ANALYSIS OF FLOW FIELD CHARACTERISTICS IN THE HYDROTURBINE INTAKE PENSTOCK OF THREE GORGES POWER STATION BY MODEL EXPERIMENT

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Abstract: The accuracy of ultrasonic flowmeter is closely related to flow field on the job site. Because the hydro turbine intake penstock of Three Gorges power station is very large and specially shaped, the flow field at position of ultrasonic flowmeter installed and its effect have a lot of uncertainty. A model pipe system and a model meter with 500mm diameter were designed and machined according to penstock of Three Gorge power station. The characteristics of velocity distribution were sketched from flow rate tested by each path at different altitude of the flowmeter, while the dispersion of each path shows the degree of disturbance. Comparing several group tests result on different experimental condition, it is quite obvious that velocity distribution is asymmetry. It's also found that ultrasonic flowmeter with double measurement planes can reduce the effect of transverse flow, but error of flowmeter is about positive 0.3% due to the special flow field of the penstock model.

Keyword: Flow field analysis; Large diameter flowmeter calibration; Model experiment; Ultrasonic flowmeter.

1. Introduction

The hydraulic turbine is the core equipment in a hydropower station, and the turbine efficiency is an important indicator to characterize the performance. A real-time monitoring on the hydraulic turbine efficiency is of great significance to the plant as it is necessary for the achievement of technical specification assessment, economic operation, and energy saving & cost reduction. The turbine discharge is the most important parameter in measuring turbine efficiency.

Large diameter multi-path ultrasonic flowmeter becomes the main method for turbine discharge measurement, owing to its small pressure loss, fast response and easy installation and maintenance, etc., and its working principle is expressed in the following formula:

$$Q = \frac{D^2}{2} \sum_{i}^{n} W_i' v_i \qquad （1）$$

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Where, Q is the pipe discharge of the circular section; D is pipe diameter; W_i is the weight coefficient of each acoustic path; and the expression of the linear mean velocity v in each acoustic path is as follows:

$$v = \frac{L}{2\cos\phi}\left(\frac{1}{t_{down}} - \frac{1}{t_{up}}\right)$$ （2）

Where L is the acoustic path length; ϕ is the acoustic path angle; t_{down} and t_{up} are the ultrasonic transit time downstream and upstream, respectively.

In order to measure the turbine efficiency in the Three Gorges Power Station, three ultrasonic flowmeters were installed in the generating sets to the right-bank. The flowmeter accuracy was widely concerned due to its close reference to the measurement result of the turbine efficiency. It was expected that the discharge measurement accuracy can be better than ± 1% for the acceptance of the turbine-generator sets. However, as the Three Gorges Power Station is the world's largest hydropower station, both the discharging section of a single set and the discharge were huge; the pipe diameter was as large as 12.4m, therefore, conventional discharge measurement methods could not be used for the performance assessment of the flowmeters installed in the Power Station. On the other hand, as is shown in Figure 1, the shape of the pipe installed in Three Gorges Power Station was special, and there almost existed no straight pipe ahead of and behind the flowmeter. However, the existing standards, such as IEC41[1] and PTC18[2], or the W_i in formula (1) adopted by the manufacturers were obtained based on fully developed turbulent flow fields, therefore, the flowmeter accuracy was greatly affected by the flow field properties of the turbine intake pipe where the flowmeter was installed.
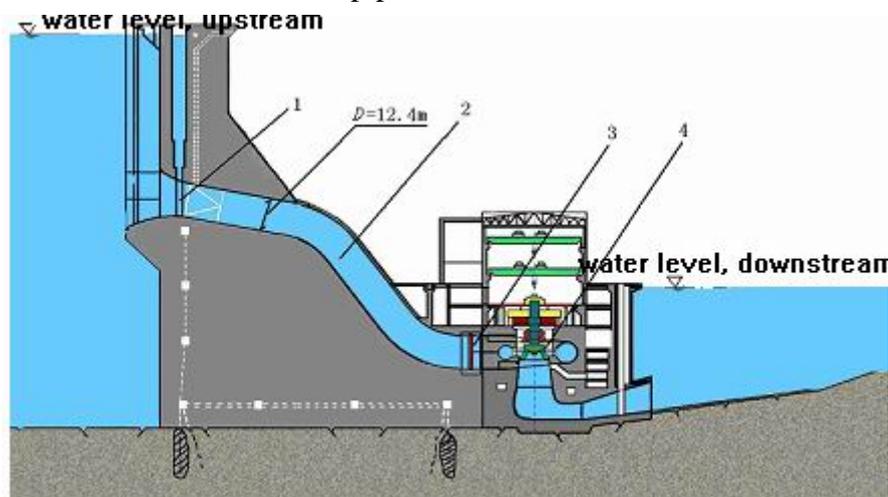
1—intake rectangular culvert, 2—intake penstock, 3—flowmeter, 4—turbine
Fig. 1 The turbine discharge passage in the Three Gorges Power Station

