Research on accuracy evaluation method of ultrasonic flowmeter used in large conduits

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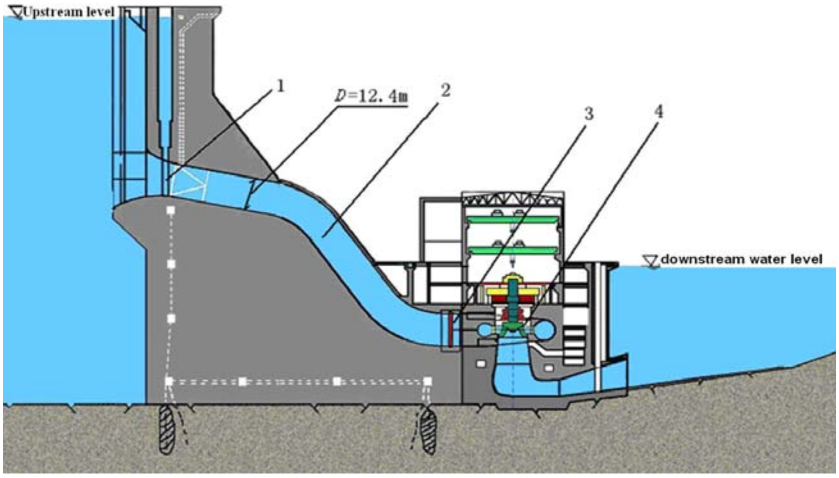
Abstract: It is always a difficult task to measure the flow in large conduits. Ultrasonic flowmeter developed in recent years is a good choice for the large flow measurement, especially for turbine performance testing in hydroelectric plant, because of its convenient installation; but it is not easy to estimate the accuracy of ultrasonic flowmeter, and there is not even a acknowledged estimation method when its installation requirements are not satisfied. Aiming at the accuracy of the ultrasonic flowmeter installed in 3-Gorge power station, both experiment method and CFD method are introduced to analyze the effect of the complex flow field on the metering performance. Reduced scaled (1:24) experiment system has been built, and a series of cases have been studied, which show the flow error related to the complex flow field is about 0.3%. Penstock flow field of 3-Gorge has been simulated, and the flow error calculated is close to the experiment result. The uncertainty of experimental results and the 3-Gorge flowmeter performance are further considered, and then it was concluded that the accuracy of flowmeter is better than 1%, indicating that the flowmeter can meet the requirements of the turbine performance testing in 3-Gorge Power Station.

Key words: 3-Gorge, ultrasonic flowmeter, accuracy, installation condition

Water is the essential resource for the existence of human. With the lack of global water resources, it is very necessary to conserve and rationally use them. Water flow measurement has become an important assessment approach for rational utilization. A great number of large hydraulic projects and water transfer projects have been developed rapidly in China, such as the 3-Gorge Project and the South-to-North Water Transfer Project. Among these projects, the flow of water turbine needs to be measured to optimize the turbine efficiency, and the amount of transferred water needs to be measured to achieve rational allocation and settlement, all of which require accurate water flow measurement. As the conduit diameters in these projects are extremely large, the conventional flowmeters can not be adopted. In recent years, the development and application of multi-path ultrasonic flowmeter have solved the technical problems of large flow measurement. There is no upper limit of the flowmeter diameter, and the multi-path configuration is suitable for complex flow structure. Moreover, it can be installed on-site on the existing conduit. Therefore ultrasonic flowmeter has become one of the best choices for the large flow measurement.

1. Introduction

The 3-Gorge Project is the world's largest hydraulic project with the total installed capacity of 22.5 million kilowatts and planned annual power generation capacity of 84.7 billion kWh. The efficiency of the turbine is an important technical indicator of the hydropower station. If the turbine efficiency of 3-Gorge Project drops by 2%, 1.5 billion kWh power will be less generated per year. Thus the efficiency assessment of the turbine units and the adjustment of optimum operating point become very important, while the generating flow is the most important parameter of the efficiency calculation. Several 700MW water turbine-generators have been assembled in 3-Gorge station, with the penstock diameter of 12.4m, rated flow of 970 m^3/s and max flow of 1020 m^3/s. The range of average flow velocity in the penstock is (0~8.5)m/s. With comprehensive consideration of installation difficulty, measurement accuracy, cost and other factors, three units of them have been chosen to install ultrasonic flowmeter for generating flow measurement. Due to the limits of site condition, ultrasonic flowmeters have to be installed at the end of penstocks as is shown in Fig.1.



