NOVEL DISCHARGE MEASUREMENT SYSTEM AT THE TURBINE INTAKES OF IRON GATE 2 HYDROPOWER PLANT: A SYSTEM DESCRIPTION

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Summary: *To quantify the hydraulic performance characteristics of hydraulic turbines several basic quantities need to be accurately determined. Discharge, or flow rate, is the most difficult quantity to measure as the measurement uncertainty is higher and more difficult to estimate in comparison to the power and head. Design of a discharge measurement system is governed by both the geometric and flow conditions at the measurement site, as well as by the physical properties of the fluid. Moreover, in adverse or non-standard flow conditions, special care must be taken to allow for the measurement system to capture the discharge data with acceptably low measurement uncertainty. In this paper, a general description of a novel discharge measurement system, designed and installed at the Iron Gate 2 hydropower plant, is provided. The system can be installed at the turbine intake, upstream of the trash rack, on one turbine at the time. Discharge value is acquired by employing a Velocity-Area aproach. Robust steel frame, carrying 15 novel 3D electromagnetic velocity probes, along with the 2 acoustic doppler velocimeters, is traversed along the cross sectional flow area allowing for accurate velocity field mapping. Position of the traversing frame is determined with two position transducers while two pressure transducers are used for the water level measurements. The measurement system was used at two turbines at the Iron Gate 2 HPP, capturing discharge with low measurement uncertainties.*

Keywords: *Discharge/Flow measurements, Measurement system, Hydropower plant, Electromagnetic probes*

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1. INTRODUCTION

Hydropower plants (HPP) are the key elements in the national power supply systems. Apart from the fact that these systems are providing a substantial proportion of the power generation, they are essential for the grid operation as they can quickly adapt to the variations in the power demand. Furthermore, hydropower is a renewable energy source although the river damming can contribute to a significant footprint on the surrounding ecosystem. In the Republic of Serbia it is estimated that the around 30% of the total electrical energy supply is stemming from the hydropower plants (www.eps.rs).

To optimize the control, operation, and management of the HPP, hydraulic efficiency of the turbines must be kept at the high levels. Several basic hydraulic, mechanical, and electrical quantities need to be accurately determined, for estimation of the hydraulic performance characteristics of the HPPs turbines. Discharge, or flow rate, is the most difficult quantity to measure as the measurement uncertainty is higher and more difficult to estimate in comparison to the power and head [1]. Several quidelines and standards have been published [2][3] to provide practical methods, help regulate and increase the quality of the discharge measurements at the various types of the HPP turbines. Although low-head Kaplan turbines with short, converging intakes are in a widespread application, supporting quidelines and literature for discharge measurements are scarce [4]. Furthermore, in the non-standard situations, with adverse flow conditions at the short intakes of the low-head Kaplan turbines, further care must be taken in design of the measurement system.

The plans of the revitalisation of the low-head Kaplan turbines at the Iron Gate 2 HPP, has inspired a need for the accurate discharge measurements in order to confirm the designed efficiency gain. Few of the existing Winter-Kennedy (WK) measurement devices have been recalibrated recently. It was concluded that the additional redundant discharge measurement system is needed in order to enable control measurements for the recalibrated WK, and primary measurement data for the rest of the system until the WK recalibration. To address this need, a discharge measurement system, based on the Velocity Area approach and novel 3D EM velocity probes, was designed and installed.

Here, the new measurement system at the Serbian turbines of the Iron Gate 2 HPP is analyzed and discussed. A novel 3D EM velocity probes are briefly presented, and the discharge evaluation methodology incorporated in the Real-time and Post-processing monitoring software is described. Finally, an example of the measurement results from the post-processing software is presented.

2. FLOW CONDITIONS AT HPP IRON GATE 2

The sector of the Danube river, shared between the Serbia and Romania, hosts two largest HPPs in the Republic of Serbia: Iron Gate 1 (srb. Đerdap 1) and Iron Gate 2 (srb. Đerdap 2). Iron Gate 2 represents a downstream step of the coupled system. The dam objects and the HPPs are located at the stationary 863 km of the Danube river. Although the disposition of the Iron Gate 2 system is assimetrical, both Serbian and Romanian HPPs are equipped with 8 turbines at the main object and 2 at the additional objects (total of 20). Total installed discharge is 8500 m^3/s (www.eps.rs).

