Experimental Study on Velocity Representation of Ultrasonic Transit-time Discharge Measurement in Open Channel

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Abstract

It is very important to accurately measure the open channel discharge, especially for trade settlement involved in water transportation projects blooming in China. Ultrasonic Transit-time method is widely used for accurate open channel discharge measurement with many advantages. Due to complexity of open channel flow, velocity representation is the main source of discharge uncertainty, including representation of cross-sectional averaged velocity from measured acoustic path velocities and path velocity itself. We built a 25m long, 2m wide, 1.2m deep open channel facility with an over-fall head tank providing a very stable flowrate of 1.5m^3/s in maximum. Two parallel-installed DN500 ultrasonic flowmeters calibrated by gravimetric facility are used as master meters, and two open channel flowmeters of different transducer mounting type are installed in series as test meters for velocity representation study. Both of the two test meters have cross-plane configuration with five acoustic paths on each plane. Path heights and mounting protrusion of transducers can be adjusted, and all geometric parameters are accurately measured using a FARO arm. Initial experiments have been done at a fixed flowrate and three different water level. Flowrate indication errors are calculated using different combinations of transducers installed at different acoustic path heights to study area-average velocity representation, and effect of transducer mounting protrusions on flowrate measurement are also analyzed for path-average velocity representation.

Key words: open channel, discharge, ultrasonic transit-time, velocity representation

1 Introduction

With society and economy development, water resources have been being strategically important in China. To alleviate the mismatch of regional economic development and water resources distribution in China, a large amount of studies, researches and projects were conducted and a series of great hydraulic projects, such as Three Gorges Project and Inter-Basin Water Transfer Project, were finished. Thereafter all regional water resources were brought into integrated planning, and they were always adjusted and distributed by open channels and large pipes. Flow rate is the base of the water resources adjusting and distribution, thus its accurate measuring was in great need, especially in the situation that the most strict water management system was proposed and implemented in China. Besides, as water fee is settled and paid according to the cumulative flow, therefore accurate flow rate measuring is in great need to avoid unnecessary economic disputes.

The flow measuring principals and methods have been studied for hundreds of years. Differential pressure flowmeter, positive displacement flowmeter, magnetic flowmeter, ultrasonic flowmeter, and several other flowmeters are widely used in flow measuring in the closed conduit while artificial weir and groove are always applied in flow measurement of open channel. In addition, electromagnetic flowmeters and ultrasonic flowmeters, which are based on the direct velocity measurements, are rapidly developed in recent years, and they are successfully applied in the closed conduit's and open-channel's flow measurement. In the water transfer system, closed-conduit enjoys good accuracy. When the flow pattern and pipe condition are both good, the measuring errors can be restricted within 0.5%~2.0%. And the flow rate measuring errors in open channel are commonly worse than 2.0%. Heiner et al. (2011) evaluated the accuracy of the flow meters which were fixed in various open channels, and the results showed: 2/3 of the instruments exceeded the allowed errors with the maximum values being 40%. In order to improve the precision of flow rate measuring in open channels, newly developed ultrasonic flowmeter maybe a very good alternative, due to its good stability and applicability.

As is known, when travelling in the flow, the ultrasonic wave will take some time. And it will take some more time when travelling in the upstream direction than in the downstream direction due to the flow velocity. Based on this time difference, we can get the flow velocity easily.

Then according to the velocities at different path heights, we can obtain the flow rate through numerical integration. This is the basic principle of velocity measuring using ultrasonic wave. Clearly, the precise measuring of the discharge is depending on the precision of geometric parameters' measurement during installation, the precision of time difference on-site measuring and best-performing averaged velocity algorithm. The averaged velocity algorithm is most important, where there is still more room for improvement of ultrasonic flowmeter in open channel. It can be expressed by two items: cross-sectional velocity representation which is integration error from measured acoustic path velocities and is related to the number of transducers and their installation heights, and acoustic path velocity representation which is a symmetric error due to local distortion of velocity profile along the acoustic path, and incomplete sampling of velocity along the path that arises from the transducer not being flush mounted in the conduit.

In this paper, we would design and construct a testing system to study the velocity representation and to improve the precision of ultrasonic flow meters.

2 Velocity representation explanation

2.1 Integration algorithm

Integrating algorithm mainly concerns how to calculate flow rate from the measured path velocities based on numerical integration. IEC 60041 Standard proposed Gauss-Jacobi Model which was appropriate for circular pipes and Gauss-Legendre Model which was appropriate for rectangular conduits. But these two models were both built on the consumption that the path velocities were uniformly distributed, which was not the fact. In addition, an optimal weighted integral method (OWICS) was proposed to adapt the velocity distribution of which is zero at the wall. Up till now, the integration model used for open channels was given by ISO 6416 - 2004. However, accuracy of this model under different flow conditions was still not seen in public publications.

