Field test for hydraulic turbine discharge and efficiency based on current-meter method

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Abstract. Hydraulic turbine efficiency is one of the important indicators during acceptance inspection. One of the difficulties in field test for hydraulic turbine efficiency is discharge measurement. Current-meter method is widely applied because of its intuition and accuracy. Through test in a Francis turbine with a circular penstock, turbine discharge and efficiency calculation based on current-meter method is discussed in this paper. Test results indicate that integration step-size needs to be small enough to get accurate discharge in graphical integration method. Uncertainty estimation is important and requisite in field test for turbine efficiency, which reflects the actual reliability of test results.

1. Introduction
Hydropower construction remains developing rapidly in recent years, especially in developing countries. A large amount of hydraulic machines go into commercial operation continuously. These achievements are the results of joint efforts of proprietor, designer, constructor, supervisor, etc. All parties execute the work under the regulations of IEC and ISO standards.

Hydraulic turbine efficiency is one of the important indicators during acceptance inspection, which is normally stipulated clearly and strictly in the contract and relates to actual benefits of all parties directly. Therefore, it is important to execute the efficiency test during commissioning work. One of the difficulties in field test for hydraulic turbine efficiency is discharge measurement, which is generally executed by current-meter method, pressure-time method, or pitot-tube method, etc. Current-meter method is widely applied because of its intuition and accuracy [1] [2].

In this paper, field test for hydraulic turbine discharge and efficiency based on current-meter method is carried out on a Francis turbine with a penstock up to 7132mm in diameter, which is rarely seen in such large penstocks using this method.

2. Test method
2.1. Discharge measurement
The current-meter method requires a number of propeller-type current-meters installed at specified locations in a suitable cross-section of a closed conduit. The water must be sufficiently clean, such that dissolved or suspended matter won’t affect the accuracy of the water readings during the test. In the test, flow velocity of each point can be measured by current-meter, then the discharge can be integrated along the cross section [2].
2.1.1. Measuring points distribution. At least 13 measuring points shall be used in a circular penstock according to IEC 60041. The distance from outer current-meter to the wall should be no less than 0.75-fold of the meter rotation diameter. The distance between two adjacent current-meters should be no less than 1.2-fold of the meter rotation diameter. The number of measuring points per radius may be determined according to table 1, which is suggested in ISO 3354 [3].

| \( D \) (mm) | 1200-2400 | 2200-3200 | 2900-4500 | 3800-5500 | 5000-7000 | 6300-8500 |
|-------------|----------|----------|----------|----------|----------|----------|
| \( p \)    | 3        | 4        | 5        | 6        | 7        | 8        |

Where

\( D \) is the diameter of a circular penstock;
\( p \) is the number of measuring points per radius.

The distance from measuring points to the center point \( r_i \) are determined as follows:

\[
 r_p = \frac{D}{2} - 0.75d, \quad \frac{r}{r_p} = \frac{i}{p}, \quad i = 1, 2, ..., p
\]

(1)

Where \( d \) is the propeller diameter of current-meter. This law corresponds roughly to equal flow-rate rings in the case of a uniform velocity distribution.

2.1.2. The mean axial flow velocity. The discharge \( Q \) shall be worked out by:

\[
 Q = U \cdot A \cdot (1 - k)
\]

(2)

Where

\( U \) is the mean axial flow velocity of the cross section;
\( A \) is the area of the cross section;
\( k \) is the blockage factor.

The mean axial flow velocity may be calculated by integration method.

2.1.3. Corrections for blockage effect. During the test, the blockage effect cannot be neglected. The blockage factor \( k \) is determined by:

\[
 k = 0.12s + 0.03s_c, \quad s = \frac{A}{A_s}, \quad s_c = \frac{\pi Z d^2}{4 A}
\]

(3)

Where

\( s \) is the blockage ratio of the measuring frame;
\( s_c \) is the blockage ratio of current-meters;
\( A \) is the axial area of measuring frame;
\( Z \) is the number of current-meters.

If the blockage ratio of the measuring frame \( s \) exceeds 0.06, the test cannot be executed. Nevertheless, if \( s \) is less than 0.02, the blockage effect may be neglected.

2.2. Other measurements

2.2.1. Turbine output. Turbine output \( P_T \) can be calculated by the formula below [4]:

\[
 P_T = \frac{P_g}{\eta_g}
\]

(4)

Where:

\( P_g \) is the output power of generator, which shall be measured by power transmitter;
\( \eta_g \) is the efficiency of generator, which shall be interpolation from the generator efficiency curve.

2.2.2. Turbine working head. Turbine working head can be calculated from differential pressure between high pressure section and draft tube outlet [5]:

\[
H = \left( \frac{p_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 \right) - \left( \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + Z_2 \right)
\]

(5)

Where

- \( p_1, p_2 \) are the pressures of high and low pressure section;
- \( Z_1, Z_2 \) are the elevations of high and low pressure section;
- \( Z_1 - Z_2 + \frac{p_1 - p_2}{\rho g} \) is static water head, which is tested by differential pressure transducer;
- \( \frac{V_1^2 - V_2^2}{2g} = \left( \frac{1}{S_1} - \frac{1}{S_2} \right) \frac{Q^2}{2g} \) is dynamic head calculated from discharge \( Q \), section areas \( S_1, S_2 \) of high and low pressure section.
- \( \rho \) is the water density referred from Local temperature and pressure.
- \( g \) is the local gravity acceleration calculated according to the latitude and elevation.

