The Application of Turbine Efficiency Measurement in Huge Hydraulic Power Stations

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Abstract
The purposes, method, results and application of hydraulic turbine efficiency test are introduced briefly in this paper about four huge cascade hydraulic power stations in a river basin, in which there are Francis and Kaplan two types turbines. The absolute efficiency measurement using ultrasonic flow meter and relative efficiency measurement using differential pressure device are applied successfully in practice. The efficiency measurement result and its application provide data support for the safety, stability, high-efficiency operation of the huge hydraulic power units. According to the summary of the practice in the turbine efficiency measurements, some topics about efficiency tests which should be concerned are pointed out, and the corresponding solutions are proposed also.

1. Introduction

1. 1 Hydraulic Turbine Efficiency Measurement

Hydraulic turbine efficiency measurement includes absolute efficiency measurement and relative efficiency measurement. Absolute efficiency measurement includes direct and indirect measurement.

1) Absolute efficiency direct measurement method

The thermodynamic method is a representative absolute efficiency measurement method. Its principle is the The law of Conservation and Transformation of Energy(the First Law of Thermodynamics). Hydraulic loss will come into being while water passes through the passageway of the hydraulic turbine, and the hydraulic loss will convert into thermal energy. And that will results in temperature difference between the inlet and outlet of the hydraulic turbine. Efficiency can be calculated by the parameters,such as temperature, pressure, velocity, elevation and the shaft power measured at specified section and location of spiral case and draft tube.[1]

2) Absolute efficiency indirect measurement method

The steps of the absolute efficiency indirect measurement method are as following. Firstly, the discharge, water head and power should be measured. Secondly, the efficiency will be calculated by the mentioned parameters. The main difficulty and key problem is the absolute turbine discharge measurement. The recommend absolute discharge measurement methods in IEC 60041 are current-meter method, pilot tubes, pressure-time method, tracer methods,weirs,etc[2]. But for huge hydraulic power units, available absolute discharge methods are limited because their pipe diameter are so large and the water head are very high.

As for current-meter method, because of the influence of the mounting bracket and the current meters on the flow regime, the measurement precision will decreases absolutely. Further more, it is difficult to install the mounting bracket before the runner of large diameter, high water head hydraulic turbines, and the installation of the bracket can bring risk for the safety operation of the turbines.

Pressure-time method is suitable for the shut down operating condition of turbine, and is not suitable for the discharge measurement under normal operating condition. For huge hydro-generators, the discharge maybe reach 1000 m^3/s[3], tracer methods is also not available in engineering application.

From the view of present technology and engineering application, it is more viable using ultrasonic flow meter to measure the absolute large-caliber turbine discharge.For a long time, the key problem for ultrasonic flow meter is the on-site calibration. Scientists and researchers represented by National Institute of Metrology of China have done many effective scientific research and practical works, including the influence of the factors such as probe installation, geometric parameter, integration method on the accuracy of the ultrasonic flow meter[4-16], and some related standards have been set[17-18] for the on-site calibration , so that we can increase the accuracy of the ultrasonic flow meter and its accuracy can meet the command of the turbine absolute efficiency test[19].

3) Relative efficiency measurement method

Turbine relative efficiency is measured by differential pressure devices. The principle of differential pressure methods is as following. When water with a certain velocity passes spiral case, centrifugal force will be produced because of the bend of the center line spiral case, differential pressure ΔH will come into being between the inner side and outside of the spiral case. Based on the Bernoulli equation, the discharge Q is proportional to the square root of the ΔH (according to IEC 60193-1999, the index is valid when it is between 0.48 and 0.52[20]). Assuming the proportionality coefficient is K. How much the K on earth is normally unknown. Assuming the highest efficiency is 100% among all the operation conditions, the K' can be calculated, for others operation conditions, the discharge and efficiency can be calculated by K'.