For the water project experiments which can't be carried out on the engineering prototypes, model experiments are often used as an important research approach to study certain characteristics of the prototype, for example, prediction and evaluation of turbine efficiency[3]. With a scaled-down model adopted, a model experiment, based on the principle of hydraulic similarity, aims to simulate the velocity distribution of actual discharge passage as exactly as

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possible, which was used to obtain the measurement errors on the ultrasonic flowmeter caused by irregular flow distribution. For pressure flowing, the experiments should be designed according to Reynolds' law of similarity. However, it makes the velocity too high to calibrate the actual flow, therefore, the common prototype velocity points was still adopted. Model CFD calculations with different scales showed that the measurement errors of the ultrasonic flowmeter in a model with small scale were much greater than that with large-scale, that accorded with the characteristic of principle and structure of the ultrasonic flowmeter [4]. Therefore, it was possible to give out a more conservative result of the measurement accuracy with the method of simulating pipes with smaller diameters.

2. Model Design

According to the existing experimental capability, the model pipe diameter was determined as 500mm, so the geometric scale between the model and the prototype was 1:24.8, the design and machining of the model were converted on this scale in accordance with the principle of geometric similarity. Based on different structures, the model penstock system was divided into five parts from upstream to downstream: elevated water tank, upstream simulation pipe, ultrasonic flowmeter, downstream spiral case, and sink, as is shown in Fig. 2.
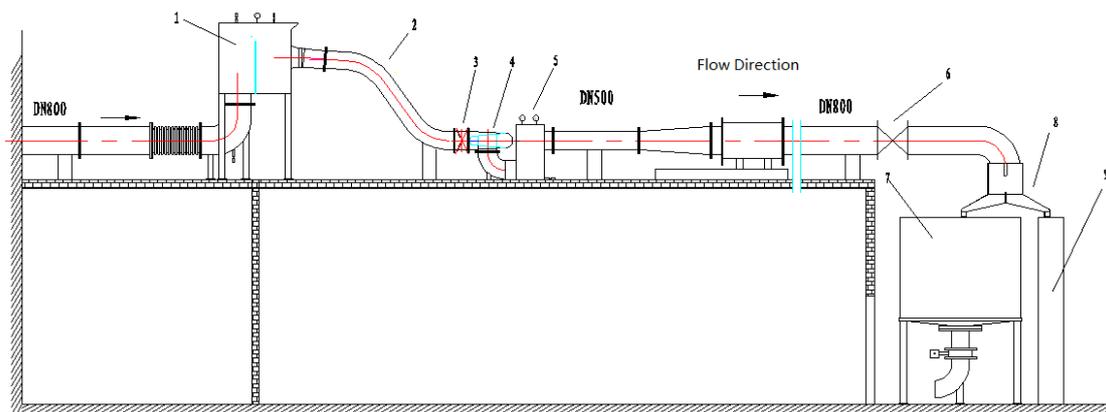