Integration algorithm for rectangular open channel is shown in Fig. 1. It can be divided into three subarea: flow rate Q_T for top-sheet, flow rate Q_M for all middle sheets, flow rate Q_B for bottom-sheet. The total flow rate of the open channel is as follows:

$$Q = Q_T + Q_M + Q_B \qquad (1)$$

$$Q_T = W \times \left(H - h_4\right) \times \frac{v_4 + K_T v_s}{1 + K_T} \qquad (2)$$

$$Q_B = \frac{1}{2}\left(v_1 + K_B \times v_1\right) \times W \times \left(h_1 - h_0\right) \qquad (3)$$

$$Q_M = \frac{1}{2}\left(v_i + v_{i+1}\right) \times W \times \left(h_{i+1} - h_i\right) \qquad (4)$$

in which, v_T is the top-sheet velocity, and is obtained by interpolation.

If H-h_4<h_4-h_3,

$$v_s = v_4 + \left(v_4 - v_3\right) \times \frac{H - h_4}{h_4 - h_3} \qquad (5)$$

If H-h_4≥h_4-h_3

$$v_s = v_4 + \left(v_4 - v_3\right) \qquad (6)$$

K_B in formulae (2) and K_T in formulae (3) are bottom parameter and top parameter separately. K_B commonly takes the value of 0.4~0.8 and the default value of K_T is 0.1.

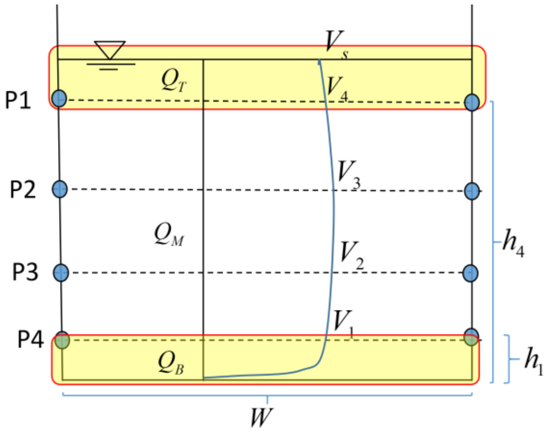


Fig. 1 integration algorithm for rectangular channel

2.2 Cross-sectional velocity representation

Theoretically, if we set a series of transducers in parallel one by one and the quantity was large enough, we could get enough path velocities and accurate flow rate. However, we could only install limited pairs of transducers in practice, because of economical consideration and necessity consideration. In fact, if we have chosen the right positions, limited pairs of transducers can give precise enough flow rate measurements. Most of researches focused on conduit flow rate measurement, and rare researches were conducted focusing on open channel. Configuration of transducers for open channel was determined mostly by experiences. Thus studying how the quantity of transducers were chosen and how the transducers were arranged are very important for precise flow rate measurements of open channel.

Fig. 2 shows the average-velocity distribution against path heights. V_1, V_2, V_3 and V_4 represent the measured velocities along these acoustic paths. Integration is actually to calculate the area of the plane formed by velocity distribution curve and vertical axis and the solid part is the systematic error of the integration model. From Fig.3, it can be seen that middle-sheets can produce very small errors, and the main systematic errors mainly come from bottom-sheet flows and sometimes the top-sheet. Take the bottom flow as the example: if K_B = 0, triangular area is chosen as the representative of the true value; if K_B = 1, rectangular area is chosen as the representative of the true value. Obviously the former is too smaller while the latter is too larger. Thus if the vertical velocity distribution is given, we can obtain K_B theoretically. However, as the real open channel flow is not uniform, thus K_B is commonly difficult to calculate. Thus we will give vertical velocity distributions and then K_B and K_T values through model tests. Based on these achievements, we will also study how to determine K_B and K_T to improve the precision of flow rate measurements.