1. 2 The purposes of turbine efficiency measurement

The purposes of turbine efficiency measurement is shown as following:

1) Verifying the efficiency parameter meets the command in contract or not by comparing the measured value with the contract;
2) Searching for the high efficiency conditions in the operating area by absolute or relative efficiencies to instruct the hydro-generator operation and increase the water power utilization rate, so as to maximize the output of a single hydro-generator unit;
3) Comparing the absolute efficiency of different hydro-generator units under same operating conditions by absolute efficiency to support scientific dispatch and economic operation in hydraulic power station, so as to maximize the output of the station[21-23];
4) Calibrating the spiral case differential pressure coefficient of same type turbines by absolute discharge and spiral case differential pressure measurement;
5) Searching for the Kaplan unit on-cam relation by absolute or relative efficiency measurement to assure the stable and high efficiency operation of the unit.

2. Turbine efficiency measurement in cascade hydraulic power stations

2. 1. Relative efficiency measurement during reservoir water level increasing in Hydraulic Power Plant A

The relative efficiency curves of 5 hydraulic turbines in Hydraulic Power Plant A are showing as Figure 1 to Figure 5. The variation tendency of the efficiency curves measured in model test and on-site prototype measurement are basically same, the maximal efficiency points in on-site prototype measurement match basically with the correction values from model tests. The measurements show that the energy parameters of the model turbines and prototype turbines are close basically[24].

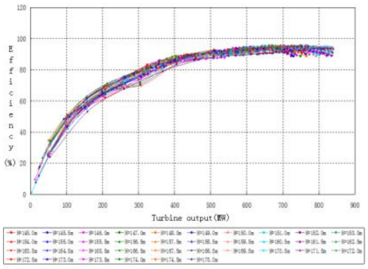

Figure.1 Prototype turbine efficiency curve of Unit 1

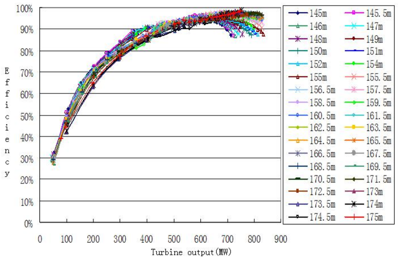

Figure 2 Prototype turbine efficiency curve of Unit 2

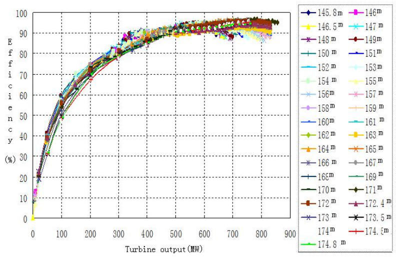

Figure 3 Prototype turbine efficiency curve of Unit 3

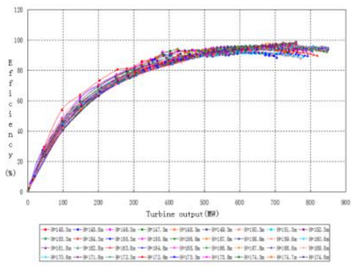

Figure 4 Prototype turbine efficiency curve of Unit 4

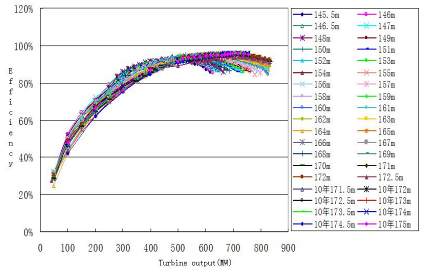

Figure 5 Prototype turbine efficiency curve of Unit 5

2. 2. Absolute efficiency measurement during type test in Hydraulic Power Plant A

A turbine absolute efficiency was measured by manufacture on-site during type test in Plant A, the test result are shown as Figure 6. From the Figure, we can know the efficiency of prototype and model are very close under the condition with output between 420MW to 680MW, there is some deviation under the condition with output more than 680MW. We can get the conclusion that the model test result and prototype test result are accurate in a certain sense, because the error is very small between the two test results, considering that the model test and prototype test are 2 independent systems in terms of time and geography, and that the discharge measurement methods in the two tests are different, electromagnetic flowmeter was used in model test, ultrasonic flow meter was used in prototype test[25].

