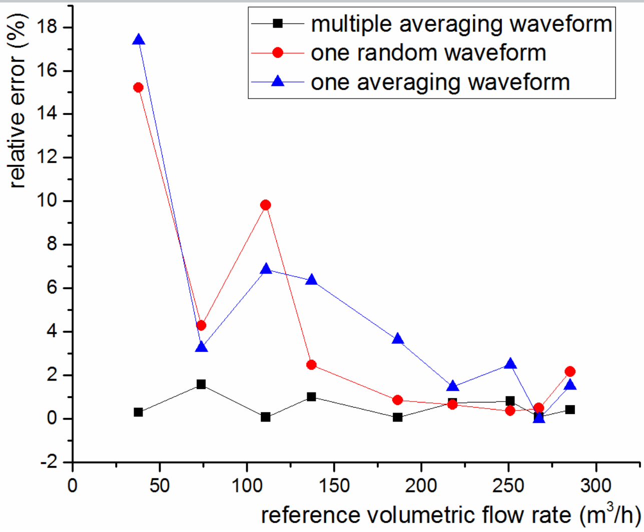

Fig.12. Relative error of flow rate based on multiple averaging waveforms, one random waveform and one averaging waveform

7 . Conclusion

In this paper we explored the noise at the transducers and make a further investigation on the difference between waveforms received by upstream and downstream transducer. Based on the analysis, we discussed the relationship between the noise and flow profile velocity. In order to improve the precision, an averaging reference wave method is proposed, in which the reference wave can be obtained by averaging multiple upstream and downstream ultrasonic waves. The result demonstrated that this method can effectively improve the accuracy of TOF determined by cross correlation. In order to validate the effectiveness of the method, a system was designed for some experiments. The experiment results proved that the method proposed above can be utilized to improve the precision of the UFM.

It must be addressed that the reference wave for cross correlation is sampled in static state. In practical application, the reference wave is pre-stored in the instrument memory before it can be installed in the pipeline to work. After a long period of operation, the flow-meter needs to be calibrated to ensure its measurement accuracy. And the reference wave may need to be updated. To ensure that the maintenance of flow meter does not affect the normal transportation of medium in the pipeline, a bypass pipe should be mounted parallel to the flow-meter. And cut-off valves need to be installed before and after the flow-meter. While acquiring the reference wave, the bypass pipe is turned on and the cut-off valves in the main pipe are turned off, which will keep the airflow in the instrument static.

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