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An improved measurement algorithm for increasing the accuracy of sing-around type ultrasonic flow meters

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1. Introduction

Nowadays measuring fluid flows accurately is an open research field. From simple steam materials flows to two-phase flows with solids [1-4], the search is ongoing for improving the accuracy and cost of flow meters [5-10]. With today's environmental regulations requiring both more accurate flow measurements and high-energy costs making fuel consumption a primary problem, traditional measurement methods are not adequate yet [11]. The rapid transmutation of ultrasonic technology is offering prospects for improved flow measurement systems. With its simple principle operation, and relative easy design, ultrasonic flow meters have become popular recently [12-15]. This trend is likely to continue. Implementation of complex ultrasonic sensor became possible considering the current advances in computing capabilities [16]. This paper presents an improved measurement algorithm for increasing the accuracy of the sing-around type ultrasonic flow measurement. The purpose of this work is to provide a new method to measure the frequency difference of the flow-sensitive oscillators which are implemented in this type of flow meter.

2. Sing-around flow meter

For the following discussion, we need a brief review of the sing-around method from references [17-19]. We will assume a configuration as shown in Fig. 1.

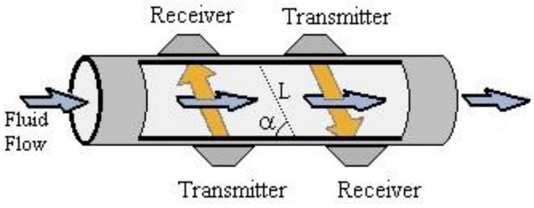

Fig. 1 The ultrasonic flow meter based on conventional dual-sensor transit time

Each transmitter emits coded sound pulses received by the receiver. The fluid flow decreases the ultrasonic signal time of flight in the direction of flow and increases the time of flight against the direction of flow. The time required by the ultrasound to propagate from the transmitter to the receiver downstream τ_1 is expressed in Eq. (1) and upstream τ_2 in Eq. (2)

$$\tau_1 = \frac{L}{c + v\cos\alpha} \quad (1)$$

$$\tau_2 = \frac{L}{c - v\cos\alpha} \quad (2)$$

A sing-around loop works as follow: the transceiver sends ultrasonic pulse along the flow and when receiver detects the signal, it sends the same pulse in the same direction, instantly. The frequency of repetition of pulses has been named as F_1, at the same time when the pulses are sent by the other transceiver pair against the flow direction, their repetition frequency has been named as F_2. We know when there is no flow $F_1 = F_2$, and with increase of the flow, F_1 become greater than F_2. Difference of the frequencies is proportional to the velocity flow [15]

$$\Delta F = F_1 - F_2 = \frac{2v\cos\alpha}{L} \quad (3)$$

From Eq. (3) we know that velocity of the flow does not depend on the ultrasound speed in the fluid and directly depends on ΔF [15]

$$v = \frac{\Delta F\ L}{2\cos\alpha} \quad (4)$$

To determine the fluid velocity we need to know the distance L (i.e. $D/\sin\alpha$ where D is the diameter of the pipe), the angle α and the downstream and upstream sing-around periods, τ_1 and τ_2, respectively. The most important problem of the sing- around systems is that they require very high resolution on the sing- around period measurement [18]. Such an example: measurement of a fluid velocity of 0.05 m/sec with accuracy of 1% needs sing-around period measurement resolution on the order of 1:10^7. For a sing-around period of 64 μs this implies an absolute time resolution of about 80 ps [18].

This high resolution obtains from a multiple period average measurement over the number of N sing-around loops. The multiple period average measurement system measures the total time for N periods [18]. Considering the clock frequency and the sing-around frequency are uncorrelated, the multiple periods averaging method will increase the measurement resolution as [18]

Time measurement resolution = t_{ref}/N, when t_{ref} is the resolution of the reference clock.

Unfortunately, the sing-around system needs a stable flow without any kind of nonstationeries like pulsation. The problem of fast changes of fluid temperature during the long sing-around measurement cycle has been solved [19].

3. Principle of operation

The proposed method is based on a new technique to measure the frequency difference of the flow-sensitive oscillators the upstream and downstream oscillators synchronously generate signals for each sampling cycle. Fig. 2 illustrates the output waveforms of these oscillators (F_1&F_2) in a sampling duration of k seconds.