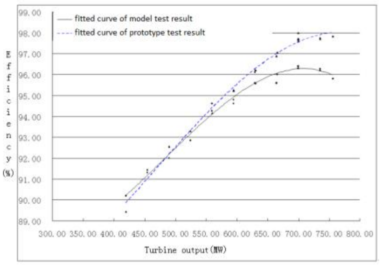

Figure 6 Absolute efficiency of Prototype and model test

2. 3. Relative and absolute efficiency measurement during reservoir water level increasing in Hydraulic

Power Plant B

Three units with ultrasonic flow meter were chosen to perform load change tests during reservoir water level increasing in Hydraulic Power Plant B, the turbine absolute efficiency and relative efficiency were both measured. The relationship between absolute discharge measured by ultrasonic flow meter and the square root of spiral case differential pressure are shown as Figure 7 to Figure 9. From the figures, we can see that the absolute discharge is proportional basically to the spiral case differential pressure. The measured prototype turbine efficiency and model test correction result are shown as Figure 10 to Figure 12. From the figures we can see that the variable changes and actual value are basically close between the prototype on-site test and model tests.

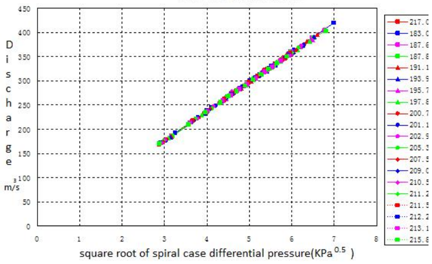

Figure 7 measured absolute discharge VS square root of spiral case differential pressure of Unit 1 in Plant B

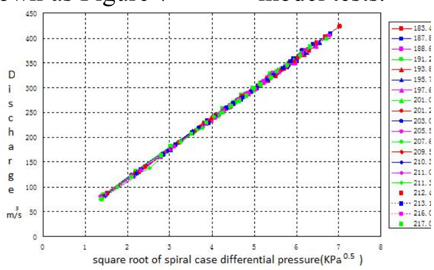

Figure 8 measured absolute discharge VS square root of spiral case differential pressure of Unit 2 in Plant B

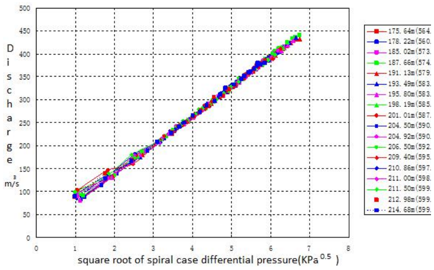

Figure 9 measured absolute discharge VS square root of spiral case differential pressure of Unit 3 in Plant B

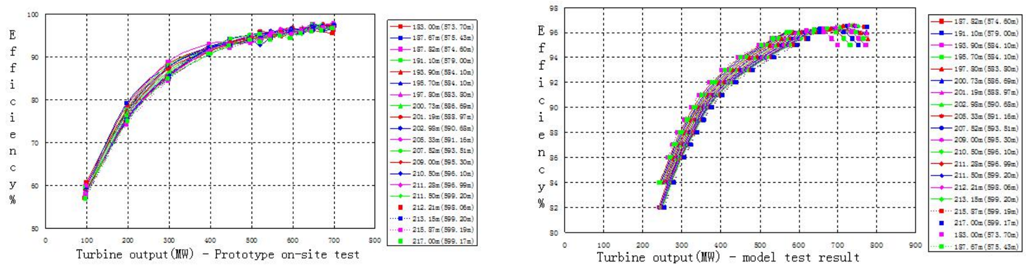

Figure 10 prototype efficiency measured on-site VS correction efficiency from model test of Unit 1 in Plant B

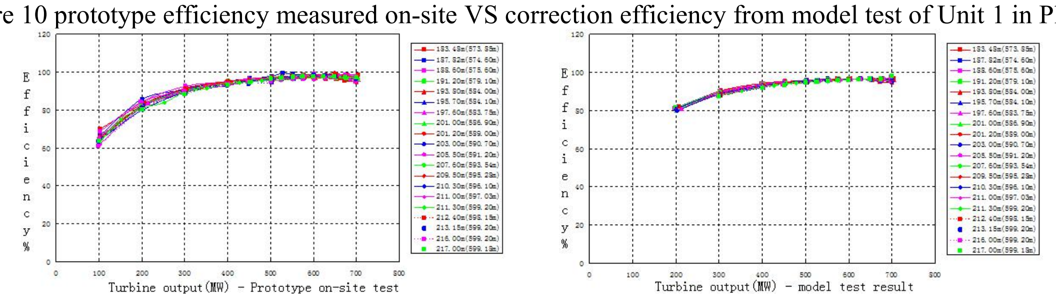

Figure 11 prototype efficiency measured on-site VS correction efficiency from model test of Unit 2 in Plant B