1-sluice-gate 2-penstock 3-flowmeter 4-turbine
Fig.1. Sketch of flow passage of the power station

The three ultrasonic flowmeters installed are from three different manufacturers. Although all of them are transit-time ultrasonic flowmeter with similar configuration, the accuracies claimed by the manufacturers are considerably different ranging from 0.3% to 1%. For the 3-Gorge flowmeter, the accuracy assessment can not be conducted using actual flow calibration method because of the huge flow-rate, and there is no generally accepted method of non-actual flow calibration at present, since the ultrasonic flowmeter has been developed for only a short period. So, the metrological authorities can not authenticate the accuracies claimed by the manufacturers, which makes it impossible to carry out the turbine efficiency evaluation of the 3-Gorge Station. Therefore, 3-Gorge Project Corporation directly asked for technical support from AQSIQ (Administration of Quality Supervision, Inspection and Quarantine) several years ago. Under this background, NIM (National Institute of Metrology) accepted the research task of AQSIQ, which was to explore an acceptable approach for non-actual accuracy assessment of ultrasonic flowmeter and to give a credible accuracy assessment of 3-Gorge flowmeters.

Transit-time ultrasonic flowmeter operates based on the transit-time difference of the ultrasonic wave when the fluid in the flowmeter flows. In Fig.2, a pair of transducers is adopted to measure the downstream transit time $t_{d,i}$, and the upstream transit time $t_{u,i}$, and the average velocity of the acoustic path will be obtained as follows,

$$\overline{v}_i = \frac{L_i}{2\cos\phi_i}\left(\frac{1}{t_{u,i}} - \frac{1}{t_{d,i}}\right) \tag{1}$$

where, L_i is the acoustic path length, and ϕ_i is the acoustic path angle. For a single-path flowmeter, there is a specific relationship between the average flow velocity of whole measuring section and the acoustic path velocity, but this relationship is vulnerable to the changes of the velocity profile. In order to improve the measurement accuracy of the flowmeter, a number of acoustic paths are designed in parallel to integrate the flow-rate as follows,

$$Q = R \cdot \sum_{i=1}^{N} \omega_i \cdot \overline{v}_i \cdot L_i \sin \phi_i \quad (2)$$

where, R is the conduit radius; ω_i is the weighting coefficient; N is the number of acoustic paths. The Gauss integration method is commonly used for the ultrasonic flowmeter in conduits to determine the optimal location of the acoustic path and the corresponding weighting coefficient, which can be found in IEC41 of International Electro-technical Commission and PTC18 of American Society of Mechanical Engineers.

