# Uncertainty assessment of flow measurements at Iron Gate 2

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## Abstract

To allow for the reliable hydraulic efficiency estimation of the tubular turbines before and after their revitalization at the Hydro Power Plant (HPP) Iron Gate 2, a novel flow measurement system was designed and tested on two turbines. In this paper the details of used approach for the assessment of the flow measurement uncertainty are presented. The presented methodology is tailored for specific application of the Velocity – Area flow measurements at HPP, based on the utilization of electro-magnetic velocity meters (EMVM), instead of traditional propeller current meters. Although the procedure for the assessment of the flow measurement uncertainty in similar cases of low-head plants and short intakes can be found in the literature, the adverse flow conditions, novel EMVM sensors and the specific operating modes have instigated a need for modifications and improvements of the procedure. Assuming analogy between the current meters and EM meters, the IEC 60041 and ISO 3354 procedure for flow rate measurement uncertainty assessment was used as a template, with implemented moderate changes accounting for the features of the applied measurement. Selected flow measurements from the 2020. campaign are analyzed, with an emphasis on the variation of the magnitudes of the measurement uncertainty components.

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## 1. Introduction

Flow-rate or discharge measurements are deemed as the most challenging task, in hydraulic efficiency estimation of the turbines. Typically, the resulting measurement process is complex, measurement uncertainties are higher and more difficult to estimate in comparison to the measurement of turbine's power or head [1]. Guidelines and standards have been published to provide practical methods, help regulate and increase the quality of the flow-rate measurements at the various types of turbines [2,3]. Although, the bulb or low-head Kaplan turbines are relatively widespread, the existing standards scarcely cover the methodology for measurements and corresponding uncertainty analysis [4]. Common practice is to refer to the ISO 3354 [5] standard for the measurements in full closed conduits, which suggests the mapping of the velocity field with an array of the propeller current meters. However, a challenge remains in providing a large number of reliable simultaneous measurements of the local velocities, with uneven and/or unstable velocity distributions.

Within the scope of the HPP Iron Gate 2 revitalization, a need for the verification of the existing Winter-Kennedy (WK) tap flow measurements has risen. Doubt in reliability of the existing method is stemming from the fact that WK flow coefficients were obtained during the lab experiments which did not take into the account the later observed high incident angles of the flow (up to $40^o$). To provide reliable flow measurements at HPP, the inherent issues of measurements in short and converging intakes, supplemented by adverse flow conditions and restrictions on the measurement locations defined by the HPP's operators [6], had to be addressed. Hence, at the design stage (of the flow measurements), it was concluded that optimal solution would include the use of current meters capable of measuring all three velocity components in both directions. Electro-magnetic velocity meters (EMVM) were designed for this task and mounted on a steel frame which was traversed across the whole cross-section to map the velocity field. They were supported by two ADVs which provided control velocity measurements. Two measurement modes were used: 1.) incremental mode in which the frame is kept fixed for at least 10 min in a number of horizontal profiles, and 2.) continuous mode, or direct integration method (as per IEC 60041) where the measuring frame is traversed from bottom, with constant speed.

This paper covers the uncertainty analysis for both types of flow measurements made at the HPP. The uncertainty analysis suggested by IEC 60041 [2] and ISO 3354 [5] standards, was used as template due to the "similarity" between the current meters and EMVMs, however moderate modifications were needed to take into account all the features of the HPP application and the EMVMs themselves. It should be highlighted that the governing standards are defined for the measurements in full, closed conduits, while here we have the case of the free-surface flow. Like in [7], we assume that these standards can be applied in our case, as the variation of cross-section area is negligible during the flow measurement process. The suggested uncertainty analysis is discussed in detail with a particular focus on the modified uncertainty components. Furthermore, the application of the analysis on the selected measurement results is shown with a short discussion on the implications and possibilities for future investigation.