During the operation of the Iron Gate 2 HPP it was concluded that the turbines near the middle of the dam (Serbian HPP) have lower hydraulic efficiency then the ones close to the left bank of the Danube (Romanian HPP) [5]. Further investigation showed that the incident water flow angle φ, deviates from the desired values, especially in the regular operating mode without overflow over sluice gates. Figure 1 (Right) shows the trajectories of the incident water resulting from the physical model investigations [6].

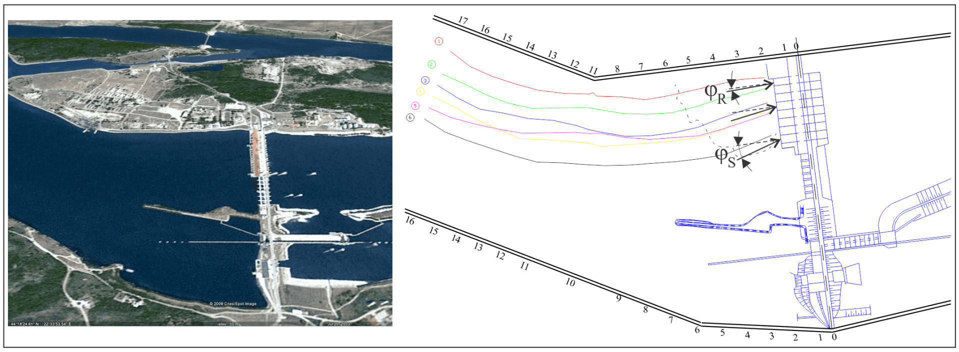

Figure 1. Left) HPP Iron Gate 2; Right) Trajectories of the incident flow recorded within the scope of the physical model testing [5]

At the Iron Gate 2 HPP, low-head Kaplan turbines are used. Stemming from the fact that hydrulic performance chacracteristics of the turbines have been analyzed on the original physical model that did not envelop the observed angle deviations, it was concluded that currently the turbines are operating in a non-standard mode. Furthermore, the installed WK flow measurement instrumentation has been originally calibrated using the index testing approach on the same physical model. Hence, the WK discharge measurement results are burdened with the unknown ammount of measurement uncertainty. In the scope of the planned revitalization process, the expected efficiency gain cannot be accurately determined as the current hydraulic efficiency of the turbines is unknown.

3. SELECTION OF THE DISCHARGE MEASUREMENT METHOD

In general, the choice of the discharge measurement method and the actual design of the measurement system as a whole, is governed by the flow conditions at the measurement site, physical properties of the fluid, geometric characteristics of the conduit, environmental conditions and the economical constraints [7]. Due to the specifics of the HPPs, the existing standards (e.g [2][3]) recommend several approaches to be applied, in the respect to the specific type of the HPP and the goal of the measurement campaign.

Most of the standard recommended methods for the discharge measruements cannot be used in the short converging intakes typical of a Kaplan unit due to the insufficient length of uniform upstream water conduit to allow their use. Only the Velocity-Area method with an array of the current meters is approved, but the restrictions on its implementation to meet standard requirements are strong, rendering its use impractical, although it is nonetheless often used in turbine tests [4]. In this method the current meters are used for the fine velocity field mapping, leading to the estimation of the mean flow velocity with low measurement uncertainty.

Similarly, at the HPP Iron Gate 2, the turbine intakes are short and converging. However, due to the high incident flow angle φ, the Y component of the incident velocity vector is significant (Figure 2).

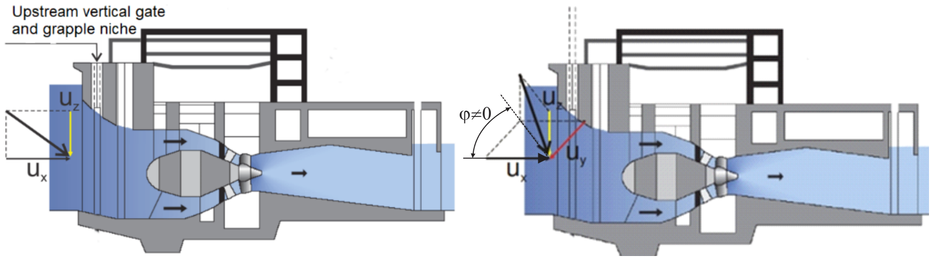

Figure 2. Left) Regular 2D flow conditions at the short and converging turbine intakes; Right) Adverse 3D flow conditions at the Iron Gate 2 HPP [5]

During the planning phase of the Iron Gate 2 discharge measurement system, it was concluded that the Velocity-Area approach must be applied, where the mean flow velocity must be determined in paralell with the flow cross section. But, the adverse 3D flow conditions at the turbine intakes, ruled out the application of the current meters for the velocity field mapping. It was deemed that the significant lateral components of the incident velocity vectors will result in the unacceptable measurement uncertainty of the velocities obtained with the current meters. It should be noted that the available current meters measure only one (flow) velocity component, and that the highly accurate measurements can be achieved with the angles φ up to 15 degrees. With higher φ, the measured velocity must be adjusted in the post-processing for which the all three velocity components need to be acquired with an additional instrumentation.