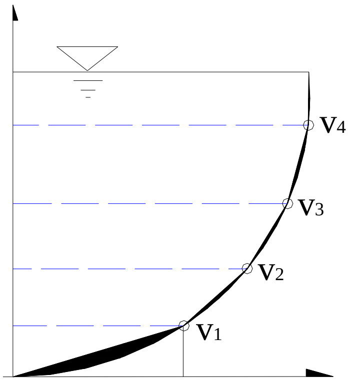


Fig. 2 sketch of systematic errors in ISO Model

2.3 Path velocity representation

Size and shape of transducers and their mounting seats are also very important, especially for small open channels. The protruding parts of probes can make the velocity field disturbed. Meanwhile, it can also make the distances sampled to be not exactly wall to wall, as is seen in Fig. 3. Path velocity representation is a symmetric error due to local distortion of velocity profile along the acoustic path, and incomplete sampling of velocity along the path that arises from the transducer not being flush mounted.

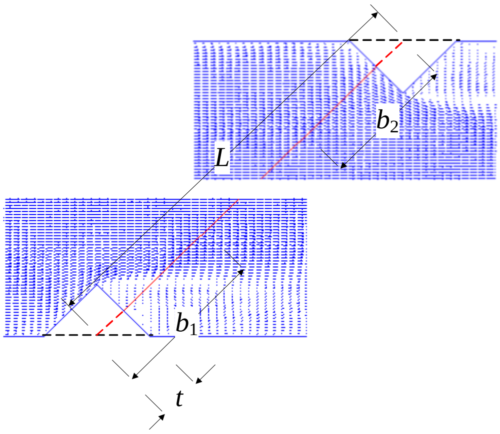


Fig. 3 sketch of transducer protrusion effect

Voser et al. (1996) analyzed the protruding parts' influences on the precision of velocity measuring using CFD, and the results showed: when the sound track angle was smaller than 45 degree, the pipe diameter was larger than 2m and the flow velocity was larger than 0.1 m/s, the measuring error produced by the protruding part was smaller than 0.5% and it would get smaller as the pipe diameter was getting larger. Zheng et al. (2014) studied the influences of different installing depths of transducers on flow velocity field and measuring errors, and made further analysis on the disturbance mechanism of transducers.

In all, the relationship of the disturbances caused by probes and path-averaged velocities can't be quantitatively described. But it's sure that as the probes are getting larger, their disturbances are getting larger and the path velocity representations are getting worse. The result is the precision of the flow rate measuring is getting worse. So studying of the probes' sizes, installing heights, shapes are significantly important to improve the path-velocity representation and eventually the flow rate measurement precision.

3 Model design and fabrication

3.1 Overall layout

The testing flume is built in Daxing Experimental Base of China Institute of Water Resources and Hydropower Research (IWHR). It is 26 m long, 2 m wide and 1.2 m deep. Its bottom is horizontal with no slope designed. The testing section is 5 m long, in which two sets of open channel flowmeters are installed as shown in Fig.4. The upstream section is 15 m including a stilling pool mainly designed to stable the incoming flow. The downstream section is 6 m designed to reduce the tailwater influence.

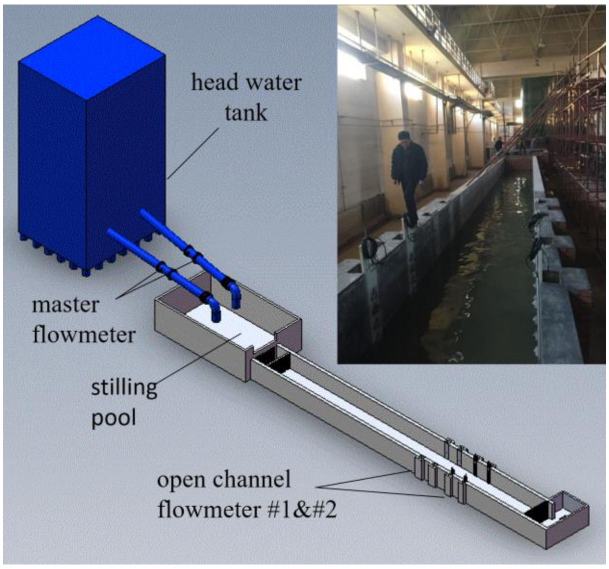


Fig. 4 layout of open channel flowmeter test system

The incoming flow is supplied by a head water tank of 13m through two iron pipes of DN500. Both pipes are equipped with a combination of a master flowmeter and a butterfly valve. The tailwater will be discharged back to underground reservoir again through tailgate. The tailgate is designed using parallel panels and a flow drop is designed downstream of the tailgate in order to alleviate the tail water’s back-propagation’s influence.