## 2. Flow measurement methodology

Flow measurement methodology used at the HPP is described in more detail in [6]. As the EMVM are novel by design, IEC 60041 [2] standard does not recognize them as absolute discharge measurement method, however they were deemed as an optimal engineering solution in current application. The main idea behind the EMVM application is to utilize their capacity in measuring bidirectionally all three velocity components (X, Y and Z) to allow for the velocity profiling, flow rate assessment, and later hydraulic analysis of the flow field (bidirectional velocities, large incident angles, swirl etc). The EMVMs are designed in such manner that their shape and mounting strut resemble the propeller current meters, therefore they can be deemed as the EM-based current meters, at least for the sake of this example application. Analogy with the application of the current meters in the flow measurements in closed conduits, as defined by [2, 5, 6], is used, to describe the general flow measurement methodology, where the flow rate or discharge $Q$ is obtained by simultaneous measurements of the mean cross-sectional velocity (or mean axial fluid velocity) $V$ and area of the wet cross-section $A$. Mean cross-sectional velocity $V$ is computed through arithmetical integration of the local velocity measurements $V_{i,j}$ made with EM-meters $i = 1{:}\,N_V$ (equal to the number of EMVMs on the frame, and to the number of measurement verticals) at the profiles $j = 1{:}\,N_H$ (equal to the number of horizontal profiles where measurements were taken):

$$V = \frac{\sum_{i=1}^{N_V}\sum_{j=1}^{N_H} k_{i,j}\cdot V_{i,j}}{\sum_{i=1}^{N_V}\sum_{j=1}^{N_H} k_{i,j}} = \frac{\sum_{i=1}^{N_V}\sum_{j=1}^{N_H} w_i\cdot d_j\cdot V_{i,j}}{\sum_{i=1}^{N_V}\sum_{j=1}^{N_H} w_i\cdot d_j} = \frac{\sum_{i=1}^{N_V}\sum_{j=1}^{N_H} A_{i,j}\cdot V_{i,j}}{A} \tag{1}$$

Where $k_{i,j}$ ($k_{i,j} = w_i\cdot d_j = A_{i,j}$) is the sensitivity coefficient, $w_i$ and $d_j$ are width and depth, respectively, of the attributed cross section area $A_{i,j}$.

**Figure 1:** Left) River vegetation entangled on the measurement frame; Right) Vortex structure on the right side of the A7 turbine inlet

For the sake of brevity, additional flow measurement features, specific for the analyzed case and applied methodology, should be highlighted prior to the description of the proposed uncertainty analysis:

- Two measurement modes were utilized: incremental (lasting up to 4 hours with > 7200 measurements taken) and continuous (lasting around 9 minutes with ~ 270 measurements). In the incremental mode, the measured velocities are linearly corrected to compensate for the flow rate fluctuations during the measurements.
- Measurements were made in “constant power” turbine operating mode.
- Extrapolation of the velocity field in the peripheral flow area is performed both with power (wall and bottom) and linear law (top – free surface).
- Negative velocities (stemming from the large-scale turbulent structures with vertical and horizontal axis perpendicular to the inlet, Fig 1. Right) were measured near the free surface
- High incident flow angles up to 40° were commonly observed throughout the wet cross section.
- During the measurements large chunks of river vegetation and debris were seen to pass the measurement system and/or get attached to it (Fig 1. Left)

## 3. Uncertainty analysis

ISO 3354 [5], identifies characteristic steps in the uncertainty assessment: computation of the random, systematic, and combined uncertainty in the local velocity measurements, the uncertainty of the mean cross-sectional velocity and later the random, systematic, and combined uncertainty of the flow-rate measurements. The distinction between the random and systematic uncertainty is in collision with the GUM [8] and ISO 5168 [9], stating that all uncertainties should be treated as random in character and can be classified as Type A or Type B uncertainties related to the methodology and data used for their computation. However, for ease of the communication of the obtained results, here the terminology related to the random and systematic uncertainty components will be used, but all the components will be treated as random in nature.