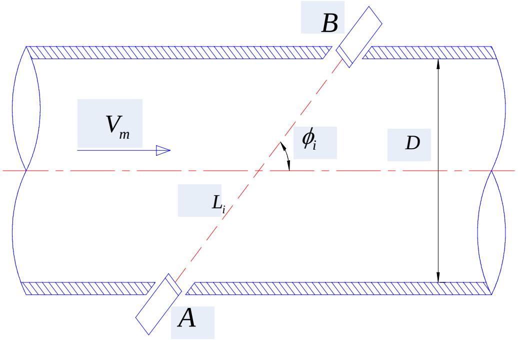


Fig.2. Velocity measurement on acoustic path

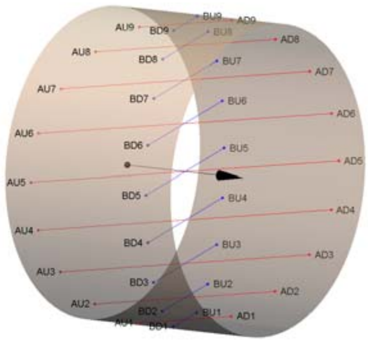


Fig.3. Configuration of 3-Gorge flowmeter

From the principle of the flowmeter, accuracy of acoustic path velocity directly depends on the accuracy of geometric measurement and transit time measurement, and the integration accuracy of flow-rate is dependent on the disturbance of the flow field. Accordingly, we have considered the three factors in accuracy assessment of the 3-Gorge flowmeter. In terms of geometric measurement, the factors which affect the accuracy of geometric parameters of the flowmeter have been studied; the geometric dimension of 3-Gorge flowmeter has been re-measured; and the uncertainty of the measurement results have been analyzed from the perspectives of the coordinate measuring instrument itself, fitting method of conduit and water temperature and pressure changes. In terms of transit time measurement, a standard device has been designed to make off-line calibration of the time delays of flowmeter system. In addition, the accuracy of transit time of the 3-Gorge flowmeter has been analyzed and assessed based on the inconsistencies of zero flow on site and the time resolution claimed by flowmeter manufacturers.

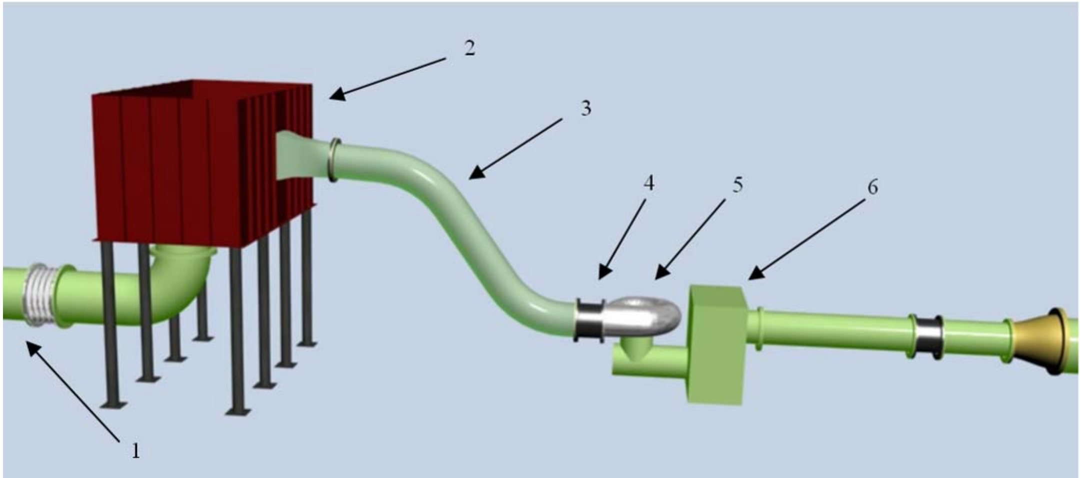
The effects of flow field disturbance are the most important issue in assessing the accuracy of 3-Gorge flowmeter, which is also the focus of this study. The installation conditions of ultrasonic flowmeters are stipulated in IEC41 and PTC18, that is, an upstream straight conduit with length of at least 10D and a downstream straight conduit with length of at least 3D should be reserved for a double-plane flowmeter with 4 acoustic paths on each plane. In the 3-Gorge Project, ultrasonic flowmeter is closely adjacent to the conduit bent upstream and the water turbine-generator downstream, almost without any straight conduit upstream and downstream, which completely violates the installation conditions specified in the two standards. In this condition, the flowmeters of 3-Gorge are designed with an 18-path configuration (see Fig.3), which is the application with the maximum number of acoustic paths currently. Although it is applicable to the complex flow field theoretically, the effects caused by flow field disturbance still need to be assessed carefully.