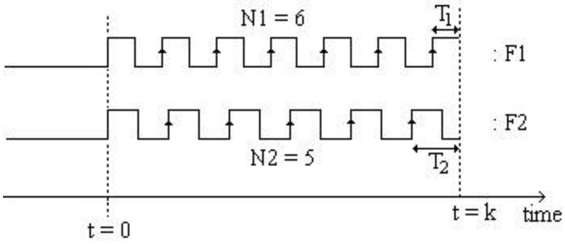

Fig. 2 The output waveforms of the flow-sensitive oscillators during a sampling duration of k seconds

If the number of rising edges of F_1 and F_2 during this cycle be N_1 and N_2, and the final rising edges of F_1 and F_2 occur T_1 and T_2 seconds before $t = k$ respectively, the frequency difference ΔF can be written as

$$\Delta F = F_1 - F_2 = \frac{N_1}{k - T_1} - \frac{N_2}{k - T_2} \tag{5}$$

Therefore measuring N_1, N_2, T_1 and T_2 allows ΔF to be calculated and finally the fluid velocity is evaluated via Eq. (4). Fig. 3 shows the block diagram of the designed embedded system used for this purpose.

At the beginning of each sampling cycle, the processor activates its "Start" output. As a result, the upstream and downstream oscillators synchronously start generating signals and the Reference Clock is applied to Counter2 and Counter4. Counter1 and Counter3 are incremented, then Counter2 and Counter4 are reset at each rising edge of F_1 and F_2, respectively. After k seconds, processor inactivates the "Start" signal. Therefore the upstream and downstream oscillators stop generating signals and the gate will be closed, preventing the Reference Clock to be applied to Counter2 and Counter4.

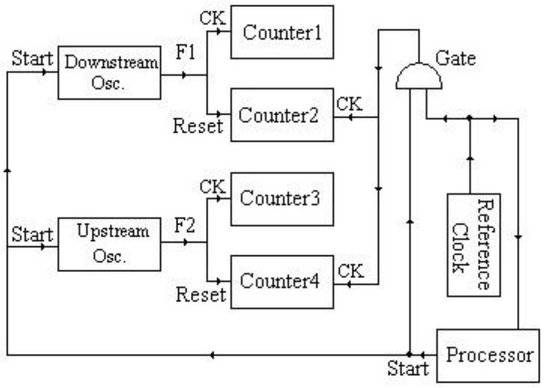

Fig. 3 Block diagram of the implemented circuitry for measuring the frequency difference of flow-sensitive oscillators

In this manner, at the end of the sampling cycle, the quantities of Counter1 and Counter3 are N_1 and N_2 respectively, and T_1, T_2 can be calculated through the following equation

$$T_1 = \text{Counter2}\, t_{ref} \text{ and } T_2 = \text{Counter4} \times t_{ref} \tag{6}$$

where t_{ref} is the period of oscillation of the reference clock.

Finally the frequency difference ΔF is calculated through Eq. (5) which allows the fluid velocity to be evaluated from Eq. (4).

4. Comparing the accuracy of the proposed method with existing methods

In the existing method, in order to measure the frequency difference ΔF, the total time of N sing-around loops of F_1 and F_2 (say t_1 and t_2 respectively) are measured as

$$\Delta F = F_1 - F_2 = \frac{N}{t_1} - \frac{N}{t_2} \tag{7}$$

If dt is the resolution of the Reference Clock, the resolution of t_1 and t_2 would be dt_1 and dt_2 where $dt = dt_1 = dt_2$. Then the resolution of ΔF is achieved by differentiating Eq. (7) with respect to t

$$d\left(\Delta F\right) = d\left(F_1 - F_2\right) = \left(-\frac{N}{t_1^{\,2}} + \frac{N}{t_2^{\,2}}\right)dt \tag{8}$$

Since $F_1 = \dfrac{N}{t_1}$ and $F_2 = \dfrac{N}{t_2}$, the previous equation can be written as

$$d\left(\Delta F\right) = \left(-\frac{1}{N}F_1^{\,2} + \frac{1}{N}F_2^{\,2}\right)dt \tag{9}$$

This equation represents the relationship between the minimum measurable time by the Reference Clock, dt, and the minimum measurable frequency difference, $d(\Delta F)$.