### *3.1 Random (statistic) uncertainty in the local velocity measurements*

For the traditional current meters two components of the random uncertainty in the local velocity measurements can be defined: Uncertainty due to the rotational frequency of the meter and uncertainty due to the slow oscillations in velocity. The first one stems from the nature of the propeller current meter, and it is not applicable here for EM meters. However, for the incremental regime of measurements, a new component originating from the linear correction of the measured velocities in profiles is introduced. Therefore, the random uncertainty contributions in local velocity measurements are:

- *Uncertainty due to the slow oscillations in velocity*

This component of uncertainty is introduced in the unstable conditions when the time of measurement is not long enough to allow for correct integration of slow oscillation in the flow velocity [5]. Hence, to adequately represent it, the period of the velocity oscillations $t$ should be captured throughout the measurements and compared to the duration of the acquisition $T$ [7]. At HPP flow measurements, apart from the “natural” oscillation drivers, the “constant power” regime of turbine operation induced the velocity oscillations when adapting the guide and runner vane position to the current turbine height difference. During the measurements, the period of “slowest” oscillations was estimated to be between 1 and 2 minutes. Two measurement modes need to be distinguished when computing this uncertainty component, as the number of measurements taken in the incremental regime is on the order of magnitude higher than in the continuous one. Hence, for the incremental regime where the duration of acquisition in each horizontal profile was > 10 minutes, and the magnitude of velocity fluctuations $\Delta V_{i,j}$ was low (< 10 % of average $V_{i,j}$), a following equation [7] was used:

$$(u_{r,i,j})_o^{ink} = 0.1 \cdot \frac{t}{T} \cdot \frac{\Delta V_{i,j}}{V_{i,j}} \cdot 100\ [\%] \tag{2}$$

In the continuous regime a different approach was utilized. The uncertainty component was correlated to the fluctuations of the flowrate $Q_{WK}$ measured by the Winter-Kennedy method:

$$(u_{r,i,j})_o^{cont} = \frac{\sigma_{Q_{WK}}}{Q_{WK}} \cdot 100\ [\%] \tag{3}$$

Where $\sigma_{Q_{WK}}$ is the standard deviation of the flow rate measurements made with WK method.

- *Uncertainty due to the linear correction of the measured velocities*

Although the ISO 3354 [5] standard identifies the need for the correction of the measured velocities in the non-simultaneous measurements (if the changes are comparatively small in the reference velocity), there is no discussion about the measurement uncertainty being introduced when applying the correction. Here, for the incremental mode, a random uncertainty component is suggested which reflects on the error of the assumption that the velocities can be linearly corrected against referent velocity. The authors believe that the due to the high incident angle of the flow, the velocity change with the flow rate fluctuations most likely will be non-linear (at least in some parts of the cross – section, smaller than 20% of $A$). Hence, additional uncertainty is introduced which can be estimated in the following manner:

$$(u_{r,i,j})_{lk}^{ink} = 0.2 \cdot \frac{2 \cdot \sigma_{\overline{Q_{WK,J}}}}{Q_{WK}} \cdot 100\ [\%] \tag{4}$$

Where $\sigma_{\overline{Q_{WK,J}}}$ is the standard deviation of the $j$ averaged flowrates $\overline{Q_{WK,J}}$ measured by the WK method.

### *3.2 Systematic uncertainty in the local velocity measurements*

The same components of systematic uncertainty are considered here, as for traditional current meters, but different interpretation is given to account for the specific measurement features:

- *Uncertainty arising from the calibration*

The velocity profiling in the measurement process is performed with the 15 EM current meters distributed along a horizontal profile. It is assumed here that from the meter expanded uncertainty of 1% (0.5% standard uncertainty) obtained through the calibration on the flume with a towing tank, part of the uncertainties is correlated and are originating from the characteristics of the calibration rig (e.g. uncertainty of the position transducer and towing tank speed) while the other part is uncorrelated. Therefore, in the calculation of the calibration uncertainty, the uncorrelated part is divided by a square root of the number of EM (measuring in parallel the flow velocity $V$) as shown:

$$(u_{s,i,j})_c^{ink+cont} = \left(0.3 + \frac{0.2}{\sqrt{15}}\right) \cdot 100\ [\%] \tag{5}$$

- *Uncertainty due to the turbulence and due to the velocity gradient*

For the traditional current meters, these uncertainty components are treated separately, but in the similar way as suggested by the standard. The spherical construction of the EM and the integrating measurement process (velocities are integrated in the control volume 0.15 m in diameter), imply that the effects of the turbulence and velocity gradient will be somewhat "smeared" and the implications on the measurements will be materialized through the "higher frequency" fluctuations in the measured velocity. To calculate the combined effects of these uncertainty components in incremental operating mode, the following equation was used:

$$(u_{s,i,j})_{t+vg}^{ink} = \frac{\sigma_{V_{i,j}}}{V_{i,j}} \cdot 100\ [\%] \tag{6}$$