1—Elevated water tank, 2—Upstream simulation pipe，3—Flowmeter, 4—Spiral case, 5—Sink, 6—Control valve, 7—Diverter, 8—Standard metal tank，9—Bypass pipe

Fig. 2 Facilities for the model experiment

According to the pipe structure of the prototype, two elbows in the upstream and the spiral case in the downstream directly connected to the flowmeter were the main factors affecting the flow field, and they were also the key points and difficulties in the model pipe designing. The pipe shape was kept in consistence with the prototype as much as possible during the pipe machining, and the "setting out" method was adopted for some details.

Another key point in the model design was the model flowmeter. Similar to the prototype, as is shown in Fig. 3, the model flowmeter was an 18-path ultrasonic flowmeter, and the acoustic path angle was 65 °, with PTC18 standard adopted in probe (ultrasonic energy converter) layout.
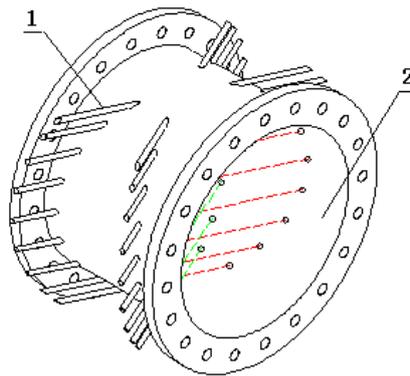
1 - Ultrasonic energy transducer, 2 –Meter body
Fig. 3 Model flowmeter

The prototype of the Three Gorges Power Station is a complete water project, and its structure is very complex, which should be simplified in the model. For example, an elevated water tank in the model was used to substitute the upstream intake of the reservoir in the prototype which was difficult to be simulated; only the scroll passage of spiral case in the downstream of flowmeter was retained which directly influenced the flowing of the fluid, while other complex mechanical structures were omitted.

3. Model Experiment

The experiment was carried out on a static-volumetric method flow facility in the National Large Water Flow Measurement Station, and the uncertainty of this facility was 0.1% (*k*=2). The model experiment consisted of three groups of the experiments in the following sequence:
(1) Ideal pipe experiment; (2) Model pipe experiment; (3) Ideal pipe retest

Ideal pipe experiment: the experiment was carried out with model flowmeter installed in the conventional experiment pipe (ideal pipe); this pipe could provide upstream and downstream straight pipe with sufficient length for the flowmeter (upstream straight pipe with a length of 20D of the flowmeter and downstream straight pipe with a length of 10D), to achieve the ideal velocity distribution conditions in IEC41. Model pipe experiment: the whole model pipe was connected in series into the standard device; the measurement performance of the flowmeter was tested in the model conditions with the standard facility, as is shown in Fig. 2. Ideal pipe retest: the flowmeter was re-installed in the ideal pipe to confirm the stability of flowmeter.

The maximum flow rate of 5m/s was provided by the standard facility, each group of experiments was carried out at two velocity points, 5 m/s and 3 m/s; the experiments at each experimental point were repeated for no less than 6 times. Compared with the standard facility, the indication error and repeatability of the flowmeter in each group of experiments were obtained, and experimental methods were accorded to the National Verification Regulation [5].