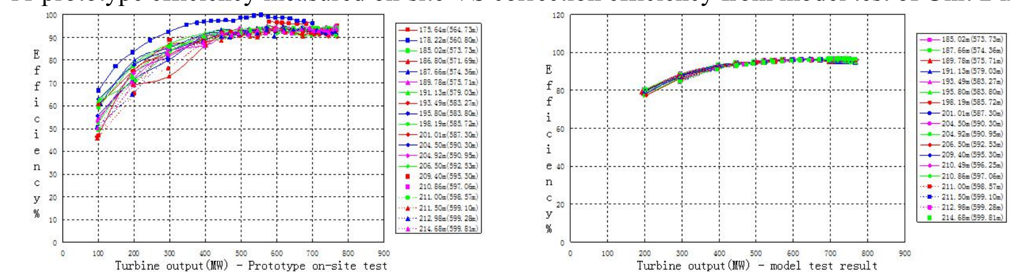

Figure 12 prototype efficiency measured on-site VS correction efficiency from model test of Unit 3 in Plant B

2. 4. Relative and absolute efficiency measurement during reservoir water level increasing in Hydraulic Power Plant C

Two units with ultrasonic flow meter were chosen to perform load change tests during reservoir water level increasing in Hydraulic Power Plant C, the turbine absolute efficiency and relative efficiency were both measured. The relationship between absolute discharge measured by ultrasonic flow meter and the square root of spiral case differential pressure are shown as Figure 13 and Figure 14. From the figures, we can see that the absolute discharge is proportional basically to the spiral case differential pressure. The measured prototype turbine efficiency and model test result are shown as Figure 15 and Figure 16. From the figures we can see that the variable changes and actual value are basically close between the prototype on-site test and model tests.

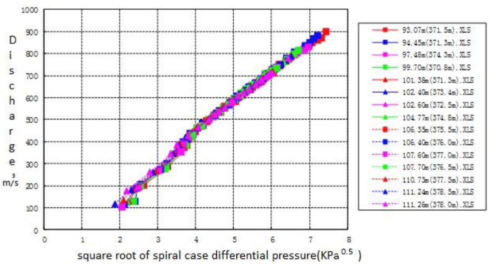

Figure 13 measured absolute discharge VS square root of spiral case differential pressure of Unit 1 in Plant C

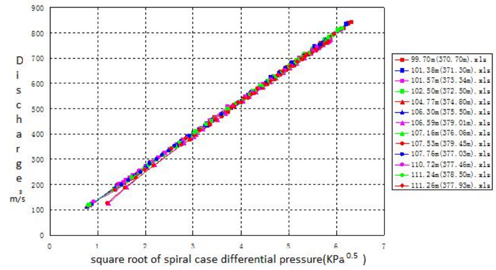

Figure 14 measured absolute discharge VS square root of spiral case differential pressure of Unit 2 in Plant C

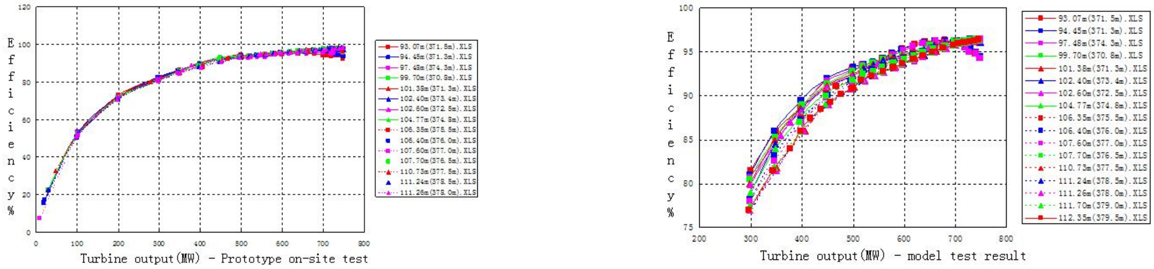

Figure 15 prototype efficiency measured on-site VS correction efficiency from model test of Unit 1 in Plant C