As a result, the focus was shifted towards the development of the novel 3D EM velocity meter. Domestic company „Svet Instrumenata“, part of the mandate consortium formed for this task, underwent the whole research and design process, constructing an instrument which could be employed instead the current meters (Figure 3). The 3D EM sensor, named „Log XYZ“, consists of a spherical head, 63 mm in diameter, which is fixed with a stainless rod to a computing unit. It can measure all three components (X, Y and Z) of the velocity vector in a range from few mm/s up to 2 m/s.

Figure 3. Left) Novel 3D EM velocity meter with accessories in the original casing, Right) Comparison of the 3D EM velocity meter to two ADV sensors at the Water institute "Jaroslav Černi"

The 3D EM sensor was riguously tested at the towing tank of the Water Institute „Jaroslav Cerni" (Figure 3). The tests have shown that the accuracy of the three measured measured velocity components is 1% for the angles φ up to 45 degrees. Furthermore, the precision of the device is better than 1%. Due to the excellent performance in the testing, it was chosen that the primary velocity measurement instrumentation at the Iron Gate 2 HPP will be the novel 3D EM sensor, while the redundant control measurements will be provided by the ADV sensors (Acoustic Doppler Velocitymeters) [8][9].

4. MEASUREMENT SYSTEM DESCRIPTION

The constructed measurement system can be installed at the intakes of the Iron Gate 2 turbines, using the niche for vertical gates and grapple, upstream of the trash rack [10]. It consists of the robust steel frame shaped to minimize flow disturbances, 14.5 m width and 3.1 m height, which can be traversed vertically through the whole flow cross section. The average water depth at the measurement cross section is around 26 m. On the steel frame, 15 3D EM velocity meters were mounted in a horizontally symmetrical, but unevenly distanced pattern (Figures 4 and 5). Redundant and control velocity measurements were enabled via 2 Nortek "Vector" [11] acoustic doppler velocitymeters (ADV), mounted 0.5 m above the EM meters. Continuous water level measurements were carried out via 2 fixed pressure transducers installed at the both sides of the intake. The position of the steel frame was precisely monitored with 2 UniMeasure "HX-EP" position transducers installed on the platforms (right and left) above the intake. Prior to the discharge measurements and the mounting of the equipment on the steel frame, 4 sonars can be mounted on the positions of the EM meters (total of 15 positions can be used) for echo sounding the bottom profile. Once powered on the measurement system is contitnuously sampling data. The measurement system can be operated in two modes, 1.) Continuous and 2.) Incremental. In the continuous mode, the steel frame is traversed from bottom to the top with the lowest speed of nearly 5 cm/s. This mode allows for the discharge measurements to be taken in 6, 7 minutes. In the incremental mode, the frame is traversed upwards between the

equidistant profiles. In each of the profile the frame is fixed for 10 minutes. In this manner, the one discharge measurement can last for couple of hours. In both modes it is recommended to keep the flow conditions at the examined turbine and two neighbouring ones, as stable as possible.
Measured signals are collected in real-time, except for the ADVs, processed and visualised using the specially developed Real-Time Monitoring software. The sampling (for all the sensors) and visualization frequency is adjustable, with the highest frequency of 1 Hz. All measurements were synchronized with HPP's SCADA, so turbine's operational parameters were downloaded off-line and merged. The merged data was later processed with another specifically tailored software for the data post-processing, measurement uncertainty and discharge computation. In the post-processing, the user can exclude data from certain time periods or instruments if the malfunctioning of the system components has accured during the measurements. Furthermore, he can slightly adjust the parameters for the velocity field integration, thus allowing for different values of the computed discharge for the same set of the measured data.

