Improvement of EM flow meter's accuracy through site-specific CFD calibration – case study HPS Trebinje

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Abstract

Flow measurement in mixed flow conditions in field applications is a challenging task, which can be performed only by few techniques like ultrasonic and electromagnetic. Despite the flowmeter's special design, flow rate bias due to irregular flow conditions can increase the systematic uncertainty. In order to overcome this issue, additional site-specific calibration procedure adapted for the flat EM sensors is presented in this paper. Procedure includes a two-stage hydraulic analysis, with a task to model the velocity field in the vicinity of the sensors. The procedure was applied in the full-scale engineering practice. The paper presents the first results of implementation and discusses further research possibilities.

Keywords
Flow measurement, CFD, electromagnetic sensors, mixed flow

INTRODUCTION

The accurate flow data is needed throughout the hydraulic engineering as well as the other scientific fields. Different applications and environment conditions require different measuring techniques, which can significantly vary in terms of accuracy, cost and robustness (Prodanović, 2007). Only in certain situations the flow can be considered as full-pipe (pressurized), where flow area is known in advance allowing the usage of flow meters with accuracy of 0.5% or even better (Baker, 2002). More often, the flow is with free surface (open flow), or even is a mixture of free surface and pressurized flow (mixed flow conditions). In such systems, the flow area is variable and has to be measured together with velocity. Also, in open or mixed flow conditions the range between maximal and minimal flow is larger than in pressurized systems. In sewer systems for example, the range of monitored minimal and maximal flow can be from 1:10 in used water networks to 1:1000 or higher in combined systems (Hager, 2010), where the accurate flow of (small) used water is important same as the peak flow during rainfall. While, in general, it is possible to distinguish applications with pressurized from the free surface flows, in some specific cases a flowmeter needs to operate well in both cases (mixed flow conditions).

It can be shown that in mixed flow conditions, due to the physics of the problem, it is difficult to obtain a good flow data with most of the meters available (Simonović, 1990). Only few techniques, like semi-integrative or sampling based ones, can successfully perform this task. Most used ones are the ultrasonic (US) transit-time or Doppler profiling devices and electromagnetic (EM) flowmeters. Despite the improved design of flow metering systems, flow rate bias as well as the systematic uncertainty will remain high (Chaundry, 2008) due to site-specific irregularities, which are more interfering with velocity profiles then in pressurized flow conditions. An attempt to address this issue for the flat design of the EM flowmeters, which can be treated as a semi-integrative measuring technique, is presented in this paper. Although, EM flowmeters are not widely used in the open channel or mixed flow conditions, historical overview with numerous applications and design possibilities has been recently published (Watral, Jakubowski, and Michalski 2015), clearly pointing out the adventages of the method. Also, there are numerous improvements in EM devices (like Beljic et al., 2012) which are aiming in improved accuracy and robustness.

Since the major drawback of the flat EM flowmeter is limited, in terms of the size, magnetic field and hence the integration zone, which is a fraction of the “wet” cross section, additional measures need to be taken in order to reach the desirable level of accuracy in mixed flow conditions. For larger cross-sections, it is possible to increase the number of used EM sensors (or probes), but the velocity-pattern irregularity will still be the issue. To improve the accuracy of the single or multiple-sensor EM flow meter, this paper suggests the Site-Specific Calibration (SSC) procedure. SSC procedure is presented along with the engineering practice application example. Recent investigations have shown the possibilities of CFD usage for bias and uncertainty computations for US and EM sensors (Weissenbrunner et al. 2016) and general velocity-area methods (Steinbock et al. 2016) in a pressurized flow. Similar approach was also used in the installation effect predictions for different flowmeters (Hilgenstock & Ernst, 1996) (Holm et al., 1995). To prepare the model of the EM flowmeter one needs the fine-scale velocity field near the EM probes same as the magnetic field produced by those probes. In this paper, the applicable model of EM flowmeter is presented. The presented procedure includes a two-stage hydraulic CFD analysis of the flow conditions at the site location. In the first stage, large scale hydraulic analysis is performed in order to determine the optimal sensor location and boundary conditions for the later, second stage. In the second stage, more detailed analysis of the conditions in the sensors vicinity combined with magnetic field is performed. The paper will also present the full-scale example from real engineering practice.

MATERIALS AND METHODS

Brief overview of the general EM flow measuring technique and the specifics of the flat-type sensors are presented first. Key points, of the presented SSC procedure follow and the section is concluded with the details of the case study example.

EM flowmeters

In general, EM flowmeters operating principle is based on the Faraday’s law, where the output signal of the meter (induced voltage between the electrodes E) is generated by motion of fluid through a transversal magnetic field (Shercliff, 1954). Thus, sensitivity can be described as cross product of the velocity and the magnetic field at a certain position (Bevir, 1970). Stemming from the relations used in the electrical networks, an idea to describe how each part of the flow contributes to the voltage E through the weight function w (Shercliff, 1954) or in a more rigorous formulation weight vector $\vec{W}$ (Bevir, 1970) was introduced:

$$E = \int_A \left(\vec{B} \times \vec{j}\right) \cdot \vec{V} dA \tag{1}$$

Where A is the integration zone of the EM sensor (Figure 1), $\vec{B}$ is the magnetic induction, $\vec{j}$ is the virtual current vector and $\vec{V}$ is the streamwise velocity field. The cross product $\vec{B} \times \vec{j}$ defines Bevir’s weight vector $\vec{W}$. The goal of the probe designers is to arrange the magnetic field and the electrodes in such manner, that the output signal can be independant of the velocity distribution. Such probe is considered „ideal“ and can be defined by a following condition:

$$curl\left(\vec{B} \times \vec{j}\right) = curl\left(\vec{W}\right) = 0 \tag{2}$$