3.2 Master flowmeter calibration

Master meters are two DN500 ultrasonic flow meters Both of them were pre-calibrated using weighing methods in laboratory. The calibration results were shown in Table 1. Indication errors of them can be lower than 0.5% after only dry-calibration, and their repeatability is better than 0.1%. It could be seen that the precision and stability could both fulfil the requirements. Through weighing calibration, we can get average errors and then adjusting factors. The standard flow rates could be obtained, which thereafter will serve as the standards to analyze the performance of the ultrasonic flow meter used in open channels.

Table 1 Calibration of master flow meter

flow rate (m^3/h)	UF1 (S)		UF2 (N)	
	errors (%)	repeatability (%)	error (%)	repeatability (%)
1414	/	/	0.31	0.07
1060	-0.18	0.04	0.36	0.05
707	-0.09	0.08	0.38	0.07
353	-0.11	0.08	0.46	0.05
average errors (%)	-0.13	/	0.38	/
adjusting factor	1.0013	/	0.9962	/

* S and N means the master flowmeters are located south and north, respectively.

3.3 Ultrasonic flow meters in the open channel

In our model, two sets of ultrasonic flow meters are installed in the flume. Both of the two test meters have cross-plane configuration with five acoustic paths on each plane. The upstream flow meter is coded as #1, and is installed in the grooves of sidewalls. Their outer surfaces are flush with the corresponding sidewalls. The ultrasonic transducer probes are cylinders with a diameter of 15 mm and can be flexible. Its maximum retraction and maximum protruding are both 4.36mm (see Fig. 6(a)). The probes are adjusted in the horizontal direction, and their installing heights remain constant.

The downstream flow meter is coded as #2, and is also installed in the grooves of sidewalls. Their mounting seats are a little bit higher than the corresponding sidewalls. However, the probes are protruding from the seats, and their shapes are of semi-sphere with diameters of 30mm. The alternative installing way is to keep the mounting seats flush with the corresponding sidewalls and to leave the probes protruding into the flume. As the probe installing changes, the probes and their seats must be re-fixed, and their geometric parameters need to be re-calibrated.

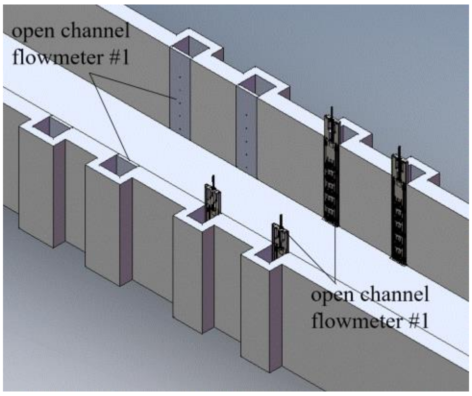
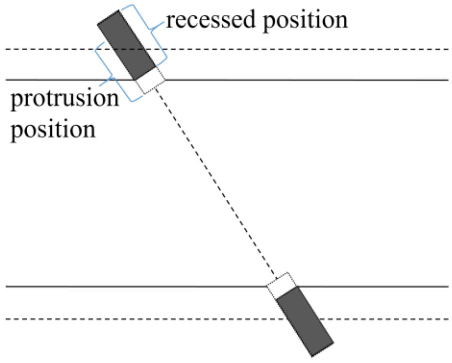


Fig. 5 open channel flowmeters under test



(a) flowmeter #11

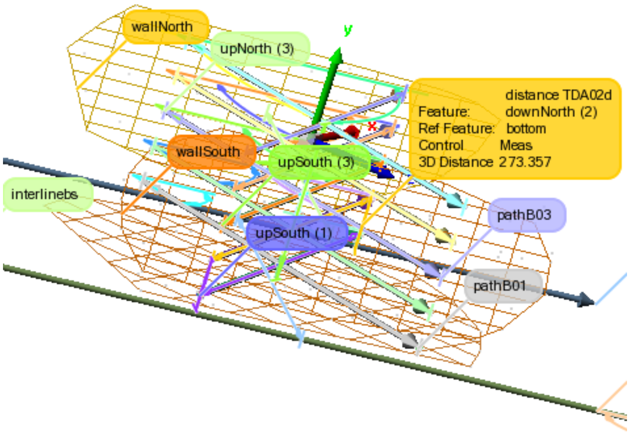
(b) flowmeter #12

Fig. 6 probe installation and protrusion effect

3.4 Geometrical parameter measurements

The geometrical parameters, such as flume width W, transducer installing height h_i, acoustic path length L_i, water level h, are all very important in the flow rate measuring in open channels using ultrasonic flowmeter. Water level h is measured using ultrasonic water level meter. The other parameters are measured using FARO arm (see Fig. 7) and analyzed using POLYWORKS. In details, sidewall and bottom are fitted by points measured using FARO arm while distance between sidewalls is calculated by POLYWORKS. If the probes were adjusted, the geometrical parameters will be refreshed.

