Research of Turbine Efficiency Test by Current-Meter Method in Circular Pipe

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Abstract. For absolute discharge and efficiency measurement of turbine with medium and low water head, the current-meter method has high precision, good reliability, and wide application range. For rectangle flow channel, it is easy to lift down a gate frame with current meters to measure the flow velocity, but for circular pipe, due to the high stress, possible deformation, and strict safety requirement, the design, installation, and implementation of the support bracket is the key to the measurement by current-meter method. In this paper, we made the research of key technology for current-meter method in circular pipe. By building a numerical model for circular pressure pipe and flow measuring bracket, we analysed the influence of meters arrangement, the force and deformation of support pole with CFD, and fluid-solid coupling method. Finally, an optimized reinforcement bracket is proposed, with combined smooth and stress calculation, the measuring bracket is verified it can withstand the flow stress and has good safety characteristics, which can provide a reference for other similar turbine efficiency tests.

1. Introduction

As the absolute efficiency of the hydraulic turbine is related to the operation performance assessment, it has become an important factor in the handover and acceptance of international hydropower projects. The measurement of absolute efficiency is relatively complex with the difference of unit type, structure, and water head conditions. Especially, the key measurement parameter - the absolute turbine discharge, has many technical difficulties in the field implementation, so the turbine efficiency test has become a technical problem that puzzles the construction party and even hinders the transfer and operation of hydropower projects, which is easy to cause a larger social impact and economic losses[1].

According to the requirements of the IEC international standard, the absolute discharge measurement of hydraulic turbine consists of several methods, such as current meter method, pressure-time method, Winter-Kennedy method, thermodynamics method, and ultrasonic method. However, the thermodynamic method is usually applicable to a turbine with water head of more than 100 meters[2]. The ultrasonic method has low accuracy without pre-installation and site calibration. The index test based on the Winter-Kennedy method cannot be used as the basis for performance evaluation and contract guarantee value assessment[3]. Therefore, the current meter method, as the most adaptable universal absolute discharge measurement method for hydraulic turbines, has become the common
method for measuring the absolute discharge of hydropower unit which is low water head or has not preinstalled ultrasonic flow meter.

The current meter method needs to determine the flow section, which is usually selected at the spiral case inlet or draft tube outlet. Then a fixed discharge measuring frame is installed to measure the flow velocity, and the cross-section discharge will be obtained by iteration algorithm. Therefore, the design, installation, type selection and structural strength calculation of the support frame are the difficulties in the measurement and implementation of the current meter method[4].

In this paper, the key issue research of absolute efficiency measurement of hydraulic turbines by current-meter method in circular pipe is carried out. With building a numerical model for circular pressure pipe and flow measuring bracket, we analysed the influence of meters arrangement, the force and deformation of support pole with CFD, and fluid-solid coupling method. Finally, an optimized reinforcement bracket is proposed, with combined smooth and stress calculation, the measuring bracket is verified it can withstand the flow stress and has good safety characteristics, which can provide a reference for other similar turbine efficiency tests.

2. The Current-Meter Method

2.1. Efficiency and flow discharge calculation

The current-meter method requires several propeller-type current-meters which are located at specified points in a suitable cross-section of a conduit. In test, the flow velocity of each point can be measured by propeller current meters, then we can integrate the cross-section velocity to determine the turbine discharge. Finally, the turbine efficiency can be calculated by the following formula (1):

\[ \eta_T = \frac{P_T}{P_h} = \frac{P_T}{\rho \times Q \times g \times H} \]  

(1)

Where \( P_T \) is output of turbine, \( P_h \) is input power of turbine, \( \rho \) is water density which can be referred from IEC 60041 Annex E, \( Q \) is turbine discharge, \( g \) is local gravity acceleration, can be calculated according to the latitude and elevation, \( H \) is water head of turbine.

To obtain the flow discharge of measurement section by the flow velocity of each measuring point, commonly used methods include graphical integration of the velocity area, and numerical integration of the velocity area, others include mathematical methods and Log-Linear method, Log-Chebyshev method, etc. [5]. At present, the double graphic integration method is used in many test examples, which has complicated calculation, needs other mathematical calculations or programming tools for integration operations.

