Discharge Measurement in Low Head Hydro Power Plants

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Abstract—Methods for discharge measurements in low head hydro power plants are presented with a series of field studies. The most classical method is the multipoint velocity measurement with propeller type current meters. For discharge evaluation, the integration of the difference between measured velocities and a known velocity distribution is recommended, thus avoiding integration in the outer zones with exponential velocity decay. The newest and best suited method for measurements in intakes is the acoustic scintillation method, a cross-correlation method. For accurate results the scintillation method must be installed downstream of trash racks. The method of acoustic transit measurement can also be adopted to measurements in low head, but new procedures for weighting the individual path velocities have to be applied due to varying shape of the flow cross sections.

Index Terms— acoustic scintillation, acoustic transit time, current meter, flow rate measurement, low head, Winter-Kennedy

I. INTRODUCTION AND PURPOSE

The motivations for discharge measurements at low head hydro power plants are multifold. Possible reasons are:

- Riparian rights
- Efficiency testing, encompassing acceptance tests of new or refurbished machines, evaluation of actual turbine state in the planning phase of refurbishment projects or cam optimization
- Calibration of Winter-Kennedy or other pressure difference devices for permanent discharge measurement
- Water managements in river systems, calibration of weir characteristics
- Level regulation of rivers in the context of navigation or tourism

Nevertheless, such measurements are rarely performed in low head hydro power plants. Many of these plants, operating for decades, have never been tested with quantitative discharge measurements. Often the effort to perform discharge measurements is considered to be too high. One of the reasons for not performing absolute discharge measurements is that optimum cam correlation of double regulated turbines can be adjusted without the knowledge of the absolute flow rate. Contracts of new hydro projects or refurbishment projects mostly rely on model tests of the turbines or for smaller units even only on numerical flow simulation.

Well established methods for discharge measurements, which can be used for low head hydro power plants, are described in standards such as the IEC 60041 [5] and the ASME PTC18 [3]. However, when planning such measurements one often encounters problems at low head power plants, because amongst others the inlet flow is not uniform, the intake is too short, or stop log notches cannot be used for installation. Measurements at the draft tube outlet are not feasible because of high turbulence, non-uniform velocity distributions, eventually with local backflow. Air bubbles in the flow at the outlet make any type of acoustic measurements impossible.

The probably most established method, which has been used since the early 20th century, is multipoint measurements of local flow velocities with propeller type current meters. The uncertainty of such measurements is generally lower than 1.5% with the exception of cases with highly non-uniform flows, oblique flow, or high turbulence.

II. METHODS OF MEASUREMENT

In the following various methods for flow rate measurements will be presented on the basis of recently performed field tests.

A. Propeller type current meters

In IEC 60041 [5] this method is attributed to the so-called velocity-area methods.

This type of method is explained with a recently performed measurement campaign in a low head power plant Erlabrunn at the river Main in Germany. The current meters were mounted upstream of the trash rack and adjusted to the main flow direction.
A total of 24 current meters were mounted on a movable frame with profiled rods and adjusted to the main flow direction. The frame was fixed on both sides to a carriage, which was sliding in the slots of the stop logs (Fig. 1). Since these slots were not vertical the measuring plane was inclined by 17 degrees towards the inflow direction.

The turbine had two inlet bays, which had to be measured one after the other. Due to the positioning of the frame on 5 elevations in each intake the measuring duration for one operating point lasted 1.5 hours. Minor variation of power and head were compensated by weighting the velocities for each frame position.

For each operating point a total of 120 local velocities in each intake could be used for integration of the flow rate. Since the sections were rectangular the integration was carried out in accordance with ISO 3354 [6] with a cubic spline interpolation and a linear extrapolation to the free surface flow. For the measured operating points the discharge varied between 25 and 115 m$^3$/s.