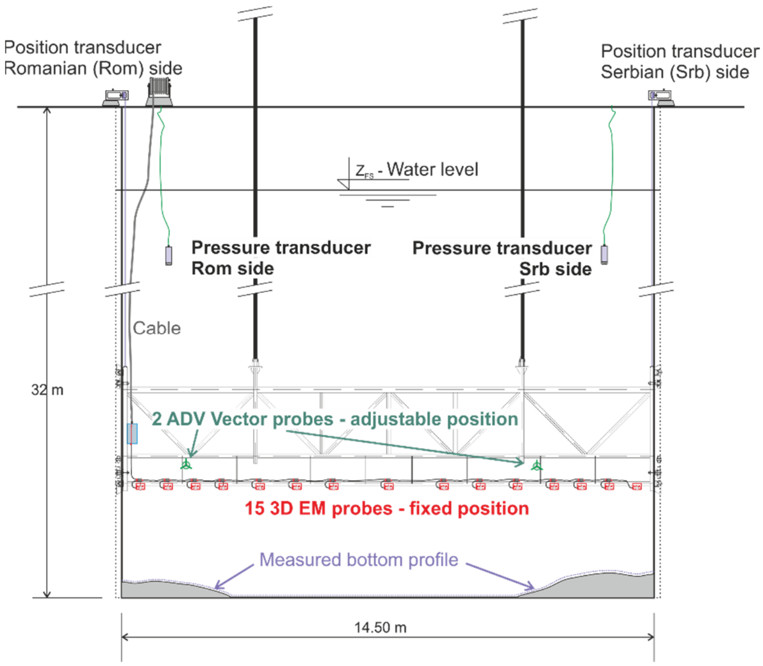

Figure 4. Schematic representation of the discharge measurement system components (view toward the inlet)

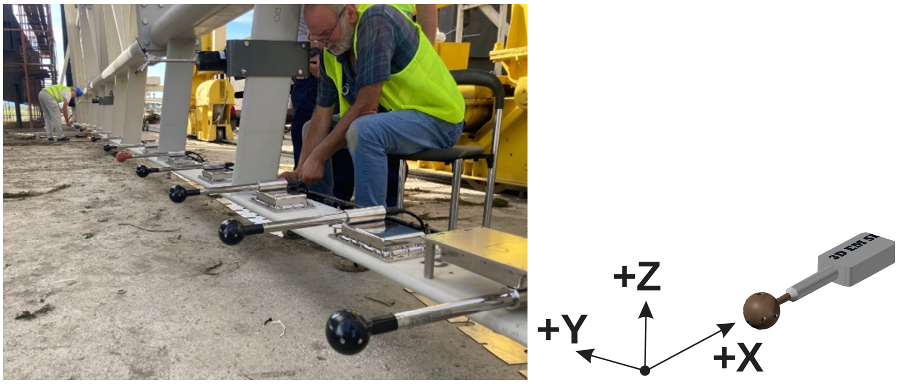

Figure 5. Left) Mounting of the 3D EM Velocity probes of the steel frame Right) Orientation of velocity components measured by EM probe

5. EXAMPLE OF MEASURED RESULTS

During the 2020, measurement system was used on the two turbines of the Iron Gate 2 HPP. Both Continuous and incremental operating mode was used, and several different discharge values were measured, including one with minimal turbine power and one with maximal turbine power (for current conditions). During the whole time of the measurements the examined turbines and the neighbouring turbines were kept at the constant power by the HPP operators. All of the measurement system components succesfully operated in dynamic environmental conditions. During the periods when the incident water flow was carrying a significant ammount of the river vegatation, trash and other debris, it was observed that the steel frame and velocity probes were prone to entaglement and build-up of this material (Figure 6.). However, even in those conditions most of the 3D EM velocity meters managed to capture good quality data.

Figure 6. Vegetation build-up on the steel frame during the measurements

The measured data was later processed and final discharge values were computed. Uncertainty assessment procedure, yielded discharge measurement uncertainties between 1.02 % and 2.00 % for incremental, and between 1.65 % to 2.79 % for continuous regime. An example discharge measurement and computation result from post-processing software is shown on the Figure 7.