In numerical integration, discharge can be numerically integrated by the following formula:

\[ Q = \int_{0}^{L} \int_{0}^{H} v_i(h,l)dhdl \]  

(2)

Where \( H \) is the depth of water on measuring cross section, \( L \) is the width of water on measuring cross section, \( v_i \) is the velocity at the measurement point.

2.2. Measurement Points Arrangement

According to the requirements of ISO 3354-2008, with the different cross-sectional shapes of pressure pipes, the arrangement of the current meter frame and measuring points are also different. For the circular flow section which the diameter is no less than 1.4m, the current meters may be arranged along with two mutually vertical diameter directions. The distance between the sidewall and meters shall be at least 0.75 times of the rotation diameter, and the distance between adjacent current-meters shall be
1.2 times greater than the rotation diameter of current-meter. The general circular measuring point arrangement for a small circular pipe is shown in Figure 1.

IEC regulation also puts forward requirements for the total number of measuring points. For circular cross-sections in penstocks, there shall be at least 13 velocity measuring points, and the number of measuring points $Z$ on each radius arm can be determined by the formula $4\sqrt{R} < Z < 5\sqrt{R}$, where $R$ is the inner radius of the pipe\[7-9\].

![Figure 1. Pictures of measuring frame with two cross bars](image1)

Here we choose the test as an example performed by us in Coast Ivory, as the diameter of measuring section is 7132mm, considering the requirement of points number, the measurement frame with 6 support arms is adopted, and there shall be 8 current-meters in each support arm, and 49 current-meters in total. There are two design schemes of six-arm measurement frame in Figure 2.

![Figure 2. Design scheme of two six-arm measurement frame](image2)

For the selection of the flow measurement section, it shall be considered the actual situation and measurement requirements on site. For example, in order to ensure the measurement accuracy, the flow measurement section is usually selected close to the inlet of the turbine spiral case; for ensuring that the section is vertical to the flow direction, the measurement section needs to be selected as located in the straight section of the pipeline. Therefore, the safety and reliability of the measuring frame has become one of the important difficulties of the flow meter method.

3. Design and Calculation of Measurement Frame
As the fluid in the pressure pipe has movement and pressure fluctuations along the pipeline, the structural strength of the flow measurement frame in the turbine pressure pipe is affected by the fluid-
structure coupling of the pipe system. So, the fluid-structure coupling method is used here to carry out the research of structural characteristics of flow measurement frame in the pressure pipe[10].

3.1. Fluid-structure coupling method
The fluid-structure coupling calculation consists of fluid and structural solutions. In the coupling area between the water body and the flow measurement frame, the pressure is generated by the water acts on the flow surface of the flow measurement frame, which causes deformation and stress to the frame, therefore, the influence of the frame on the flow field is almost negligible, so here we only consider the one-way fluid-structure coupling of the water analysis results to the flow measurement frame[11].

The calculation of the fluid is only to the fluid part in the pressure pipe except for the flow measuring frame, but the structural calculation will be made to the pressure pipes and flow measuring frame. As the connecting arm structure of the flow measurement frame can be reinforced, so we analyzed the deformation of pressure pipes, flow measuring frame, supporting structures, and connecting arms.

![Figure 3. Modelling and meshing for the frame and pipeline](image)

We used the Fluent and ANSYS Mechanical to perform the combined calculation of fluid-structural coupling based on Workbench platform. There are three kinds of method to make data exchange between Fluent and ANSYS Mechanical, as using Temperature, Convection and Pressure. In the paper, the Pressure data exchange is adopted for applying the calculation load of CFD to the structural model. When current-meters on the measuring framework in a pressure pipeline, as the frame is made of steel material usually, there is less deformation for the frame under the impact of fluid. So here unidirectional fluid-structure coupling method is used for optimizing the structural characteristics of flow measurement frame[12].

Figure 4 shows the schematic diagram of unidirectional fluid-structure coupling method with Fluent and ANSYS Mechanical.

![Figure 4. Schematic diagram of unidirectional fluid-structure coupling](image)
3.2. Stress analysis on the support structure of flow measurement

3.2.1. Analysis for general support frame. For general measurement frame, a support structure can be added at the front side, which consists of six steel pipes with the same length and outer diameter. The outer diameter of each steel pipe is 100mm, and the inner diameter is 90mm. The strong impact of the fluid will deform the structure of the flow measurement frame and support structure, so with the analysis of the structural part by fluid-structure coupling method, the deformation of the support and support structure made of steel can be obtained. Figure 5 shows 150 times enlarged deformation of the flow measurement frame without support arm.