2. Assessment with experimental method

As the conduit diameter is as large as 12.4m in the 3-Gorge Project, actual flow calibration cannot be performed. Therefore, a model flowmeter with the diameter of DN500 was designed and manufactured with the same configuration of 3-Gorge flowmeter, and the effects of flow field disturbance on the flowmeter were analyzed using actual flow calibration in the National

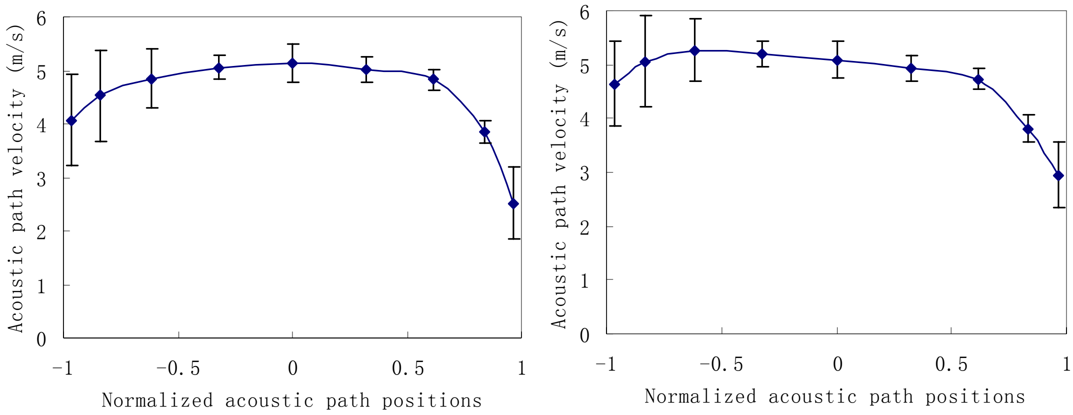
Water Large Flowrate Measurement Station (Kaifeng). According to the 3-Gorge flowmeter, model flowmeter has double-plane 2×9 acoustic paths with the acoustic path angle of 65°. Meanwhile, the plugging transducer is adopted, which is different from the patch transducer of the 3-Gorge flowmeter. As the transducer size of 3-Gorge flowmeter is very small comparing with the conduit diameter, the local flow disturbance of the transducers has little effect on the 3-Gorge flowmeter. But for the model flowmeter, the effect of the transducer dimension is more obvious, so the transducer of the model flowmeter should be as thin as possible on the condition of ensuring the mechanical strength and signal level. In our experiment, the transducer diameter is 12mm.

The National Water Large Flow Measurement Station has the largest water flow standard facility with constant head water tank and static volume method in the world. The uncertainty of their facility is 0.1% (k=2), flow range is (200~16000)m^3/h. The reduced model of DN500 was established with some simplification as shown in Fig.4. The S-type penstock upstream of the flowmeter is the focus of model, and strict geometric similarity should be assured. The upstream reservoir model is simplified as a pressure water tank, and the downstream turbine is simplified as a turbine shell without rotary vanes. The model flowmeter is not an approved product. If the indication error of the flowmeter was calibrated directly with the 3-Gorge model penstock, many other factors would be brought about. The relative method was used in the experiment in order to acquire the effects of special flow passages of 3-Gorge on the flowmeter accuracy. Indication error was obtained firstly through calibrating the flowmeter with the ideal conduits (long enough straight length upstream and downstream), and then indication error was obtained through calibrating the flowmeter with the 3-Gorge model conduits system. The difference of the two values can be regarded as the impact of the flow field disturbance on the 3-Gorge flowmeter.