2.3. Turbine efficiency.

With the measurements of discharge, working head and output power, the turbine efficiency shall be worked out.

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

(6)

Where \( \eta_T \) is the efficiency of turbine.

3. Test execution

3.1. Relevant parameters

The field test for discharge and efficiency has been carried out on a Francis turbine with a circular penstock. Relevant parameters of the unit are shown in table 2.

**Table 2. Unit parameters**

| Item                        | Unit | Detail       |
|-----------------------------|------|--------------|
| Type of Turbine             | /    | HLF250-LJ-533|
| Rated Working Head          | m    | 43           |
| Rated Speed                 | rpm  | 107.14       |
| Rated Discharge             | m³/s | 238          |
| Runner Diameter             | m    | 5.33         |
| Generator rated power       | MW   | 105.88       |

3.2. Arrangement of current-meters

An ideal measurement cross-section requires 20 penstock diameters upstream and 5 penstock diameters downstream. However, penstocks in hydropower stations are usually short penstocks and dissatisfy this requirement. The penstock layout of this field test is shown in figure 1.
Figure 1. Lateral view of penstock in this test (mm)

The measurement cross-section is arranged at spiral case inlet (A-A section), which is shown in figure 2. The section diameter is 7132mm and the area is 39.95m².

Figure 2. Location of measurement cross-section (mm)

Generally the number of measurement radii is 4–6. Too many measurement points may expand the influence of blockage effect. On the contrary, too little points cannot reflect the flow velocity distribution. Considering the large size of measurement section, 6 measurement radii are arranged in this test. According to table 1., 8 points per radius are arranged as shown in figure 3. The total number of measurement points is 49.

Figure 3. Measurement points arranged in radial direction (mm)

According to IEC 60041, current-meter propellers shall be not less than 100mm diameter except for measurements in the peripheral zone where propellers as small as 50mm may be used. Current-meters
of 2 types are used in this test as shown in table 3. All the current-meters have been calibrated both before and after the test with the rods in calibration laboratory.

| No. | Type    | Propeller diameter | Starting speed | Quantity | Mounting |
|-----|---------|--------------------|----------------|----------|----------|
| 1   | LS1206B | 70mm               | 0.05m/s        | 6        | welding  |
| 2   | LS20B   | 120mm              | 0.03m/s        | 43       | welding  |

### 3.3. Test procedure

This test is executed through these following steps:
1. Start the unit to rated rotational speed and synchronize with the grid.
2. The operation points are 40%Pr, 50%Pr, 60%Pr, 70%Pr, 80%Pr, 90%Pr, 100%Pr and should be regulated by stepping from lower to higher.
3. Keep the guide vane opening unchanged on stable operation in 5 min. Synchronously record the rotational speed, active power, water head, discharge, guide vane opening, high pressure and low pressure.
4. These requirements must be satisfied:
   - Power variation should be kept in ±1.5% of mean value.
   - Water head variation should be kept in ±1.0% of mean value.
   - Rotational speed variation should be kept in ±0.5% of mean value.

### 4. Test results

#### 4.1. Discharge calculation

The test is carried out along the steps in 3.3. At each operation point, the local flow velocities are measured and \( u_i \) (the value of the arithmetic mean of local velocities at the measuring points located on the circle of radius \( r_i, i = 1, 2, \ldots, p \)) are calculated out. Velocity distribution curves within the radius range at each operation point are traced out in figure 4. Velocities close to the wall are estimated from Karman’s law about variation in the peripheral zone [3].

![Figure 4. Velocity distribution within the radius range](image-url)
Graphical integration method is used in discharge calculation. Generally smaller integration step-size (minimum integration calculation range in radial direction) means more accurate results. Discharge results of different integration step-sizes at each operation point are listed in Table 4.

**Table 4.** Discharge results of different integration step-sizes at each operation point (m$^3$/s)

| Step-size | 1mm | 2mm | 5mm | 10mm | 20mm | 50mm | 100mm |
|-----------|-----|-----|-----|------|------|------|-------|
| 40%Pr     | 125.66 | 125.66 | 125.67 | 125.67 | 125.68 | 125.76 | 125.87 |
| 50%Pr     | 138.00 | 138.00 | 138.00 | 138.00 | 138.01 | 138.10 | 138.22 |
| 60%Pr     | 154.62 | 154.62 | 154.62 | 154.64 | 154.73 | 154.87 |
| 70%Pr     | 169.17 | 169.18 | 169.18 | 169.20 | 169.30 | 169.45 |
| 80%Pr     | 187.23 | 187.24 | 187.24 | 187.26 | 187.38 | 187.54 |
| 90%Pr     | 208.55 | 208.55 | 208.56 | 208.58 | 208.70 | 208.87 |
| 100%Pr    | 228.66 | 228.67 | 228.67 | 228.69 | 228.82 | 229.01 |

As shown in Table 4, when integration step-size is small enough (1mm), the calculated discharge seems unchanged. So it doesn’t need to minish the step-size more and the bold values are picked out to efficiency calculation.