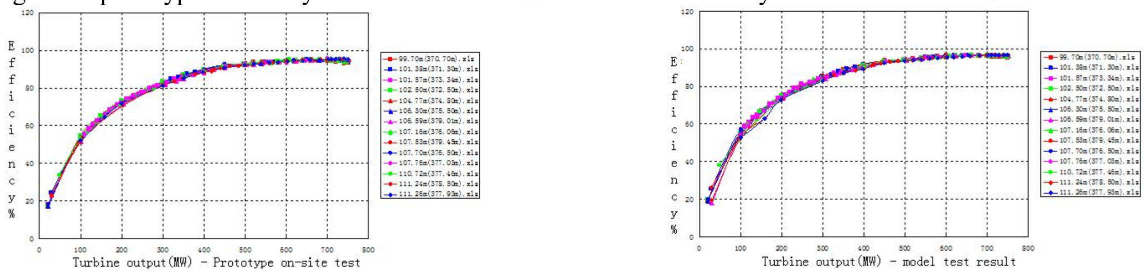

Figure 16 prototype efficiency measured on-site VS correction efficiency from model test of Unit 2 in Plant C

2. 5. Relative efficiency measurement after capacity expansion reformation in Hydraulic Power Plant D

One Kaplan turbine unit was selected to measure relative efficiency after capacity expansion reformation in Hydraulic Power Plant D. Load change tests under on-cam operating conditions given by the manufacture were performed, load change test under the conditions with fixed guide vane opening and variate propeller blade opening were performed also. The measured relative efficiency and turbine output of load change tests under on-cam curve conditions are shown as Figure 17. From Figure 17, we can see the turbine efficiency is higher relatively under the operating conditions closing to the rated water head. The measured relative efficiency and output of load change tests under the operating conditions with fixed guide vane opening and variate propeller blade opening when water head is 19.9m are shown as Figure 18. By the envelop line for the highest efficiencies measured in the load change tests under the operating conditions with fixed guide vane opening and variate propeller blade opening, we can get the actual on-cam curve under a certain water head. According to the test results, the on-cam curve given by the manufacture and measured by the on-site test are basically the same.

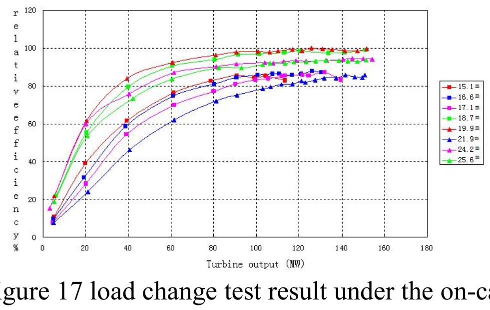

Figure 17 load change test result under the on-cam operating conditions in Plant D

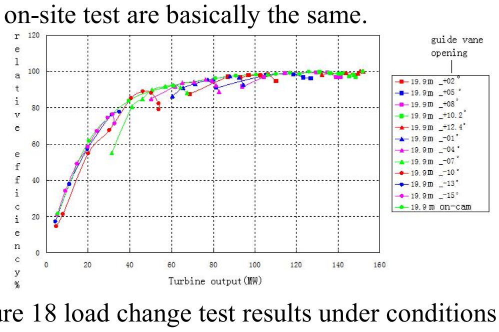

Figure 18 load change test results under conditions with fixed different guide opening when H=19.9m in Plant D

3. Application of efficiency measurement test result

3. 1 Economic operation for hydraulic power plant

Scientists and engineers have done many works about hydraulic power plant economic operation combining the unit efficiency and stable operating conditions, and the research results have been applied in practise[21-23]. As for a single unit, it should be operated under the high efficiency operating conditions. As for a plant, the overall efficiency should be maximized to use the water resource sufficiently. Based on the result of reference [23], 1% to 2% of total annual power generating capacity would be increased if an optimized operating strategy was performed according to the actual river discharge in 2012.

3. 2 On-cam relationship confirmation for Kaplan turbines

It is dangerous for Kaplan turbine operated under off-cam conditions, its efficiency is low and the stability is poor. The on-cam curve can be gotten by the relative efficiency test so as to guarantee the high efficiency and stable operating for the Kaplan unit.

