CFD optimized acoustic flow measurement and laboratory verification

Introduction

The South to North China Water Diversion project is the largest river diversion project ever planned. The main aim of the project is to alleviate the water shortage in northern China by redirecting water from the south of the country. The three south-to-north canals, which will stretch across the eastern, middle and western parts of China, will link the countries four major rivers - the Yangtze River, Yellow River, Huaihe River and the Haihe River. By 2050 it is expected the project will be capable of shifting 44.8 billion cubic meters of water annually.

Obviously, such a costly project demands for high accuracy flow rate measurements and the operators decided in favor of the acoustic travel time discharge measurement (ADM). For two gauging stations of the eastern line at the Wan Nian Zha and Bao Ying pumping stations model tests of the ADM were performed. In both gauging stations the acoustic sensors are installed within converging rectangular sections. 8 paths configurations (2 crossed acoustic planes with 4 paths each) were chosen.

In the following the ADM was optimized on the basis of numerical flow simulation (CFD). These simulations included the upstream and downstream flow development from the measuring section at different flow rates. Local flow separations, uneven velocity distributions and secondary flows were observed. Basing on the results of these flow simulations optimum path positions for acoustic travel time measurements and optimum weights of the individual paths could be determined. Both measures aimed to adapt the ADM to the local flow and to improve the integration method for flow rate determination.

The witnessed laboratory tests performed at the China National Water Large Flowrate Measurement Station in Kaifeng and at Yangzhou University confirmed twice the correctness of the chosen procedure. The maximum deviations of the comparison with the reference discharge measurements for the Bao Ying pumping station tested in Yangzhou lay between -0.39% and +0.19%, while the average deviation was only -0.03%. The deviations of the Wan Nian Zha station tested in Kaifeng were within the limits of ±0.85%.

1. Flow situation of the model tests

Yangzhou

The tests in the laboratory of the Yangzhou University included not only the flow cross section for the acoustic discharge measurement but also a model of the pump Bao Ying pumping station. The model scale was 1:10.

Fig. 1 shows a schematic with intake and the rectangular flow cross section upstream of the pump. The height of the section where the acoustic transducers are installed varies between 0.48 m and 0.33 m while the width is 0.71 m. Ten flow rates between 288 l/s and 413 l/s were tested, corresponding to 2.88 m³/s and 4.13 m³/s of prototype flow.

In the flow cross section 2 times 4 horizontal acoustic paths at an angle \( \varphi = 60^\circ \) were installed. The reference meter was a calibrated magnetic flow meter with a measuring uncertainty of ±0.17%. This reference flow meter was calibrated at the China National Water Large Flowrate Measurement Station in Kaifeng. The primary method used in this laboratory was a volumetric method with a stated accuracy of ±0.1%.
Kaifeng

The tests in the laboratory China National Water Large Flowrate Measurement Station in Kaifeng encompassed only the gauging section for the acoustic discharge measurement of the Wan Nian Zha pumping station. The scale of the model was 1:5. Here the ADM was directly compared to the volumetric measurement (measuring uncertainty 0.1%).

Fig. 2 shows a schematic with intake and the rectangular flow cross section upstream of the pump. The height of the section where the acoustic transducers are installed varies between 0.96 m and 0.70 m while the width is 0.6 m. Here, 2 times 4 vertical acoustic paths were installed. The tested flow rates were between 316 l/s and 928 l/s.

2. Numerical flow simulation

The computations were performed with ANSYS-CFX10, a commercial finite volume CFD code. The turbulence model used for all the computations is the SST Model. All the computations were performed in unsteady mode (URANS), with a second order discretization scheme in space and time.

The mesh was generated with ICEM CFD Version 10. A structured mesh of 10^6 elements showed to be adequate. The mesh quality check showed that:
- The smallest angle is larger than 29 degrees.
- The maximum aspect ratio of the elements is below 100 in the boundary layer and below 40 in the outer flow.
- The boundary layer is discretized with 15 elements.
- The y⁺-values are between 30 and 60.
Yangzhou

Flow simulation for the Yangzhou tests shows flow separation at the inlet to the rectangular flow cross section at the bottom and the sides (blue recirculation areas in Fig.3). On Fig. 3, left, with a velocity range from 0 to 1.7 m/s it can be seen that the flow is strongly accelerated within the cone and accordingly in the section of the acoustic paths. On Fig. 3, right, with a velocity range from 0.5 to 1.3 m/s the velocity distribution is displayed in the midplane where the acoustic paths cross. The integration of the normal velocity components on this midplane results in the flow rate.