(a) photo of geometric measurement with FARO arm



(b) geometric result showed in POLYWORKS
Fig. 7 Sketch of geometrical measurement

4 Initial results and discussions

4.1 Variation of flow rate and water level during flume test

The flume is designed to test the performances of open channel ultrasonic flowmeters. We have done some initial experiments in about one week of this April to test capacity of the flume system and to get some basic idea of the two ultrasonic flowmeters. There are 14 cases which fix the flow rate and adjust the water level at three different value as shown in Fig. 8. We record directly the transit time of the two open channel flowmeters and calculate flowrate using ISO integration model.

4.2 Comparison with measurements by master flowmeters

Table 2 gives all the 14 tested cases and indication errors of flowmeter #11 and #2. Most of them are with a fixed flowrate of 1400 m^3/h, and only the last one is at 3600 m^3/h which is to test the flowrate capacity of the flume system. Either flowmeter #1 or flowmeter #2 could give good approximations of flow rates, no matter in the case of high water level and low water level. The maximum error came from flowmeter #2, and the absolute value was 9.91%. By contrast, flowmeter #1 can give better approximation than #2, and most errors were restricted within 1%. Besides, flowmeter #1 performed more stable than #2

In all, according to the tested results, it was sure that: ultrasonic flowmeter could give high-precision flow rate measurement in open channels. The factors influences the measuring precision were mainly probes and their bases' configuration, water level measurement and integration algorithm. Water level measurement was another important factor in the flowrate measuring, as it determined the range of integration. In Table 2, it could be seen that water levels measured by flowmeter #1 and flowmeter #2 are not exactly the same. Thus we should improve the precision of water level measuring in later researches.

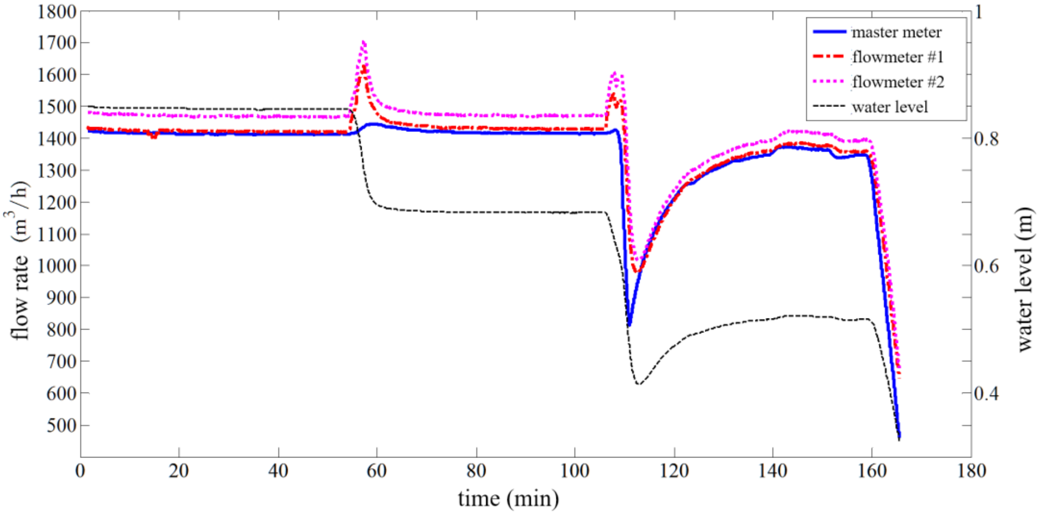


Fig. 8 variation of flow rate and water level change during open channel flowmeter test