**4.2. Efficiency calculation**

With the results of discharge, working head and output power, the turbine efficiency shall be worked out. Test results are shown in Table 5, in which the discharge values are amended by the blockage factor.

**Table 5.** Test result at each operation point

| Operation point | Measured discharge $Q_m$ (m$^3$/s) | Actual discharge $Q_a$ (m$^3$/s) | working head $H$ (m) | Generator output $P_g$ (MW) | Generator Efficiency $\eta_g$ | Turbine efficiency $\eta_T$ |
|-----------------|---------------------------------|-------------------------------|------------------|----------------------|----------------------|-----------------------|
| 40%Pr           | 125.66                          | 124.67                        | 43.63            | 36.11                | 97.23%               | 70.11%                |
| 50%Pr           | 138.00                          | 136.91                        | 43.39            | 45.76                | 97.62%               | 81.03%                |
| 60%Pr           | 154.62                          | 153.40                        | 43.37            | 55.87                | 97.86%               | 88.12%                |
| 70%Pr           | 169.17                          | 167.84                        | 43.66            | 64.60                | 97.98%               | 92.39%                |
| 80%Pr           | 187.23                          | 185.76                        | 43.59            | 73.86                | 98.06%               | 95.52%                |
| 90%Pr           | 208.55                          | 206.91                        | 43.40            | 82.53                | 98.10%               | 96.20%                |
| 100%Pr          | 228.66                          | 226.86                        | 43.23            | 90.26                | 98.11%               | 96.33%                |

**4.3. Uncertainty estimation**

The uncertainty of turbine efficiency consists of systematic uncertainty and random uncertainty and can be worked out as follows [3]:

$$f_\eta = \pm \left( (f_\eta)_s^2 + (f_\eta)_r^2 \right)^{1/2}$$

$$ (f_\eta)_s = \pm \left[ (f_q)_s^2 + (f_H)_s^2 + (f_P)_s^2 \right]^{1/2}$$

$$ (f_\eta)_r = \pm \frac{(e_\eta)_r}{\eta} = \pm t_{0.95} \frac{S_{\eta}}{\sqrt{n}} \eta$$

Where

- $f_\eta$ is the uncertainty of turbine efficiency;
- $f_q$ is the uncertainty of discharge measurement;
- $f_H$ is the uncertainty of the measurement of working head and estimated by accuracy of differential pressure transducer;
\( f_p \) is the uncertainty of generator output measurement and estimated by accuracy of power transmitter;

Subscript \( s \) means systematic uncertainty and subscript \( r \) means random uncertainty.

Generally the systematic uncertainty of working head and generator output are caused by measurement accuracy of transducers. While the uncertainty of discharge may be worked out as follows:

\[
f_Q = \pm \frac{e_Q}{Q} = \left[ \left( e_{Q_s} \right)^2 + \left( e_{Q_r} \right)^2 \right]^{1/2} / Q
\]

\[
\left( e_{Q_s} \right) = \pm \left[ U^2 \left( e_A \right)^2 + \left( e_p \right)^2 \right]^{1/2}
\]

\[
\left( e_{Q_r} \right) = \pm \left[ A^2 \left( e_U \right)_R^2 + \left( e_i \right)_R^2 + \left( e_m \right)_R^2 + \left( e_l \right)_R^2 \right]^{1/2}
\]

Where

- \( e_A \) is the uncertainty of the measurement of the cross-section area of the penstock, taken as 0.004 \( A \);
- \( e_p \) is the uncertainty of the number of measuring points, taken as 0.002 \( Q \);
- \( e_U \) is the uncertainty of the mean axial fluid velocity and calculated by accuracy of all the current-meters used;
- \( e_i \) is the uncertainty from the use of graphical integration method, taken as 0.002 \( Q \);
- \( e_m \) is the uncertainty of the estimation of wall roughness factor, taken as 0.001 \( Q \);
- \( e_l \) is the uncertainty of the current-meter positioning taken as 0.001 \( Q \).

After uncertainties estimation, the turbine efficiency curve is portrayed as shown in Figure 5. Through further inspection, test results satisfy the contract requirements.

![Figure 5. Turbine efficiency curve with uncertainty bandwidth](image)

5. Conclusion

Field test for hydraulic turbine discharge and efficiency based on current-meter method is discussed in this paper. Through test in a Francis turbine with a circular penstock, turbine discharge and efficiency are worked out. The paper draws these following conclusions:

- Discharge measurement based on current-meter method can be applied to large-size penstocks (here to 7132mm in diameter) with strict arrangement of current-meters.
- To calculate accurate discharge, integration step-size needs to be small enough (here to 1mm)
using graphical integration method.

- Uncertainty estimation is important and requisite in field test for turbine efficiency, which reflects the actual reliability of test results.

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