On the other hand, in the proposed method, $dt = dT_1 = dT_2$, where dT_1, dT_2 and dt are the resolutions of

T_1, T_2 and the Reference Clock, respectively. The function ΔF represented by Eq. (5) is differentiable except at the points where N_1 and N_2 have suddenly changed. The resolution of ΔF is achieved by differentiating Eq. (5) with respect to t

$$d(\Delta F)=d(F_1-F_2)=\left(\frac{N_1}{(k-T_1)^2}-\frac{N_2}{(k-T_2)^2}\right)dt \quad (10)$$

Since $F_1=\dfrac{N_1}{k-T_1}$ and $F_2=\dfrac{N_2}{k-T_2}$, (10) can be represented as

$$d(\Delta F)=\left(\frac{1}{N_1}F_1^2-\frac{1}{N_2}F_2^2\right)dt \quad (11)$$

By dividing the absolute values of right sides of Eqs. (9) and (11), it can be found that how more accurate is the proposed method than the existing method.

Accuracy improvement factor (AIF) can be expressed by the following equation

$$AIF=\left|\frac{\dfrac{1}{N}F_1^2-\dfrac{1}{N}F_2^2}{\dfrac{1}{N_1}F_1^2-\dfrac{1}{N_2}F_2^2}\right| \quad (12)$$

The function AIF was sketched versus the sampling duration k for several amounts of F_1 and F_2. Figs. 4-6 illustrate AIF versus k for $F_1 = 12000$ Hz and $F_2 = 11994$ Hz.

From the numerical analysis of AIF as a function of F_1, F_2 and the sampling duration k, the following results are inferred:

1. *AIF* may have some peaks as illustrated in Fig. 4. The amount of the sampling duration at which *AIF* takes its maximum value, is depended on F_1 and F_2. (i.e. it is depended on the fluid velocity.) Thus, there is not a fixed sampling duration for which AIF is maximum for different fluid velocities. Therefore, these points are not helpful for our purpose.

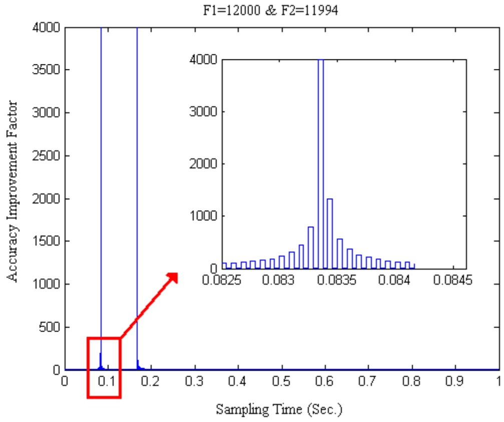

Fig. 4 *AIF* versus the sampling duration for $F_1 = 12000$ Hz and $F_2 = 11994$ Hz

2. Regardless of the amount of F_1 and F_2, for $1/(4\Delta F) < k < 1/\Delta F$, *AIF* is greater than 0.999 and its average is greater than 1 (Fig. 5). Therefore the average accuracy of the proposed method is greater than the existing method in this interval.

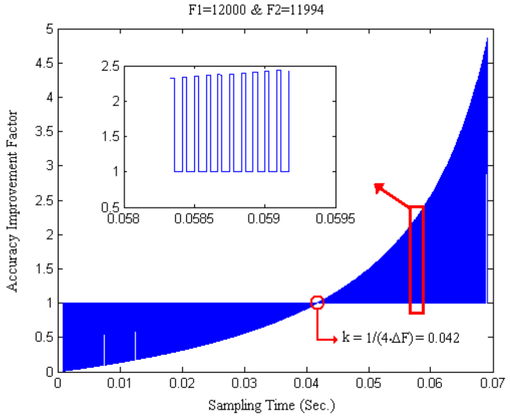

Fig. 5 *AIF* versus the sampling duration for $F_1 = 12000$ Hz and $F_2 = 11994$ Hz near the sampling duration of $k = 1/(4\Delta F)$

3. For $k > 1/\Delta F$ (Fig. 6), *AIF* is greater than 1 regardless of the amount of F_1 and F_2, and the proposed method would be more accurate.