4. Discussion

Many absolute efficiency tests and relative efficiency tests and research have been performed in the basin cascade power station by ultrasonic flow meter and differential pressure devices, some achievement and experience have been gotten also, and some scientific research results have been applied in practise. But some points about the application of efficiency measurement in large hydraulic power units should be payed attention and further discussed.

4. 1 The efficiency measurement method selection

The thermodynamic method is recommended to measure the absolute efficiency directly in GB/T 20043 (IEC 60041:1991 MOD), and some other methods are recommended to measure indirectly also.

As for huge hydraulic power unit with large diameter, high water head, it is more viable to measure absolute efficiency online by ultrasonic flow meter[26]. If the test is performed just one time and is not real time, thermodynamic method is also available.

As for the turbines with short passageway, irregular passageway section,low water head, the spiral case differential pressure device is more feasible to measure the relative efficiency.

4. 2 Problems existing in differential pressure measurement

The main problem existing in differential pressure measurement is the blocking of the pressure taps. There are 21 units in Plant D,but only a small number of units' taps of spiral case differential pressure, spiral case inlet pressure, draft tube outlet pressure are not blocked after 30 years operation. The taps blocking problem is also different degrees existing in Plant A, B, C after a short time operation. Its recommended to dredge the taps during drainage overhaul, so as to guarantee the taps' clear status.

The other problem is the spiral case pressure data fluctuating, and the stability of measured data is poor. Some technological means have to be used during the measurements.

4. 3 Problems should be focused on water head measurement

The efficiency calculation involves the parameters, such as discharge, water head and output. The output can be measured with high accuracy. The precision of discharge is payed more attention during the efficiency measurement, but actually, it is very import for the precision of the water head measurement. The key is the selection of measurement sections. For example, three units share a single draft tube in Plant B, the operating condition of the closing 2 units will influence the water head of the other unit. The measurement and data process of the water head is very important in this case.

Furthermore, in general operators pay more attention to the gross water head in practise. For the plant with narrow bed downstream, the plant water release will put considerable influence on the water head. It should be taken into account during the efficiency measurement also

References

[1] YOU Guang-hua,ZHOU Xi-jun,YU He-zhi,Field thermodiunamic efficiencu tests for pumps and water turbines of Tianhuangping Pumped Storage Power Station[J]. East China Electric Power.2005(33),12:41-42

[2] General Administration of Quality Supervision,Inspection and Quarantine of P.R.C./Standardization Administration of The People's Republic of China. GB/T 20043-2005 Field acceptance test to determine the hydraulic performance of hydraulic turbine, storage pumps and pump-turbines(IEC 60041:1991,MOD)[S]. Beijing:China Zhijian Publishing House. 2005

[3] YI Lin , LI Wenxue , HOU Jingjun , LI Youping. Discharge Measurement System of Three Gorges Right Bank hydraulic power Station. hydraulic power Automation and Dam Monitoring.2007,31(6):43-45

[4] LI Youping, MIAO Yusheng,XIA Zhou, ZHENG Honglai. Calibration of Multi-path Ultrasonic Flow meter and Relative Discussion[J] .hydraulic power Automation and Dam Monitoring.2007,31(5):44-46

[5] YIN Yongzhen,PENG Bing,CAO Changchong,WANG Jianlan. Ultrasonic Flow Measurement for hydraulic power Turbine Units in XiangJiaBa hydraulic power Station[j] .hydraulic power AND NEW ENERGY.2016(1):42-45

[6] Xia Zhou, LI Youping, Liu ZhanGuo, Zheng HuiJuan. Application and Research of the Technology of 18-Path Ultrasonic Flow Meter Used in Three Gorges Right Bank Plant[J].hydraulic power Automation.2007(4):232-235,242

[7] MA Jie , XIA Zhou, LI Youping,etc.Data Processing and Analysis with Acoustic Method for Hydraulic Performance Test in TGHP[J]. 2009,33(2):25-27

[8] XIA Zhou,CAI Fulin,LI Youping,etc.Ultrasonic FlowMeasurement Accuracy Analysis Based on CFD Technology[J].hydraulic power Automation and Dam Monitoring.2010,34(3):32-34