Fig. 3. Yangzhou: Simulation results in the measuring cross section for acoustic discharge measurement at 325 l/s

Kaifeng

The results of flow simulation for the Kaifeng tests show also local flow separations at the inlet to the rectangular flow cross section. Also here the flow is accelerated within the measuring cross section. Again flow separation at the inlet occurs and secondary flows prevail in the midplane.

Fig. 4. Kaifeng: Simulation results in the measuring cross section for acoustic discharge measurement at 300 l/s

3. Optimized acoustic discharge measurement

For both tests configurations the flow fields are everything else but ideal for ADM. There is no straight section for the installation and the flow fields are heavily disturbed. In this difficult situation it was decided to rely on the results of the numerical flow simulations. Basing on the results of the flow simulations optimum path positions for acoustic travel time measurements were determined. Furthermore, weights of the individual paths were adjusted to the simulated velocity distributions. These parameters were transmitted to the Rittmeyer crew in
China, who implemented the predicted weights in the software and positioned transducers as specified. No further adjustments were done during the tests.

This method of using numerical flow simulation to adjust the parameters of the acoustic discharge measurement is called in the following OWISS: Optimized Weighted Integration for Simulated Sections

**OWISS**

Determination of the path positions and of the weights for the integration bases on the algorithms of the Gaussian Quadrature. The corresponding theory applied to the acoustic discharge measurement is described by Tresch [1] and in more general ways by Stewart [2] and Press [3].

For the determination of the path positions and the weights the so called area flow function \( F(z) \) is introduced.

For a given path number this area flow function is the only input for the calculation of positions and weights using the Gaussian Quadrature.

\[
F(z) = \overline{v}_{ax}(z) \cdot B
\]

whereas \( \overline{v}_{ax}(z) \) is the normal velocity component averaged over the width and \( B \) is the width of the rectangular cross section.

**Fig. 5. Area flow function for the rectangular flow cross section**

The flow rate \( Q \) results to

\[
Q = \int_{-H/2}^{H/2} F(z)dz
\]

For the example of a four paths installation in a rectangular section \( Q \) can be approximated by

\[
Q = \int_{-H/2}^{H/2} F(z)dz \approx \frac{H}{2} \sum_{i=1}^{4} w_i \cdot F(d_i) = \frac{B \cdot H}{2} \sum_{i=1}^{4} w_i \cdot \overline{v}_{ax}(d_i)
\]

where \( v_{ax} \) are the measured (mean) velocities at the path positions \( d_i \) and \( w_i \) the weights of each path.

General statement is that the better the area flow function approximates the real flow distribution the better the accuracy of the discharge integration gets. For this reason it is of outmost importance to choose an adequate area flow function for each specific case. Here numerical flow simulations bring a unique possibility to improve the integration, since an excellent approximation of the area flow function can easily be extracted from the CFD simulations. This allows improving the accuracy of the method considerably compared to the constant area flow function as implicitly assumed in the appendix J of IEC 41 [4]. For \( F(z) = const \) also the averaged velocity \( \overline{v}_{ax}(z) \) is assumed to be uniform which does not reflect physical reality. A first step in this direction was done by Voser [5], who assumed a fully developed turbulent pipe flow to adjust the weights for the circular flow cross sections and who introduced the OWICS-method (Optimized Weighted Integration for Circular Sections).
Both methods, The IEC Gauss Legendre and the OWISS-method are confronted in Fig. 6.

\[ F(z) = \bar{v}_{ax} \cdot B = \text{const} \]

\[ F(z_i) = \bar{v}_{ax}(z_i) \cdot B \]

**Fig. 6. Area flow function of the Gauss-Legendre Method (left) and OWISS (right)**

For both tests, Yangzhou and Kaifeng, the area flow function was determined on the basis of the velocity distributions calculated in the midplane (see Fig. 3 and 4). In following only the data for the Yangzhou case are presented.