Table 2 tested cases and indication errors of flowmeter #11 & #2

case no.	master flow rate (m³/h)	flowmeter #11				flowmeter #12			
		water level (m)	measured flow rate (m³/h)	indication error	probes states	water level (m)	measured flow rate (m³/h)	indication error	probe seats states
1	1385.9	1.046	1391.4	0.39%	retracted	1.047	1436.7	3.67%	protruded
2	1396.5	0.844	1400.7	0.30%	retracted	0.843	1445.4	3.50%	protruded
3	1405.2	0.685	1424.3	1.35%	retracted	0.687	1472.6	4.80%	protruded
4	1330.6	0.516	1339.6	0.68%	retracted	0.521	1462.5	9.91%	protruded
5	1412.5	0.846	1421.1	0.60%	protruded	0.849	1469.1	4.01%	protruded
6	1412.6	0.846	1420.8	0.58%	protruded	0.849	1468.2	3.93%	protruded
7	1416.2	0.683	1430.9	1.04%	protruded	0.686	1471.0	3.87%	protruded
8	1415.1	0.683	1428.7	0.96%	protruded	0.686	1470.9	3.94%	protruded
9	1366.8	0.520	1379.1	0.90%	protruded	0.520	1414.3	3.48%	protruded
10	1412.8	0.848	1420.5	0.55%	protruded	0.851	1406.9	-0.42%	retracted
11	1409.4	0.849	1421.1	0.82%	protruded	0.852	1407.8	-0.12%	retracted
12	1404.9	0.701	1422.1	1.22%	protruded	0.705	1425.2	1.44%	retracted
13	1350.8	0.529	1362.9	0.90%	protruded	0.531	1367.4	1.23%	retracted
14	3601.1	0.933	3613.4	0.34%	protruded	0.934	3610.1	0.25%	retracted

4.3 Velocity representation analysis

We used ISO integration algorithm to analyze the tested data. Since it has bottom parameter K_B and top parameter K_T, we evaluated their sensitivity upon flowrate calculation. We found flowrate is not sensitive to top parameter but very sensitive to bottom parameter under such a rectangular open channel condition. Fig. 9 gives indication errors by ISO integration model using different bottom parameter for flowmeter #1. There is a difference of about 1.5% when K_B changes from 0.7 to 0.9. Whether there is more optimal algorithm and how to evaluate KB and KT to make the measuring precision of flow rates improved are still in question.

Table 3

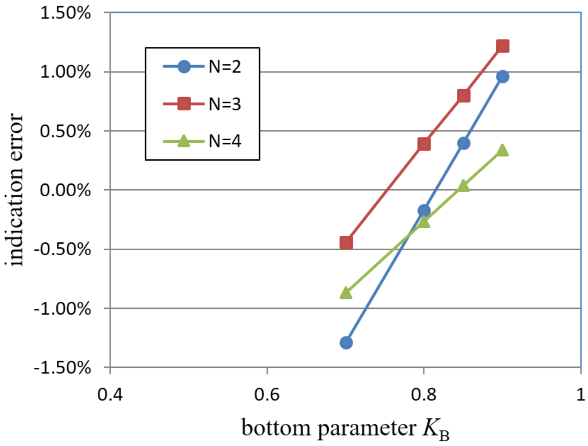


Fig. 9 indication errors by ISO integration model using different bottom parameter

Probe protrusion effect performed very differently for the two flowmeters. As for meter #1, indication errors remained almost unchanged no matter the probes were retracted or protruded. The reason for that was the probes of #1 were very small in size and their influences on the velocity field were so limited. In contrast, whether the probes' bases were protruded or retracted would exert greater influences on the flow rate measurements. From Table 3, it could be found that when the probes' bases were protruded, the measured flow rate error of flowmeter #2 is about 4.2%. However, after the probes' bases were retracted, the errors could be restricted within 1.5%. There is a difference of about 2.8% for flowmeter #2 which is less than 0.4% for flowmeter 0.3%.

Table 3 indication error under different probe protrusion condition

flowmeter #11		flowmeter #12	
probes recessed	0.30%	probe seats retracted	1.44%
probes protruded	0.65%	probe seats protruded	4.20%

5 Conclusions

In order to test the representation of velocities and then performance of ultrasonic flowmeters, we have design and constructed a flume system. Two sets of ultrasonic flowmeters used in open channels were fixed. After testing, we could get some initial conclusions as follows:

1) Due to complexity of open channel flow, velocity representation is the main source of discharge uncertainty, including representation of cross-sectional averaged velocity from measured acoustic path velocities and path velocity itself.

2) Bottom parameter of ISO integration model for open channel is very sensitive for flowrate calculation. It is better to give it a suitable value based on estimation of the specific path velocity distribution near the bottom.

3) Probes and their seats' configuration should be optimized, especially for relative small open channel.

3) In order to improve the precision of ultrasonic flow meters, the precision of water level measurement should also be given enough attention.

Since we have got a good start of our ultrasonic flowmeter test facility, we will continue our experiments to understand more clearly of velocity representation of ultrasonic transit-time discharge measurement in open channel. Proper integration algorithm for given condition, such as rectangular open channel, is expected to be developed.

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