[9] HU He-ming,DU Xiao-kang，MENG Tao，LI You-ping ， GAO Feng.Automatic Measurement Method of Geometric Parameter of Large Diameter Ultrasonic Flow meter[J]. ACTA METROLOGICA SINICA.2012,33(5A):114-119

[10] National Institute of Metrology China. Site Calibration Report about Ultrasonic Flow Meter of Unit No.18,No.22 and No.23 for Three Gorges hydraulic power Station[R]: Yi Chang: China Yangtze Power Co.,Ltd.2011

[11] National Institute of Metrology China. Site Calibration Report about Ultrasonic Flow Meter of Unit No.28,No.30 and No.31 for Three Gorges hydraulic power Station[R]: Yi Chang: China Yangtze Power Co.,Ltd.2011

[12] Hu Yue,Zhang Tao,Zheng Dandan..Estimation on Influence of Probe Protrusion Length of Ultrasonic Flowmeter on Measurement[J].Journal of Tianjin University(Science and Technology). 2013,46(9):776-783

[13] Zhang Liang， Meng Tao， Wang Chi， Hu Heming，Qin Chenglin.Probe installation effects on the accuracy of feed thru ultrasonic flowmeters[J].Chinese Journal of Scientific Instrument. 2012,33(10):2307-2313

[14] GUO Xiao-li,ZHENG Dan-dan,ZHANG Tao.Adaptability study of ultrasonic flowmeter in the flow field of reducer and straight pipe[J].Transducer and Microsystem Technologies. 2012,31(5):68-72

[15] ZHANG Peng-yong,ZHENG Dan-dan,XU Tian-shi,ZHANG Li-xin,HU He-ming. Study on the influence of ultrasonic probes on flow field and measurement performance of ultrasonic flowmeter[J].Journal of Experiments in Fluid Mechanics.2011,25(3):60-65

[16] HuHeming, WangChi, MengTao.Integration method of multi-chord ultrasonic flowmeter and its accuracy analysis[J].Chinese Journal of Scientific Instrument.2010,31(6):1218-1223

[17] General Administration of Quality Supervision,Inspection and Quarantine of P.R.C./Standardization Administration of The People's Republic of China.GB/Z 35717 Discharge measurement for hydraulic turbines, storage pumps and pump-turbines Acoustic transit time method. Beijing:China Zhijian Publishing House.2017

[18] General Administration of Quality Supervision,Inspection and Quarantine of P.R.C. JJF 1358-2012 Calibration Specification for DN1000~DN15000 Liquid Ultrasonic Flowmeters Calibrations by Non Practical Flow Method[S]. Beijing:China Zhijian Publishing House.2012

[19] Wang Chi， Meng Tao， Hu Heming.Estimation on measurement accuracy of ultrasonic flow meter in Three Gorges Project[J].China Metrology.2012(3):75-78

[20] IEC 60193 Hydraulic turbines ,storage pumps and pump-turbines - Model acceptance tests[S].

[21] Liyouping， ChengJian. Benefits Analysis of the Selection of Operated Unit for Multi-type hydraulic power Plants ， HydroVision 2013 ， Denver USA.2013.7

[22] Li Zhixiang. Analysis of Economy and Stability Operation for Three Gorges Left Bank Power Plant[J]. Mechanical and Electrical Technology for hydraulic power Station.2004(4):71-73

[23] LI Youping, Yin Yongzhen, Cheng Jian. Discussion on Start-up Strategies of hydraulic power units of Three Gorges Right Bank Plant[J]. Yangtze River.2016，47(4):84-87

[24] LIU Zhihui.Test and Research on Stability and Capacity of hydraulic power Units in Three Gorges Left and Right Bank Stations[J].Water Power.2013,39(7):68-72

[25] LI Youping， Li Wenxue， Liu Lianwei.Analysis and Discuss on Measurements of Multi-path Ultrasonic Flow Meter for Three Gorges Hydro Generating Unit[J]. Water Power.2009,35(12):72-75

[26] LI Youping,Ren Zheming,Song Ke.The Turbine Efficiency online Monitoring System[J] . hydraulic power Automation and Dam Monitoring.2004,28(1):4-5