One of the major purposes of this measuring campaign was the calibration of the Winter-Kennedy pressure difference for permanent discharge monitoring. This calibration could be performed successfully since the coefficients of the Winter-Kennedy equation did not depend on the guide vane opening. The equation for calculation of discharge [m$^3$/s] from the measured pressure difference [Pa] is according to [5]:

$$Q = k \Delta p^n$$  \hspace{1cm} (1)

Fig. 3 shows the measured pressure differences as a function of discharge. The regression curve fits well the measured points. The scatter of the points is small. Applying the equation resulting from regression to the measured pressure difference at any operating point the instantaneous flow rate can be determined.

In case of circular or rectangular flow cross sections the standards [3], [5], and [6] describe methods for integration of the flow fields. However in many cases the flow cross sections deviate from such ideal shapes. A case with irregular section was encountered on the occasion of measurements in the tidal hydro power plant of La Rance in France [12].

Fig. 4 shows the cross section and the positions of the current meters. Also in this plant 2 rows of current meters mounted on a frame were moved vertically in the stop log slots.
For this kind of sections it is recommended to perform a numerical flow simulation (CFD) with a first estimation of the flow rate and to calculate the difference of the measured and simulated velocities at each measuring point, as shown for one measuring point in Fig. 5. These differences should then be integrated, what is unproblematic since the usual difficulties of integration in the outer zones, where there is an exponential decay to zero velocity, can be avoided. The integral value of the differences, determined in such a way, can then be added to the numerically simulated flow rate, giving the measured flow rate with high accuracy. This procedure is described in [14].

**Figure 4.** Flow cross-section in the tidal power plant of La Rance [12]

**Figure 5.** Velocity difference of measured velocity and CFD velocity

### B. Acoustic scintillation method

The acoustic scintillation method is not yet considered as a primary method in the IEC and ASME standards [5], [3]. However, recent comparative tests show promising results for this method. In its implementation, always three transmitters arranged as triangle are placed on one side of the flow conduit and as counterpart three receivers on the other. In this way an average velocity and an average flow angle of the flow perpendicular to the acoustic paths can be determined. Having measurements on multiple elevations it becomes possible to integrate the flow rate through a given flow cross section.

The principle of this method is based on the physical effect of the turbulence in the flow, which adds a certain amount of random scatter (“scintillation”) to the received signal. Because the distances between the transmitting sensors and also in between the receiving sensors are short, the turbulent structures are only modified to a minor degree (Taylor hypothesis) and accordingly also the received signals, which however are shifted by a time delay. This time delay is determined by performing a cross-correlation and is a measure for the path averaged flow velocity.

Recently the American Society of Mechanical Engineers (ASME) and the Centre for Energy Advancement through Technological Innovation (CEATI) sponsored comparative tests for flow rate measurements suitable for use in short converging intakes [2]. These tests were performed at BC Hydro’s four-unit Kootenay Canal hydro power plant. Although the plant is not low head, the intakes are of a low-head design with the essential features of a short, converging intake. For this measuring campaign a frame was designed to fit into the slots of the stop logs. In this frame the acoustic sensors for the scintillation method were mounted as well as a vertically movable rod with 14 current meters, as shown in Fig. 6. It is important to note that stop logs and thus the frame were downstream of the trash rack. The small scale turbulence produced by the trash rack bars is essential for a good signal quality of the scintillation method.

Furthermore, an acoustic transit time installation with 18 paths was mounted in the non-uniform, converging section of the intake within the transition from rectangular to circular section (Fig. 9).

As reference measurements served a code-accepted 8 path acoustic flowmeter in the penstock. Deviations of the individual methods from the reference are listed in Table I. All measurements were performed as so-called blind tests, meaning that the flow rate data was not shared among test participants during testing.

Current meter measurements were performed on the one hand with current meters on fixed elevations and on the other hand with continuously varying elevation profiling slowly the velocity distribution. Surprisingly the current meters showed the largest deviation from the reference. Most likely this is due to the fact that the current meters were not adjusted to the main flow direction in these tests.