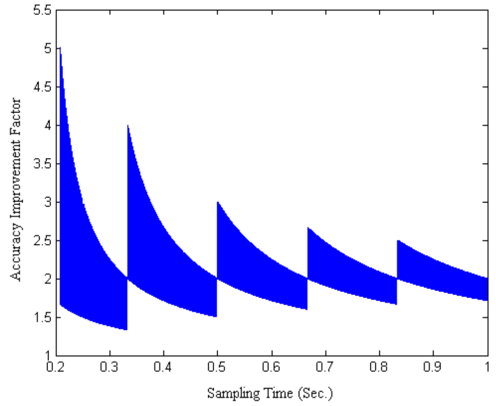

Fig. 6 *AIF* versus the sampling duration for $F_1 = 12000$ Hz and $F_2 = 11994$ Hz and the sampling duration $k > 1/\Delta F$

As a result, the proposed method can be replaced with the existing method when the sampling duration is greater than $1/(4\Delta F)$.

The average value of *AIF* was calculated for $1/(4\Delta F) < k < 1$ and $1\text{ Hz} < \Delta F < 6$ Hz, and it was repeated for different zero-flow frequencies (that is the oscillating frequency of the flow-sensitive oscillators when there is no flow). Compared to existing technique, the average accuracy improvement factor was equal to 2.04 regardless of the amount of the zero-flow frequency.

5. Experimental results

Consider the ultrasonic flowmeter system as illustrated in Fig. 3. This circuit contains two oscillators, one in the upstream and the other in downstream direction. Two accurate crystal oscillators with the frequencies of $F_1 = 10788.460513$ Hz and $F_2 = 10787.214737$ Hz are used as downstream and upstream oscillators.

The simulation results around $1/(4\Delta F)$ are shown in Fig. 7. All the simulations are done with MATLAB.

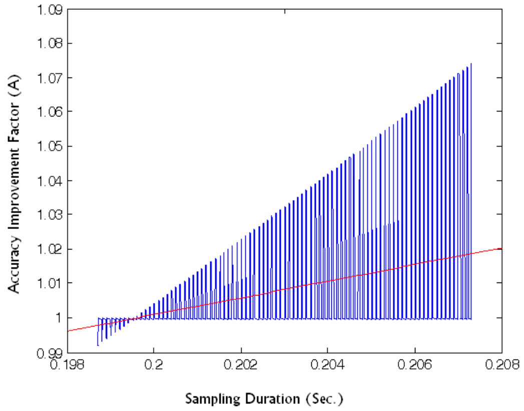

Fig. 7 Expected value for *AIF* VS sampling duration for $k = 1/(4\Delta F)$

The average of the blue curve is illustrated with continuous cross line in Fig. 7. The best fitting line of experimental results is expected to be similar to the best fitting line of the simulation results which is this red line.

Experiments are done at a sampling time of 24 microseconds and for each point, *AIF* is calculated by the processor. Results are plotted in Fig. 8.

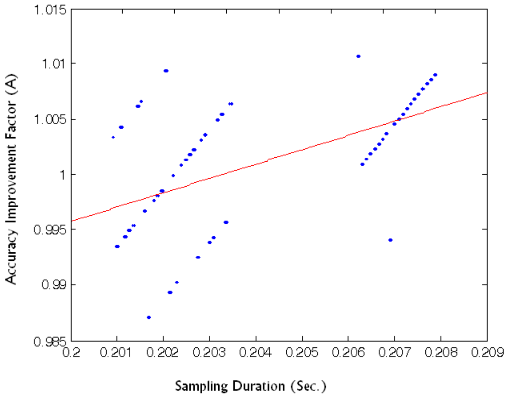

Fig. 8 Experimental value of *AIF* VS sampling duration for $k = 1/(4\Delta F)$

The best fitting line for experimental results is plotted in Fig. 8. This line varies from the values smaller than 1 to the values greater than 1 which is similar to the best fitting line achieved from simulation. This demonstrates the validity of the simulation results.

The simulation results for $k > 1/\Delta F$ are shown in Fig. 9.