Where the $\sigma_{V_{i,j}}$ is the standard deviation of the $V_{i,j}$ measurements. For the continuous mode, modified equation should be used, where the uncertainty component is attributed to the $i$-th EM meter:

$$(u_{s,i})_{t+vg}^{cont} = \frac{\sigma_{V_i}}{V_i} \cdot 100\ [\%] \tag{7}$$

$\sigma_{V_i}$ is the standard deviation of all the measurements made during the traversing, with the $i$-th EM meter, while $V_i$ is the average velocity measured with $i$-th EM meter.

- *Uncertainty due to the misalignment of the current meter (higher incident angles)*

Unlike the case of the propeller current meter, EM meters are capable of bidirectional measurements in X, Y and Z direction. However, the calibration uncertainty is declared for the incident angles $\alpha_{i,j}$ up to 15° in respect to the orientation of the EM meter. For higher $\alpha_{i,j}$, the values of calibration uncertainty are larger (reaching up to 5% in total for 180°) as shown in the Prodanović et al., (2022) (Fig 3. Rightmost). If the diagram is unwrapped and normalized for the angles in the vertical plane up to 180° a second order polynomial could be used to approximate the relation between the calibration uncertainty contribution stemming from the larger incident angles $(u_{s,i,j})_{\alpha}^{inc+cont}$ and the values of incident angles $\alpha_{i,j}$:

$$(u_{s,i,j})_{\alpha}^{inc+cont} = 6 \cdot 10^{-5} {\alpha_{i,j}}^2 + 0.0133 \cdot \alpha_{i,j} - 0.2121[\%] \tag{8}$$

Where $\alpha_{i,j}$ is defined in degrees.

### *3.3 Combined (total) uncertainty in the local velocity measurements*

The combined uncertainty in the local velocity measurements $(u_{i,j})$ is obtained by summing the contributions from the random $(u_{r,i,j})$ and systematic $(u_{s,i,j})$ components as the square root of the sum of the squares, or:

$$(u_{r,i,j}) = \sqrt{(u_{r,i,j})_o^2 + (u_{r,i,j})_{lk}^2} \tag{9}$$

$$(u_{s,i,j}) = \sqrt{(u_{s,i,j})_c^2 + (u_{s,i,j})_{t+vg}^2 + (u_{s,i,j})_{\alpha}^2} \tag{10}$$

$$(u_{i,j}) = \sqrt{\left(u_{r,i,j}\right)^2 + \left(u_{s,i,j}\right)^2} \tag{11}$$

It should be highlighted that appropriate equations should be used for the computation of the uncertainty components depending on the measurement mode (incremental and continuous).

### *3.4 Uncertainty in the mean cross-sectional velocity measurements*

To arrive at the uncertainty in the mean cross-sectional velocity based on the previously computed combined uncertainties for the local velocity measurements, eq. (1) should be referred to. The sensitivity coefficients used for the computation of the velocity $V$, are used here also, hence the following equation should be used:

$$(u_V) = \sqrt{\frac{\sum_{i=1}^{N_V} \sum_{j=1}^{N_H} \left(A_{i,j}^2 \cdot \left(u_{i,j}\right)^2\right)}{A^2}} \tag{12}$$

### *3.5 Random uncertainty in the flow-rate measurements*

Four components are distinguished: uncertainty in the mean cross-sectional velocity measurements (defined by eq. 12), uncertainty arising from the estimation of the value of $m$ (extrapolation in the peripheral zone), uncertainty arising from the current-meter positioning and uncertainty arising from the free-surface estimation. Here, the last three are discussed:

- *Uncertainty arising from the estimation of the value of m (uncertainty in the velocity extrapolation in the peripheral zone)*