The agreement of the scintillation method with the reference has to be considered to be excellent taking into account that the uncertainty of the reference meter has the same order of magnitude as the deviation.
C. Acoustic transit time measurement in sections of varying shape

The IEC and ASME standards [5], [3] describe in detail the procedures required for multi path acoustic transit time measurements (ATT). However, the application is restricted to circular and rectangular cross sections in straight conduits. In low head power plants usually no straight sections are available and often converging sections prevail. Basically, installations of sensors in converging sections are well possible, but no standard method for discharge evaluation is available. A theoretical treatment of ATT measurements in sections with varying sections is described in [8]. The transit time measurement of acoustic pulses is an absolute measurement, but the weighting of the individual path velocities has to be determined. A well suited method to determine weights is by using numerical flow simulation.

For installation of an ATT in the low head hydro power plant Wettingen at the river Limmat in Switzerland [1] the only possible location for installation was in the converging section just upstream of the inlet butterfly valve, as depicted in Fig. 7. The special challenge was that the cross section shape changed from rectangular to circular along the acoustic paths.

One of the advantages of an ATT measurement over current meters is that such an installation can be permanently mounted and the plant operator is able to monitor the performance of his machines continuously. In this plant all three units were equipped with an ATT and the cam correlation could be optimized for each of the Kaplan turbines. The permanently installed ATTs will also allow determining quantitatively the efficiency increase once the old turbines are replaced by new ones in case of a refurbishment project.

Testing time to find the optimum cam correlation is much shorter in comparison to current meter measurements. Typically the duration for acquiring data for one operating point lasts only about 5 minutes. Fig. 8 gives an example of such measurements in above mentioned power plant.

<table>
<thead>
<tr>
<th>Intake Flow Rate Measurement Method</th>
<th>Deviation from Reference Flow Meter</th>
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<tbody>
<tr>
<td>Acoustic Scintillation</td>
<td>+ 0.44 %</td>
</tr>
<tr>
<td>Acoustic Transit Time</td>
<td>+ 0.09 %</td>
</tr>
<tr>
<td>Current Meters - Fixed</td>
<td>+ 1.06 %</td>
</tr>
<tr>
<td>Current Meters - Profiling</td>
<td>+ 1.07 %</td>
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D. Further methods

IEC 60041 [5] cites further methods for discharge measurement. Pitot tubes, another technique of the velocity-area method, are generally not suitable for measurement in low head hydro plants due to the low velocities and the accordingly low pressures to be measured.

The application of the pressure-time method demands a series of conditions to be fulfilled as listed in [5]. Due to the short conduits these conditions are rarely fulfilled for low head hydro plants. Recent field tests of such measurements are described in [11] and [13]. Research on the applicability of the pressure time method for low head machines is also carried out in the laboratory [7].

Dye dilution measurements are, in principle, suitable for measurements in low head plants, but also here a series of conditions have to be fulfilled to achieve good results, as listed in [5]. Recent field test with this method are described in [4].

For very small power plants also standardized thin-plate weirs, standardized differential pressure devices, or calibrated magnetic inductive devices might be possible.

Because of the lack of reservoirs in case of low head plants, the volumetric gauging method is not applicable.

III. CONCLUSIONS

Discharge measurements in low head hydropower plants are possible and the involved efforts are, in most cases, economically justifiable. The chosen method has to be appropriate for the individual goals of the measurement campaign and to the local situation in each of the plants.

Depending on the chosen method, the accuracy of the discharge measurement to be expected will be in the order of one or two percent, if conditions match the requirements mentioned in the standards. If comparative tests are planned or a cam correlation should be optimized, then also index measurements can be considered, were the absolute value of discharge is not needed.

The acoustic scintillation method is a new and promising method with the important advantage that the flow perpendicular to a flow cross section (e.g. in the stop logs) can be measured, non-intrusively, with a frame which easily can be moved from bay to bay in case of multiple units of a specific low head hydro power plant.

REFERENCES