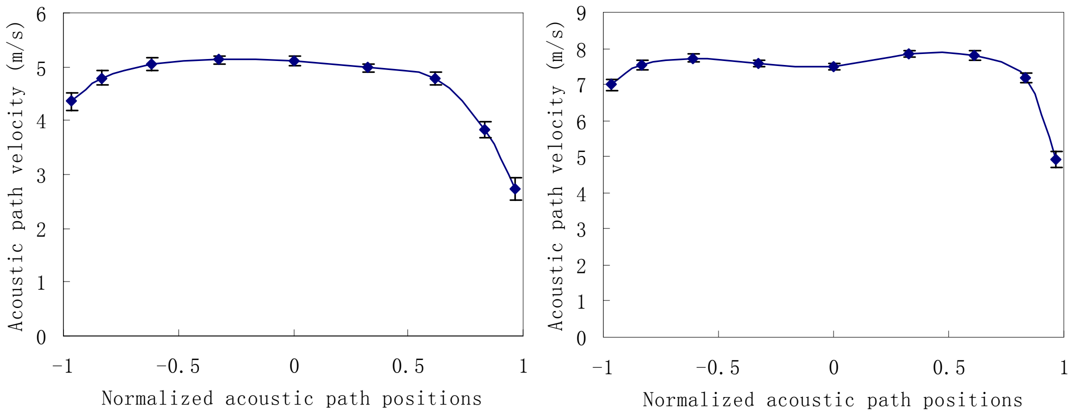


1- inlet, 2- water tank, 3- penstock, 4- flowmeter, 5- turbine, 6- downstream water tank
Fig.4. Experimental model conduits

The velocities of acoustic paths in different positions can be directly given to analyze the flow field distribution and fluctuation in the flowmeter. Fig.5a-c shows the distribution of acoustic path velocity at the average velocity of 5m/s for the model flowmeter. Due to the flow field disturbance, velocity distributions are no longer symmetrical, and there are some differences between plane A and plane B. The vertical line in Fig.5 indicates the standard deviation of velocity changes during a period of time, and the fluctuation of both plane A and B is relatively strong, but after averaging the values of plane A and B, the fluctuation is offset to a large extent. This is a reason why the double-plane configuration is adopted by ultrasonic flowmeter in the complex flow field. Fig.5d shows the distribution of acoustic path velocity measured by the 3-Gorge flowmeter at the average flow velocity of 7.5m/s, and it is found that the velocity distributions of the model flowmeter and 3-Gorge flowmeter are similar to each other. This is also the basis that the experimental results can be used to analyze the impact of flow field disturbance on 3-Gorge flowmeter.



(a) Plane A of model flowmeter (b) Plane B of model flowmeter



(c) Average of model flowmeter (d) Average of 3-Gorge flowmeter

Fig.5. Distribution of acoustic path velocity

In the model experiments, the indication errors of the flowmeter respectively installed in the ideal conduit and model conduit with different flow were obtained. Table 1 shows two experimental results with the interval of two months. Although the absolute values of indication errors in the twice measurements have changed obviously, the difference of indication errors between the ideal conduit and model conduit has changed just a little, always around 0.3%. This value can be used to reveal the impact on the flowmeter from a special conduit system in the 3-Gorge station. Considering the facility uncertainty and the model flowmeter stability, the uncertainty of our result is 0.4% (k=2). Since the same configuration is adopted in both the model flowmeter and 3-Gorge flowmeter and the measured distributions of acoustic path velocity are very close, 3-Gorge flowmeter can be regarded to have a positive error of 0.3% also. Considering the uncertainty of flowmeter itself is claimed as 0.5%, the accuracy of 3-Gorge flowmeter is better than 1% that can meet the needs of efficiency measurement.

Table 1. Comparison of indication errors of model experiment and ideal conduit

Average velocity （m/s）	Model experiment 1			Model experiment 2		
	Ideal conduit	Model conduit	Difference	Ideal conduit	Model conduit	Difference
5	-1.84%	-1.58%	0.25%	-1.58%	-1.32%	0.26%
3	-1.64%	-1.35%	0.30%	-1.63%	-1.25%	0.38%

3. Assessment with numerical method

With the development of computer and modern computing technology, numerical simulation has become one of the most important academic tools. Commercial CFD software Fluent is applied to simulate the flow field in the ultrasonic flowmeter, and virtual acoustic paths are placed to investigate the flow error, which is the difference between the indicated flow and the real flow. The difference from the experimental method is that the numerical simulation does not require reduced scale modeling, and the same thing to do is the simplification of calculation domain. The calculation domains included reservoir, penstock, turbine and draft pipe sequentially along the flow direction as is shown in Fig.6. The free surface is not taken into account in the upstream reservoir by modeling it as pressure flow. The internal structure of the downstream turbine is also neglected while only the turbine shell is considered.