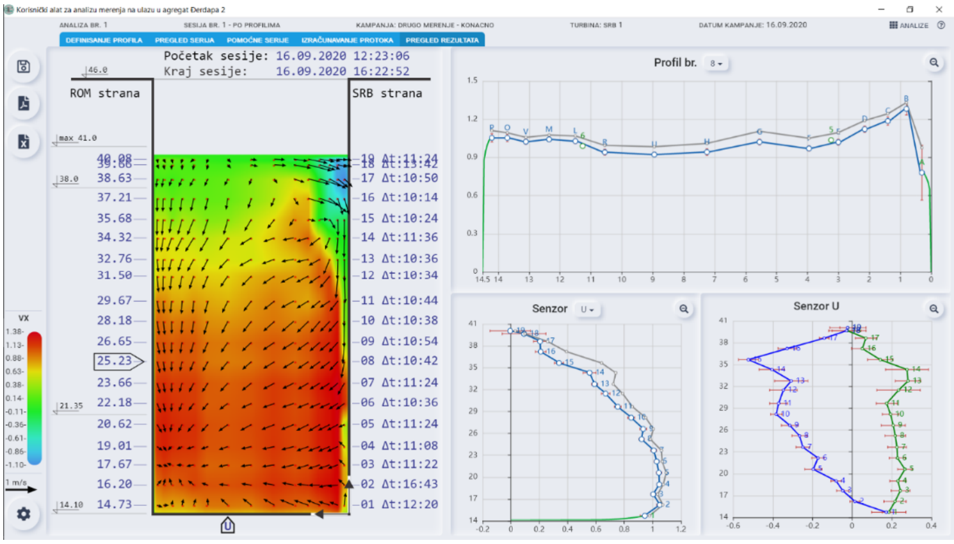

Figure 7. Example of the post-processing of the measured data for the discharge computation; Left): velocity field; Upper right) streamwise component at 25.23 depth; Lower right) all three components at U vertical.

6. CONCLUSIONS

Previous studies and the operational experience have shown that the incident water flow angle is deviating from the designed values at one of the largest hydropower plants (HPP) in the Republic of Serbia, Iron Gate 2. To allow for the evaluation of the current operating efficiency of the turbines, and furthermore the efficiency gain from the planned revitalization of the turbines, a novel discharge measurement system was designed. Due to the specific flow conditions, and the geometry of the short and converging intakes, a Velocity-Area approach was adopted. Primary velocity measurement instruments were 15 newly designed 3D EM velocity meters, mounted on a robust steel frame in a horizontally symmetrical, but unevenly distanced pattern. Control velocity measurements were collected via 2 Nortek “Vector” ADVs, while the water level measurements were carried out via 2 fixed pressure transducers installed at the both sides of the intake. Accurate position of the steel frame was monitored with 2 position tranducers. Specific real-time monitoring software was designed to enable the collection and visualization of the sampled data from various instruments. Additionally, a post-processing software was developed to allow for the various data processing approaches, measurement uncertainty and discharge computation.

During the 2020., the system was used on two turbines of the Iron Gate 2 HPP. The system succesfully managed to collect and process data in two operating modes (Continuous and Incremental) leading to the discharge measurements uncertainties between 1.02 % and 2.00 % for incremental, and between 1.65 % to 2.79 % for continuous regime. The used 3D EM velocity probes operating even in the case of the significant vegetation build-up over the probe sensors and housing.

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ИНОВАТИВНИ СИСТЕМ ЗА МЕРЕЊЕ ПРОТОКА НА УЛАЗИМА У ТУРБИНЕ ХИДРОЕЛЕКТРАНЕ ЂЕРДАП 2: ОПИС СИСТЕМА

Резиме: *Како би се кватификовале карактеристике хидрауличких перформанси турбина, неопходно је поуздано дефинисати неколицину основних величина. Проток кроз турбину је величина коју је најтеже измерити, будући да је мерна несигурност већа и теже се одређује него у случају снаге или пада турбине. Пројектовање система за мерење протока је условљено геометријом и условима течења на мерном месту, као и физичким карактеристикама флуида. Такође, у сложеним или нестандардним условима течења, посебну пажњу треба посветити у поспутпку пројектовања како би се омогућило систему да измери податке о протоку са прихватљиво ниском мерном несигурношћу. У овом раду је дат генерални опис иновативног мерног система који је пројектован и инсталиран на хидроелектрани Ђердап 2. Мерни систем се може поставити на улазу у турбину, узводно од грубе решетке, на једној од турбина. Вредност протока се одређује применом приступа Брзина-Протицајни пресек. Робусни челични рам, опремљен са 15 новоразвијених 3Д електромагнетних сензора брзине, заједно са 2 акустична Доплер сензора, се помера по протицајном пресеку како би се поуздано мапирало поље брзина. Положај рама се прати помоћу два енкодера положаја, док се два сензора притиска користе за мерење дубине воде. Мерни систем је коришћен на два агрегата хидроелектране Ђердап 2, омогућавајући да се измере протоци са ниском мерном несигурношћу.*

Кључне речи: *Мерења протока, Мерни систем, Хидроелектране, Електромагнетне сонде*