4. Experimental Results and Analysis

4.1 Flow Field Analysis Based on the Acoustic Path Velocity

According to the principle of multi-path ultrasonic flowmeter, the average linear velocity of one line on the installation cross-section of the flowmeter was measured on each path; as for 9-path flowmeter, 9 path velocities on the axial direction could be measured, which could reflect the general velocity distribution of the cross-section. The differences of the path velocity distribution between the ideal pipe and the model pipe were compared at first.
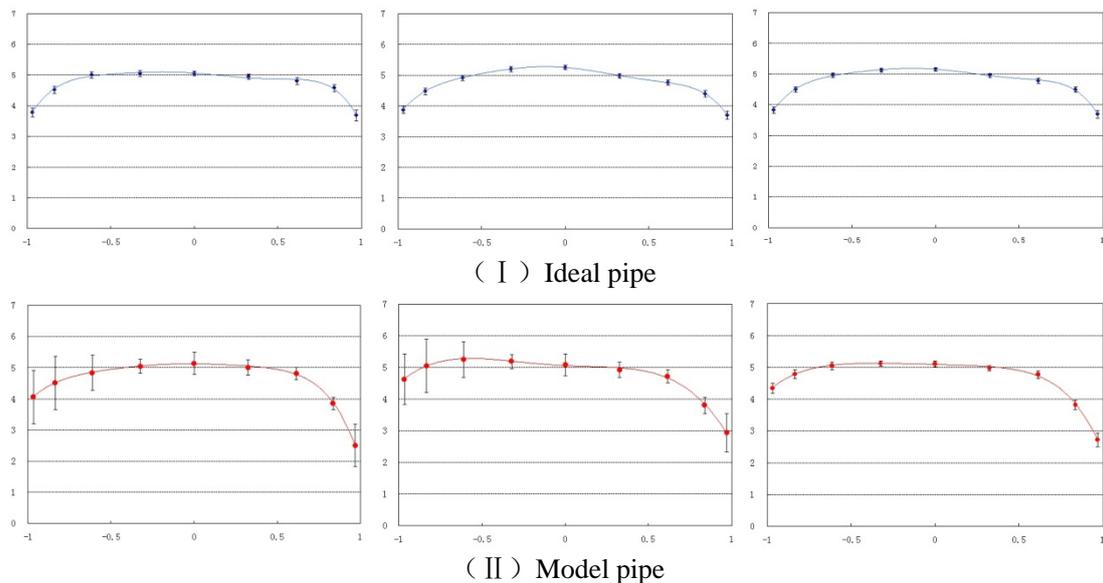
（Ⅰ）Ideal pipe

（Ⅱ）Model pipe

Fig. 4 The velocity distribution of ideal pipe and model pipe

In the horizontal direction in each group of the diagrams, there were average "path velocity distribution profiles" of the planes in a sequence of plane A, plane B, and plane A-B (average of plane A and plane B). The vertical coordinate of each small profile was the velocity (unit: m/s) and the horizontal coordinate was the relative height of the acoustic path (d/R, distance between acoustic path position and axis line of pipe, and R is radius of the pipe); the 9 points stand for the average values of the fluid velocity measured on the 9 paths (serial number of path, 1# to 9#, from left to right); the line of each point on the vertical coordinate stands for the standard deviation of the path fluid velocity; the greater the line length was, the greater the dispersion of measurement result was, which also suggested that the flow disturbance at the position of this acoustic path was higher.

By comparative analysis, it can be clearly seen that the dispersion of a single path flow measurement result in the model pipe was significantly greater than that in the ideal pipe, which indicated that the flow was complex and there existed mixed flow (horizontal flow) under the model pipe conditions. The most severe dispersion appeared on the Path 9# on the top and Path 1#, 2#, and 3# at the bottom, and the phenomena on the planes A and B were consistent, which indicated that flow field fluctuations were greater on the top area and in large area at the bottom. It was noteworthy that plane A-B, the average of the measurement values from the corresponding paths on the two planes showed a good stability and its dispersion was not only far smaller than that of a single plane, but also close to the ideal pipe level. This indicated that flow was instable

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and there existed apparent horizontal flow in the model pipe. That is, simultaneous measurement on sections A and B could effectively eliminate most of the influences caused by horizontal flow, and the repeatability and reliability of measurement results were also improved.

Comparing the velocity distribution patterns, it can be found that the ideal pipe velocity distribution curve was generally close to the fully developed turbulent distribution, and symmetrical; while for the model pipe, it was apparently asymmetrical, with the velocity measured on the top paths low and that on the bottom paths high. In case that only the experimental pipe conditions of the flowmeters were changed and other measurement conditions were kept the same, the measurement errors could be mainly attributed to different velocity distributions caused by different pipe conditions.