Flow field in the flowmeter is the basis for analyzing flowmeter accuracy. In the computed numerical flow field, an 18-path ultrasonic flowmeter is virtualized, and the 3-D flow velocity can be interpolated to the acoustic paths. Fig.7 shows the 3-D velocity on acoustic paths of the plane A when the average velocity $\overline{v} = 5\text{m/s}$. The four subfigures show the velocity vector and the three components of the velocity vector respectively. The former three are sketched in the same scale, and the last one is sketched in a scale 5 times zoomed in as its value is too small. Significant transverse flow in the flowmeter is observed. Among the two transverse components, V_y is vertical to the acoustic paths with no contribution to acoustic path velocity, while V_z has a certain intersection angle with the acoustic paths with a not negligible contribution to acoustic path velocity. However, this contribution is a kind of disturbance for flow measurement and also the reason why the single-plane configuration should not be adopted in the flowmeter when the transverse flow is obvious.

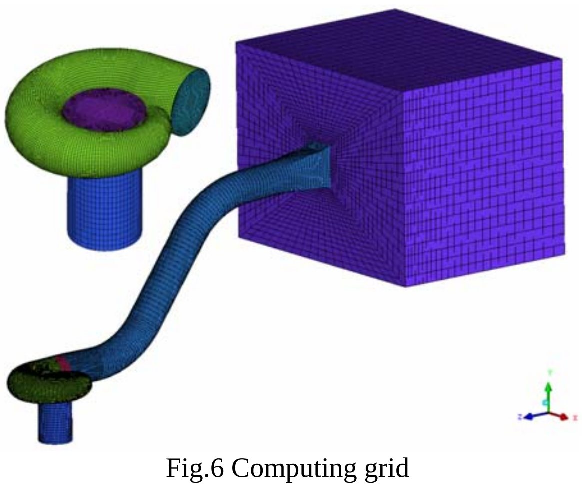
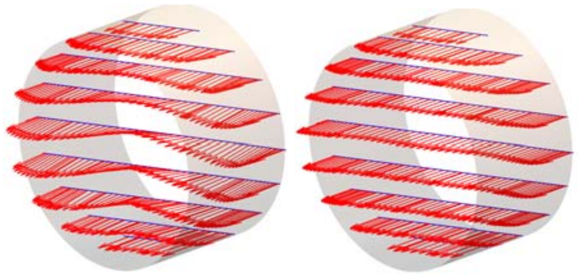
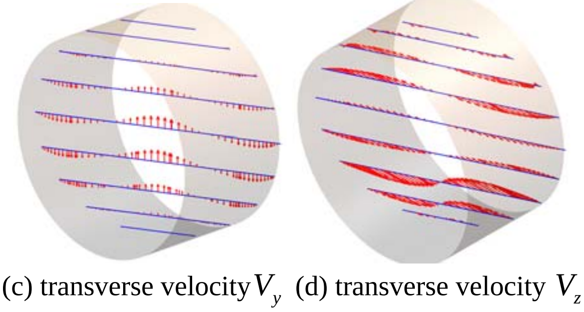


Fig.6 Computing grid



(a) 3-D velocity V (b) axial velocity V_x



(c) transverse velocity V_y (d) transverse velocity V_z

Fig.7. 3-D velocity distribution of the acoustic lines

On the basis of 3-D velocities of the acoustic paths, the distribution of acoustic path velocity of the flowmeter can be obtained through integration method. The simulation results of acoustic path velocity (including the contribution of both the axial flow and the transverse flow) and the historic records of 3-Georges flowmeters in the same flow-rate condition are compared, as is shown in Fig.8, which indicates a perfect match with a common distribution pattern of acoustic path velocity. It suggests that the numerical result can reveal the actual flow field to a certain degree. Both model experiments and field observation data show that the distributions of acoustic path velocity on plane A and B have a certain difference. However, the numerical results have no such difference. The reason may be that the protrusion effect of the transducer is not considered in the numerical calculation, as the local flow disturbance is very important to the model flowmeter.