In the cases of closed full conduits, the wall coefficient $m$ is defined based on the surface roughness of the conduit and flow conditions (Reynolds number, velocity distribution, etc.) or by graphical determination (see Annex E of ISO 3354). In the HPP measurements, the way extrapolation is performed, towards the stiff boundaries (e.g. walls and bottom) and free surface, is defined by user. Additional investigations during the flow-rate measurements in 2020., have revealed that the most suitable fit for the stiff boundaries is obtained when exponential fit is used with power of 1/9 and different scale coefficients for right and left wall (due to the flow asymmetry), and linear for the free surface. The size of the peripheral zone $A_{p,st}$ in the vicinity of the stiff boundaries was in average 6 – 6.5% while near surface $A_{p,fs}$ it was 0.8 – 1.3%. Thus, the resulting uncertainty component is computed by adding two contributions, assuming the $m = 9$ for both types of boundaries and by using the random uncertainties (eq. 11) in the extreme measurement points:

$$\left(u_{Q,r}\right)_m = \sqrt{\left(\left(u_{r,i,j}\right)_{p,st}\frac{A_{p,st}}{A\cdot m}\right)^2 + \left(\left(u_{r,i,j}\right)_{p,sf}\frac{A_{p,sf}}{A\cdot m}\right)^2} \tag{13}$$

- *Uncertainty arising from the current meter positioning*

The position of the current meter is monitored with two position transducers mounted at both ends of the measuring frame. The uncertainty of the position measurements can be estimated to be around 10 mm or 0.02% of the measurement range (50 m), from the declared instrument linearity and precision and by assuming the rectangular distribution [9]. Modelling the flow rate measurement with this hypothetical shift in EM meter position would lead to the difference of $\Delta Q$, and can be used to determine the magnitude of this uncertainty in flow rate measurements:

$$\left(u_{Q,r}\right)_{pos} = \sqrt{\sum_{i=1}^{N_V}\sum_{j=1}^{N_H}\left(\frac{\Delta Z\cdot\Delta Q}{Z}\right)^2} \tag{14}$$

- *Uncertainty arising from the depth measurements*

The uncertainty in measurement of the depth or the height of the cross-section is originating from the depth sensors, the sonar bottom sensors, and survey data. Depth measurements were made with two pressure transducers (left and right) placed in still pipes during the whole measurement process, while the sonar data is obtained prior to the measurements. In all cases the sonars detected distances distributed within the measurement uncertainty, hence it was assumed that the bottom was clean from sediment deposits. The corresponding uncertainty component is calculated from the depth measurement uncertainty:

$$\left(u_{Q,r}\right)_{dm} = \frac{\sigma_{H_{i,j}}}{\sqrt{2}\cdot H}\cdot 100\ [\%] \tag{15}$$

*3.6 Systematic uncertainty in the flow-rate measurements*

- *Uncertainty from the measurement of the cross-sectional area*

Systematic uncertainty in the width of the section (depth measurements are already considered in 3.5.), obtained through survey and in reference to the construction drawings, is assumed to be $\left(u_{Q,s}\right)_A = 0.15$ [%].

- *Uncertainty arising from the use of arithmetic or numerical integration method*

The integration of the measured velocity field introduces the uncertainty reversely proportional to the number of measurement points and coverage of most important flow characteristics. For cases where velocity distribution are expected to be non-uniform, the IEC standard defines a minimal number of measurement points as $24\cdot\sqrt[3]{A} < Z < 36\cdot\sqrt[3]{A}$. For the average depth of 27 m , 15 probes per profile and 16 to 19 profiles, number of measurement points is between $240 < Z < 285$. Used velocity integration is bi-linear. However, due to the adverse flow conditions, a pessimistic value is assumed $\left(u_{Q,s}\right)_{in} = 0.3$ [%].

- *Uncertainty from the number of measuring points*

In both incremental and continuous mode, the number of measurement points can be deemed as sufficient, but the condition of simultaneous measurements is not achieved. Hence, the uncertainty arising from the number of measuring points can be assumed to be $\left(u_{Q,s}\right)_{nm} = 0.2$ [%].