![Image](image1.png)

**Figure 5.** 150 times enlarged deformation of the flow measurement frame without support arm

We can see from Figure 5. that the six steel pipes of the flow measurement frame have been deformed under the impact of the high head pressure, the maximum deformation is 0.012955 m, which is significant.

From the front view of the frame, it can be seen that the greatest deformation appears on the rightmost hollow steel pipe. In addition to the model test shown in Figure 5., with the studies on a variety of model test in different inlet and outlet conditions, it is found that when the deformation of the frame becomes larger, there will always be a steel pipe deforms greatly first, and the deformations of other five steel pipes are relatively small.

From Figure 6, the deformation occurs both on the flow measurement frame and support arms, due to the impact of the fluid, the central part of the frame moves backward. Through the gradient value of deformation, it is observed that the maximum deformation of the flow measuring frame and support arms is 0.0032 m, compared with the pressure pipe with an inner diameter of 7.132 m, which is not large. During the efficiency test, the deformation of about 0.0032 m will not significantly change the flow measurement position of the flow meter.

![Image](image2.png)

**Figure 6.** Frame model with support arms and 150 times enlarged deformation of the frame

According to the above analysis, under the same inlet pressure, the deformation of the flow measuring frame without supporting structure is about 0.013 m and is only 0.0032 m after adding support
arms, so when the flow measuring frame is used in the middle head pressure pipeline to measure the flow discharge, the installation of the supporting structure is very necessary. Furthermore, with the stress analysis for the frame model, it can be found that after the support structure is installed on the flow measurement frame, the equivalent stress of the support and its structure is significantly reduced, the maximum stress is about 95.8 MPa, which does not reach the yield strength of Q235 structural steel, and the plastic deformation will not occur. So common structural steel can be used as the material of the flow measuring frame and supporting structure.

3.2.2. Analysis for optimized support frame. After adding the support structure, the deformation and equivalent stress of the flow measurement frame are reduced a lot. Considering that adding connecting rods between the arms to the flow measuring frame will also have a strengthening effect, the flow measuring frame is reinforced again, and we calculated the deformation for the optimized support frame.

![Optimized frame and 150 times enlarged deformation of the frame](image)

**Figure 7.** Optimized frame and 150 times enlarged deformation of the frame

From Figure 7, we can see the deformation also occurs on the flow measurement frame, with the impact of the fluid, it is observed that the whole part of the frame tends to move backward. The largest deformation point appears in the center of the frame.

Compared with the case where the hexagonal fixed structure is not installed, the maximum deformation of the flow measuring bracket is about 0.0032 m, after adding hexagonal fixed structure, the maximum deformation reduces to 0.0019 m. Therefore, when both the support structure and connecting rods are used, the structure strengthening effect is obvious and magnificent.

**Table 1.** Max deformation and mass equivalent stress list for four types of frame

| frame structure                  | unit | without any support | with support arms | with hexagonal fixed rods | with support arms and hexagonal fixed rods |
|----------------------------------|------|---------------------|------------------|---------------------------|------------------------------------------|
| max deformation                  | mm   | 13                  | 3.2              | 4.7                       | 1.8                                      |
| mass equivalent stress           | MPa  | 318                 | 60.3             | 95.8                      | 50.4                                     |

4. Conclusion

In this paper, the unidirectional fluid-structure coupling technology is used to verify the impact of water flow on the measurement frame under different structural forms, and it is concluded that adding support structures and connecting rods can reduce the deformation of the flow measurement frame greatly when it works in the pressure pipeline. The test process and calculation results can provide valuable reference and basis for subsequent similar tests of hydropower plants.

Furthermore, according to the actual situation of the site, a series of support design and optimization work can be carried out in the future. For example, airfoil pipe fittings can be used instead of round steel pipes to reduce the impact of water flow, and in this test, welding method is adopted for the frame
installation and assembly, it could be better to use bolt connection to reduce the impact and effect of vibration on pressure steel pipe wall.

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