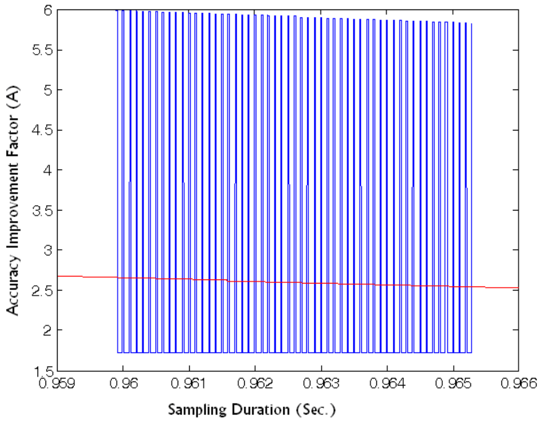

Fig. 9 Expected value for *AIF* VS sampling duration for $k > 1/\Delta F$

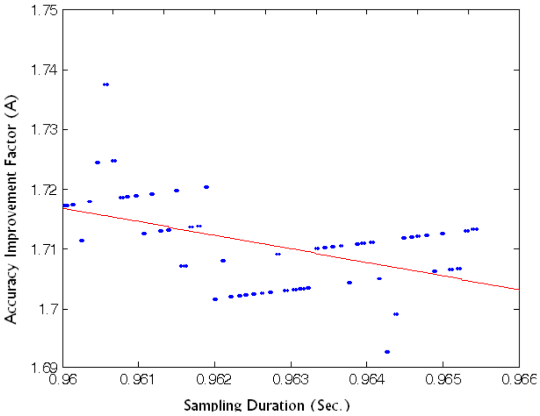

Fig. 10 Experimental value of *AIF* VS sampling duration for $k > 1/\Delta F$

Experimental results are shown in Fig. 10.

Best fitting lines for simulation result and experiment result are plotted in continuous line in Fig. 9 and Fig. 10. The best fitting line for experimental results is always above 1 which is similar with simulation results best fitting line.

6. Conclusion

We have proposed and demonstrated a novel sing-around type ultrasonic flow meter which was approximately two times more accurate than current ultrasonic sing-around type flow measurements.

The accuracy of the proposed method was compared with the existing method numerically. The results indicate that if the sampling duration be greater than $1/(4\Delta F)$, the proposed method would be more accurate.

Compared to the existing technique, the average accuracy improvement factor was calculated for $1/(4\Delta F) < k$ and $1\ \text{Hz} < \Delta F < 6\ \text{Hz}$ for different zero-flow frequencies. It was equal to 2.04 regardless of the amount of the zero-flow frequency.

References

1. **Lian, L.; Zhu, J.** 1998. Liquid-solid two-phase flow theory and its application, Proceedings of the International Symposium on Underwater Technology, 350-354. http://dx.doi.org/10.1109/UT.1998.670125.
2. **Dong, W.; Hu, L.Z.** 2002. Gas–liquid two-phase flow measurement using ESM, Experimental Thermal and Fluid Science 26(6-7): 827-832. http://dx.doi.org/10.1016/S0894-1777(02)00171-1.
3. **Xu, J.; Wu, Y.; Zheng, Z.; Wang, M.; Munir, B.; Oluwadarey, H.I.; Schilaberg, H.I.; Williams, R.A.** 2009. Measurement of solid slurry flow via correlation of Electromagnetic Flow Meter, electrical resistance tomography and mechanistic modeling, Journal of Hydrodynamics, Ser. B, 21(4): 557-563.
4. **Yian, L.; Zhiyao, H.; Haifeng, J.; Haiqing, L.** 2008. Solids volume fraction measurement of gas-solid two-phase flow based on terahertz time-domain spectroscopy technique, Proceedings of Instrumentation and Measurement Technology Conference, 2141-2145.
5. **Bode, F.; Giurgea, C.; Hodor, V.; Unguresan, P.** 2009. Investigation of the nonreactive flow in a swirl-

ing burner, Mechanika 79(5): 42-47.