*3.7 Combined uncertainty in the flow-rate measurements*

When random and systematic components are computed, combined uncertainty in the flow-rate is estimated:

$$\left(u_{Q,r}\right) = \sqrt{A\cdot(u_V)^2 + (u_{Q,r})_m^2 + (u_{Q,r})_{pos}^2 + B\cdot V\cdot(u_{Q,r})_{dm}^2} \tag{16}$$

$$\left(u_{Q,s}\right) = \sqrt{V\cdot H\cdot(u_{Q,s})_A^2 + (u_{Q,s})_{in}^2 + (u_{Q,s})_{nm}^2} \tag{17}$$

$$\left(u_Q\right) = \sqrt{\left(u_{Q,r}\right)^2 + \left(u_{Q,s}\right)^2} \tag{18}$$

## 4. Analysis of the selected flow-rate measurements

During the 2020. campaign, flow-rate measurements were performed on two turbines A1 and A7. The suggested uncertainty analysis has shown that the relative combined uncertainties in flow-rates obtained with incremental regime are spanning from 0.96% up to 2.28%, while for the continuous mode, the uncertainties were ranging from 1.47% up to 4.62%. Here, selected measurements on A1, one incremental and three continuous for similar flow-rate, are shown in more detail.

Figure 2 illustrates the obtained velocity field in the incremental mode for A1 turbine, while in Table 1, the measurement results are reported along with the significant uncertainty components. In general, the dispersion of the measurements between incremental and continuous modes is low which is verified with low combined uncertainties in measured flow rates (1.08% – 1.80%). Computed combined uncertainties for the continuous measurements are in average 65% higher, mainly due to the larger random uncertainty in velocity measurements. This is expected as in this mode the uncertainties from the slow oscillations are pronounced due to the short acquisition time.

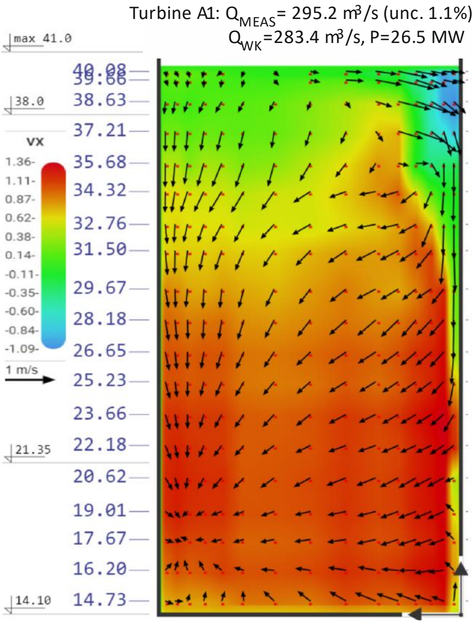

**Figure 2:** Velocity field at A1 turbine.

**Table 1:** Measurement results and computed uncertainty components and combined uncertainties for A1 turbine.

| **Measured data** | **Incremental measurement** | **Continuous measurements** | | |
|---|---|---|---|---|
| | | **nº1** | **nº2** | **nº3** |
| $Q$ [m$^3$/s] | 295.20 | 296.99 | 296.80 | 299.87 |
| $Q_{WK}$ [m$^3$/s] | 283.41 | 284.87 | 283.16 | 280.88 |
| **Uncertainty components** | / | / | / | / |
| Random velocity [%] | ±0.80 | ±1.61 | ±1.22 | ±1.59 |
| Systematic velocity [%] | ±0.58 | ±0.77 | ±0.69 | ±0.66 |
| Random flow rate [%] | ±1.00 | ±1.79 | ±1.41 | ±1.74 |
| Systematic flow rate [%] | ±0.39 | ±0.48 | ±0.50 | ±0.48 |
| **Combined flow rate [%]** | ±1.08 | ±1.85 | ±1.50 | ±1.80 |
| Combined flow rate [m$^3$/s] | ±3.17 | ±5.51 | ±4.45 | ±5.40 |

## 5. Conclusions

A modification of the flow-rate measurement uncertainty analysis defined by IEC 60041 and ISO 3354 are suggested here to accommodate for the specific features of the measurement system, based on the EM meters, used at the Iron Gate 2 HPP. Both incremental and continuous (direct integration) measurement modes and results are discussed. Due to the shorter measurement time in the continuous mode, random uncertainties in the velocity measurements yielded larger uncertainties in the flow rate measurements in comparison to the incremental. However, the duration of the incremental mode measurements motivates the further investigation of faster continuous mode of operation, as the preliminary analysis indicate low dispersion of the obtained results.

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