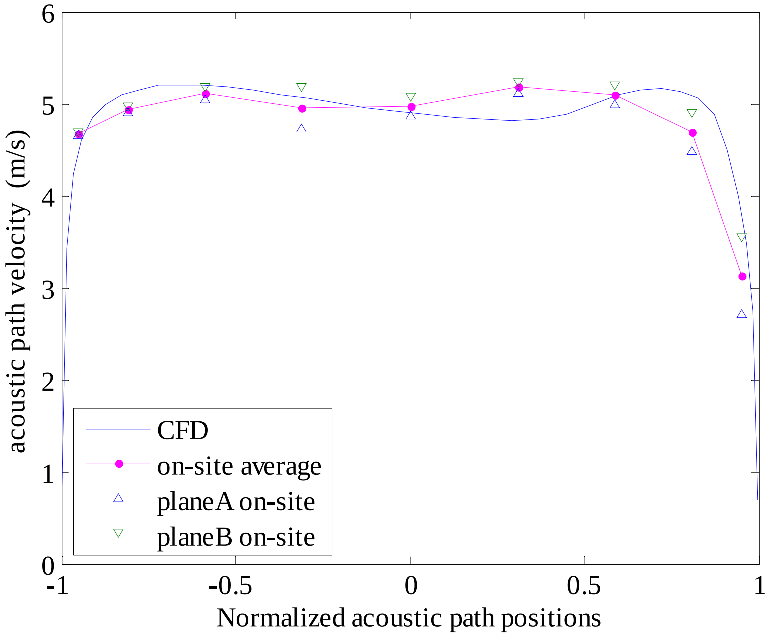


Fig.8. CFD velocity distribution vs. observed results

Through the comparison between the indication flow and the real flow, the flowmeter error related to complex flow field can be analyzed. The indication flow can be obtained through the weighted sum of acoustic path velocities, while the real flow can be obtained through a surface integral in the flow field. The difference between them is the flow error caused by the special conduit. The flow errors at different average velocities are shown in Table 2. The simulation reveals that complex flow filed of 3-Gorge will make the flow indication of the flowmeter 0.2% higher, and this value almost can not be affected by flow-rate. In addition, transverse errors of two planes are around 0.1% and -0.3% respectively, and it can be offset through averaging the two planes' values. This is the main reason why the double-plane configuration should be adopted in the flowmeter under complex flow condition.

Table 2. Flow-rate errors at different average velocity

Average velocity (m/s)	Plane A		Plane B		Average of plane A and B		
	Axial Error	Transverse Error	Axial Error	Transverse Error	Axial Error	Transverse Error	Total Error
1	0.33%	0.10%	0.25%	-0.29%	0.29%	-0.10%	0.19%
3	0.32%	0.08%	0.24%	-0.30%	0.28%	-0.11%	0.17%
5	0.34%	0.10%	0.25%	-0.31%	0.30%	-0.11%	0.19%

4. Conclusion

The installation conditions of the flowmeter are of great significance, especially for the 3-Gorge Power Station, because there is almost no straight conduit upstream or downstream of the flowmeter, which will cause a great measurement error of the flowmeter. Since flow measurement involves huge economic interests, it has aroused extensive concerns. In this study, both of experiments and numerical simulation have been used to analyze the effect of installation conditions. The combination of those two methods can be verified mutually to ensure the reliability of the results and are the most feasible and effective methods for this kind of problems.

The relative method is used in the experiment, and the indication error difference of the model flowmeter in the model condition and ideal condition is regarded as the impact of special penstock of the 3-Gorge on the flowmeter. It is concluded that this impact will make the flowmeter indication higher by about 0.3%, while the same value is about 0.2% by numerical simulation. With further consideration of the uncertainty of results and the performance of flowmeter, the accuracy of 3-Gorge flowmeter is better than 1% that can meet the need of the efficiency measurement.

The diameter of 3-Gorge flowmeter is huge, thus the local flow disturbance of the transducer can be neglected. However, for the ultrasonic flowmeter with relatively small diameter, the local flow disturbance of transducer may cause a significant impact on the flowmeter. We have found that the impact of the local flow disturbance may cause a negative flow error of about 1% for the flowmeter with DN500 diameter, and the in-depth researches related to this point are to be conducted in the near future.

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