In a further experiment of flow field analysis, the upstream pipe and the downstream pipe of the flowmeter in the model were changed into long straight pipes respectively, and a comparison of velocity distributions were carried out:
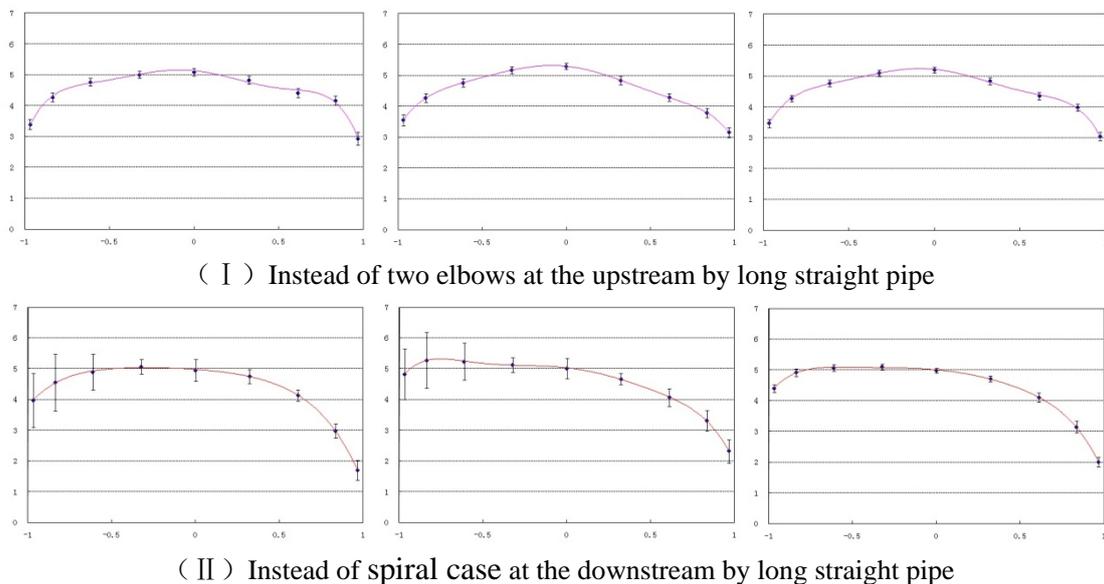

（Ⅰ）Instead of two elbows at the upstream by long straight pipe

（Ⅱ）Instead of spiral case at the downstream by long straight pipe
Fig. 5 Velocity distribution of different upstream and downstream pipe conditions

A contrast of Fig. 4 and Fig. 5 showed that while the upstream pipe of the flowmeter in the model pipe experiment were changed into long straight pipe, the velocity distribution curve and the velocity measurement dispersion of each path were similar to those in the ideal pipe experiment. But while the downstream pipe were changed into long straight pipe, the velocity distribution curve and the velocity measurement dispersion were very close to those of complete model pipe. Therefore, it can be concluded that as major flow field influence of the model pipe came from upstream pipe, with relatively small influence from the downstream pipe.

4.2 Quantitative Analysis of the Influence of Flow Field

With comparison of the experiment results of the ideal pipe and the model pipe, the influence of special flow fields in the model on the measurement performance of the flowmeter was estimated. The quantity of the influence, E_d, can be obtained with the following formula:

$$E_d = E_m - E_p \qquad\qquad (3)$$

Where, E_m and E_p are the indication errors of the flowmeters of the model pipe experiment and ideal pipe experiment. It was mainly about to avoid the performance deficiencies of the flowmeter itself and failure to reflect the experimental results exactly that a contrast described above rather than an evaluation of the performance only based on the experiment result of model pipe experiment was adopted. The flowmeter was newly designed and manufactured, still in the model machine phase, and the reliability of its absolute values of the indication error was still in need of further study. For this experiment method, good stability was required for the flowmeter. The model experiment was repeated twice with an interval of two months between each other, so as to observe the experimental reproducibility. The statistical data of the twice experiments are shown below:

Table 1 Model experiment result

Experiment No.	Velocity point	E_p	E_m	E_d
	m/s	%	%	%
Model	5	-1.84	-1.58	0.25
experiment 1	3	-1.64	-1.35	0.30
Model	5	-1.58	-1.32	0.26
experiment 2	3	-1.63	-1.25	0.38

4.3 Uncertainty Analysis

The uncertainty of E_d, u_d, can be obtained with the following formula:

$$u_d = \sqrt{u_m^2 + u_p^2 + u_s^2} \qquad\qquad (4)$$

Where, u_m and u_p are the uncertainty of flowmeter indication error in the ideal pipe experiment and the model pipe experiment, respectively. With the same mathematical model, the main source of uncertainty was the uncertainty of the facility and the repeatability of measurement. Because different metal tanks and diverters in the same facility were used in the two kinds of experiments, the uncertainties introduced were both: 0.1%/2 = 0.05%, and the correlation was neglected. The uncertainty, u_s, was introduced by the stability of the flowmeter. The stability of the flowmeter was obtained from the difference between the ideal pipe and the retested ideal pipe in one time of model experiment, and its distribution was uniform. It could be obtained from the calculation of formula (5):

$$u_s = \frac{|E_P - E_F|}{\sqrt{3}} \qquad\qquad (5)$$

Where, E_F is the indication errors of the flowmeters of ideal pipe retest. See uncertainty analysis in Table 2:

Table 2 Uncertainty analysis on the model experiment results

Experiment No.	Velocity point	u_P	u_M	u_s	u_d
	m/s	%	%	%	%
Model experiment 1	5	0.09	0.08	0.14	0.18
	3	0.05	0.14	0.05	0.16

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| Model experiment 2 | 5 | 0.10 | 0.11 | 0.12 | 0.19 |
| | 3 | 0.06 | 0.10 | 0.18 | 0.21 |

As is shown in Table 1, the results of the 4 groups of experiments were relatively consistent with each other; the values of E_d were all positive and close to each other; therefore, the arithmetic mean value was taken as the final result, with a maximum uncertainty in Table 2, namely:

$$\overline{E_d} = 0.30\%，\ U_d = 0.42\%，（k=2）$$

Since $\overline{E_d}$ value is positive, the influence of model pipe on flow field made the flowmeter indication a bit higher.

The model experiment results were further applied to the prototype. Although the actual flow calibration of the ultrasonic flowmeter installed in power plant was not carried out, the manufacturer's products of identical pattern had passed strict product certification. The accuracy of the factory products was up to class 0.5 under ideal installation conditions. Although the flowmeter had certain indication errors due to the specific conditions in the Three Gorges Power Station, and the uncertainty had been magnified, it was estimated that its accuracy still achieved $\pm$ 1%, which met the requirement of turbine efficiency in the hydropower station.

5 Conclusions and Discussions

The problems in flowmeters measurement encountered in Three Gorges Power Station were also common in the calibration of the large-diameter ultrasonic flowmeter and plant discharge measurement. Introducing the model experiment method into the flow measurement field was one of the most applicable and effective methods to solve the problems. It is found that the flow field distribution in the flowmeter in the model showed obvious asymmetry. Although the double planes flowmeter was effective in reducing the influence of horizontal flow, a special flow field in the model penstock still caused about 0.3% of positive deviation. At present, the model experiment method is in need of further improvement, for example, the application of model results depends on the basic performance of reliable flowmeters in the prototype, which needs to be guaranteed by establishing a complete set of on field calibration standard; on the other hand, the influence introduced by different scales used in the models also needs further evaluation.

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