6. **Mingwei, L.; Guosheng, L.; Yanguo, H.** 2010. Research on improving the accuracy of the ultrasonic flow-meter with time difference method, International Conference on Electrical and Control Engineering (ICECE), 1704-1707. http://dx.doi.org/10.1109/iCECE.2010.419.
7. **Mandard, E.; Kouame, D.; Battaul,t R.; Remenieras, J.P.; Patat F.** 2008. Methodology for developing a high-precision ultrasound flow meter and fluid velocity profile reconstruction, IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control 55(1): 161-172. http://dx.doi.org/10.1109/TUFFC.2008.625.
8. **Mingwei, L.; Guosheng, L.; Yanguo, H.** 2010. Research on improving the accuracy of the ultrasonic flow-meter with time difference method, International Conference on Electrical and Control Engineering (ICECE), 1704-1707. http://dx.doi.org/10.1109/iCECE.2010.419.
9. **Eren H.** 1998. Accuracy in real time ultrasonic applications and transit-time flow meters, Proceedings of Instrumentation and Measurement Technology Conference (IMTC/98), 568-572.
10. **Gatabi, J.R.; Forouzbakhsh, F.; Darkhaneh, H.E.; Gatabi, Z.R.; Janipour, M.; Gatabi, I.R.** 2010. Auxiliary fluid flowmeter, European Journal of Scientific Research 42(1): 84-92.
11. **Rabalais, R.A.** 2002. Ultrasonic flow measurement: technology and applications in process and multiple vent stream situations, Proceedings of the Texas A&M Symposium.
12. **Yang, S.; Liang, G.; Zhao, W.; Xie, D.; Huang, Z.** 2009. Design of low-power consumption ultrasonic open channel flow meter, International Conference on Electronic Measurement & Instruments (ICEMI '09) 1:999-1002.
13. **Joshi, S.; Nagaraj, G.; Zaitsev, B.; Kuznetsova, I.** 2009. Efficient mode conversion transducers for use in ultrasonic flow meters, International Ultrasonics Symposium (IUS), 1491-1494.
14. **Deventer, J.V.** 2005. Introduction of a 2 transducer ultrasonic mass flow meter, Proceedings of the IEEE Instrumentation and Measurement Technology Conference, 1369-1372. http://dx.doi.org/10.1109/IMTC.2005.1604372.
15. **Reyes, J.; Acevedo, A.** 2010. Modeling and simulation of ultrasonic flow meters: State of art, ANDESCON, 1-7.
16. **Yeh, T.T.; Espina, P.I.** 2001. Special ultrasonic flowmeters for in-situ diagnosis of swirl and cross flow, Proceedings of ASME FEDSM'01.
17. **Poviliunas, G.; Kazys R.** 2000. Measurement ultra slow dynamic flow, Ultragarsas 34(1): 34-43.
18. **Delsing, J.** 1990. The Zero flow performance of a sing-around type flow meter, Proceedings of 1990 IEEE Ultrasonics Symposium, 1541-1544.
19. **Delsing, J.** 1987. A New velocity algorithm for sing-around-type flow meters, IEEE Transactions on UFFC 34(4): 431-436. http://dx.doi.org/10.1109/T-UFFC.1987.26963.

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PATOBULINTAS MATAVIMO ALGORITMAS UŽDAROS KILPOS TIPO ULTRAGARSINIO SROVĖS MATUOKLIO TIKSLUMUI PADIDINTI

Reziumė

Šiame straipsnyje pasiūlytas naujas uždaros kilpos tipo srovės matuoklis. Nors uždaros kilpos tipo srovės matuokliai įvertina problemas, iškylančias, kai srovė yra nestabili, pasiūlytas matavimo metodas yra apytikriai du kartus tikslesnis nei matuojant ultragarsiniais uždaros kilpos tipo srovės matuokliais. Įrenginys susideda iš dviejų ultragarsinių srovei jautrių osciliatorių. Vienas iš jų yra įrengtas srovės įtekėjimo vietoje, antras – jos ištekėjimo vietoje, įvertinant tekėjimo kryptį. Skirtingai nei taikant esamą metodą, įtekėjimo ir ištekėjimo osciliatoriai „sinchroniškai“ pradeda generuoti kiekvieno tiriamo ciklo signalus. Pasiūlyto metodo tikslumas skaitiniu metodu buvo palygintas su esamu, ir jo efektyvumas buvo parodytas kiekybiniais rezultatais.

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AN IMPROVED MEASUREMENT ALGORITHM FOR INCREASING THE ACCURACY OF SING-AROUND TYPE ULTRASONIC FLOW METERS

Summary

In this paper a new sing-around type flow meter is proposed. Although sing-around type flow meters encounter problems when the flow is not stable, the proposed measurement method is approximately two times more accurate than current ultrasonic sing-around type flowmeters. The device comprises two ultrasonic-based flow-sensitive oscillators, one is installed upstream and another is installed downstream with respect to the flow direction. Unlike existing method, the upstream and downstream oscillators "synchronous-sly" start generating signals for each sampling cycle. The accuracy of the proposed method was compared with the existing method numerically, and its effectiveness was demonstrated with quantitative results.

Keywords: measurement algorithm, accuracy of sing-around type ultrasonic flow meters.

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