**Discharge integration**

As described above the positions and the weights of the acoustic paths were determined using the algorithm of the Gaussian Quadrature. However, the \( d_1 \) position became too close to the wall and acoustic reflections had to be feared. For this reason \( d_1 \) was shifted to a lower value and the weights were adjusted. Furthermore, corrections of the weights were necessary due to path velocity inclination. The measured path velocity \( v_{path} \) is not perpendicular to the midplane (see Fig. 7). Accordingly \( v_{path} \) is not identical to \( v_{ax} \) and the weights were corrected corresponding to the angle difference of the two velocity components. Weights and positions of the paths in the two acoustic planes are identical.

<table>
<thead>
<tr>
<th>path</th>
<th>( d_i/(D/2) )</th>
<th>( w_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.813311</td>
<td>0.365755</td>
</tr>
<tr>
<td>2</td>
<td>0.367821</td>
<td>0.531691</td>
</tr>
<tr>
<td>3</td>
<td>-0.268017</td>
<td>0.624188</td>
</tr>
<tr>
<td>4</td>
<td>-0.740428</td>
<td>0.361419</td>
</tr>
</tbody>
</table>

*Tab. 1. Final path positions and weights for the horizontal installation*
4. Comparative tests

The outcome of witnessed laboratory tests performed at the China National Water Large Flowrate Measurement Station in Kaifeng and at Yangzhou University confirmed twice the correctness of the chosen procedure. The maximum deviations of the comparison with the reference discharge measurements for the Bao Ying pumping station tested in Yangzhou lay between -0.39% and +0.19%, while the average deviation was only -0.03%. The deviations of the Wan Nian Zha station tested in Kaifeng were within the limits of ±0.85%.

The Kaifeng tests were performed September 26, 2006, and the Yangzhou tests October 11, 2006. With the experience gained from the first test the method could be further improved reflecting in the better results of second tests.

![Calibration Certificate](image)

**Fig. 8. Extract from the calibration certificate of the Kaifeng tests [6]**

<table>
<thead>
<tr>
<th>Point No.</th>
<th>Q_{ref} [l/s]</th>
<th>Q_{ADM} [l/s]</th>
<th>(Q_{ADM}-Q_{ref})/Q_{ref} [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>413.90</td>
<td>413.04</td>
<td>-0.21%</td>
</tr>
<tr>
<td>2</td>
<td>390.00</td>
<td>388.49</td>
<td>-0.39%</td>
</tr>
<tr>
<td>3</td>
<td>369.60</td>
<td>369.33</td>
<td>-0.07%</td>
</tr>
<tr>
<td>4</td>
<td>354.40</td>
<td>353.75</td>
<td>-0.18%</td>
</tr>
<tr>
<td>5</td>
<td>330.20</td>
<td>330.81</td>
<td>0.18%</td>
</tr>
<tr>
<td>6</td>
<td>306.00</td>
<td>306.36</td>
<td>0.12%</td>
</tr>
<tr>
<td>7</td>
<td>287.50</td>
<td>287.57</td>
<td>0.02%</td>
</tr>
<tr>
<td>8</td>
<td>323.10</td>
<td>323.72</td>
<td>0.19%</td>
</tr>
<tr>
<td>9</td>
<td>366.50</td>
<td>366.45</td>
<td>-0.01%</td>
</tr>
<tr>
<td>10</td>
<td>380.70</td>
<td>380.85</td>
<td>0.04%</td>
</tr>
</tbody>
</table>

**Tab. 2. Results of the Yangzhou tests**
5. Conclusion
With the comparative test performed at the China National Water Large Flowrate Measurement Station in Kaifeng and at Yangzhou University an excellent accuracy of the ADM in highly disturbed flow could be demonstrated. This accuracy could only be achieved by applying the OWISS-method. The OWISS-method uses simulated velocity distributions in the midplane for determination of the area flow function. Using the Gaussian quadrature for integration optimum positions and weights for each acoustic path can be determined.

References
2. Stewart G.W., Afternotes on Numerical Analysis, SIAM 1996
4. IEC60041: Field acceptance tests to determine the hydraulic performance of hydraulic turbines, Storage, pumps and pump turbines, IEC 1991
5. Voser A., Analyse und Fehleroptimierung der mehrpfadigen akustischen Durchflussmessung in Wasserkraftanlagen, ETH Zürich, Dissertation Nr. 13102, 1999
7. Yangzhou University, Calibration Certificate 061011302, 2006

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