Usually, weight vector $\vec{W}$ can be replaced with the Shercliff function w, for the full pipe EM flowmeters. Weighting functions for the rectangular EM flow meters have also been derived in the work of Smyth (1970), using the Green's theorem. An interesting approach for weighting function or *K*-factor computations, which utilizes double Fourier series, was presented (Hemp et al., 1986) for the circular EM flowmeters in general. Furthermore, these results lead to the development of the dry-calibration procedures for the particular EM flowmeters, where some of them were based on the magnetic field measurements (Al-Rabeh & Baker, 1986) while others on the analytical solution of the Laplace's equations (Hu et al. 2009). Unfortunately, lack of the similar research for the EM flowmeters used in open channel application, could be a reason for its limited popularity.

In the research presented in this paper, flat type EM flowmeters designed by *Svet Instrumenata* for the free surface and mixed flow conditions, were used. Application of these flowmeters, significantly differs from the standard full pipe EM probes. While the full pipe EM probes are treated as fully integrative flow measurement technique, flat EM meters are semi-integrative as only limited parts of cross sectional flow rate contributes to the output signal (Figure 1). Integration area *A* of each probe is defined by the probe's design, in terms of the size and position of the electrodes and the strength of the magnetic field, as well as by conduits geometry and water depth. Since, the geometry of the cross section is not known *a priory* and the water depth is a temporal variable, the effect of the velocity distribution inside a variable integration area is significant.

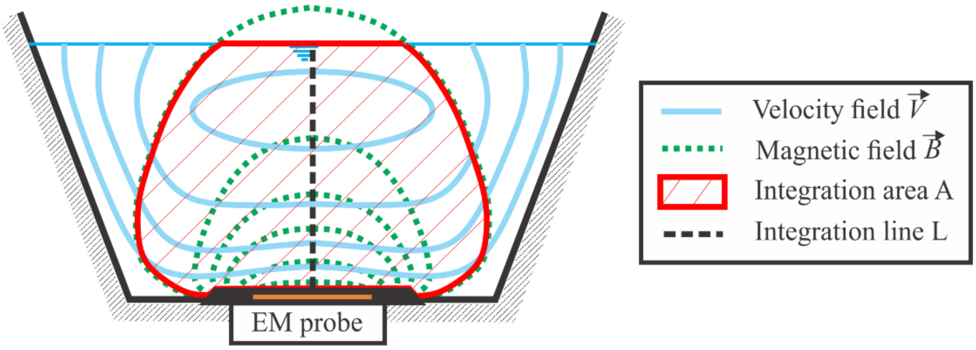

Figure 1. An example of velocity and one flat EM magnetic field distribution in an open channel

On the other hand, analytical derivation of the appropriate weighting function is difficult in this case, thus manufacturer's data is used. So far only 1D manufacturer's approximation of the 3D weighting function is available. Additional drawbacks, like the signal noise interference are not treated in this paper. The main benefit of EM sensors is the possibility to measure velocities from few millimetres per second up to 10 m/s. Also, the EM sensor can work both in clean water (but not distilled) and in dirty water with lot of sediments.

Site Specific Calibration

Depending on the problem at hand, in terms of the dimensions and the condition of the conduit, single or multiple flat EM sensors can be used at a particular measuring location. Each EM sensor is calibrated in towing tank with, what manufacturer claims to be, a homogenous velocity field. However, in real field applications, the velocity field definitely is not homogenous and it is essential to accurately predict the true field and calculate the deviation from the field used in a calibration for all mixed flow conditions, for each used EM sensor. The goal of the Site Specific Calibration (SSC) procedure is to simulate real flow conditions in the vicinity of the EM probes, in order to reduce the effect of the local velocity distribution on the flow data bias and uncertainty. CFD, as an established tool can be used for this task, but prior to its usage, great care must be taken in order to prepare the necessary data.

In order to perform an adequate CFD analysis of the local flow conditions in hydraulic systems, boundary conditions and the problem domain must be carefully prepared. For this purpose, the hydraulic analysis inside the SSC procedure is split into two stages:

1. *Global hydraulic analysis* – the aim of this analysis is to obtain adequate boundary and, if possible, initial conditions for the later local hydraulic analysis. Usually, flow metering system is placed at the outlet of a particular hydraulic system or at a specific cross section inside. In most of the cases, significantly accurate CFD analysis of the global system would require extreme computational burden. For that reason, the CFD analysis must be limited to the specific section of the problem domain in the vicinity of the EM probes. The global hydraulic analysis, on the other hand, is performed using more affordable tools. For example, water levels at the domain boundaries can be modelled through steady or unsteady 1D analysis of the system, or they can be obtained through additional measurements. Furthermore, global analysis should be used for the definition of the sensor location, so the geometry of the sensors can be incorporated in the later problem domain.

2. *Local hydraulic analysis* – prior to the CFD computations, it is essential to include real data about the domain into the model. If necessary, additional survey should be performed, as the local irregularities of the geometry may have a significant impact on the velocity distribution at the probes locations. In the presented example, URANS turbulence modelling strategy was utilized and the governing equations were solved using the open-source toolbox, OpenFOAM. Currently, *k*-*ω* SST (Menter 1993) model is most commonly used URANS two-equation, eddy viscosity, turbulence model as it is was shown to produce good results in numerous examples (Wilcox, 2006).

Using the velocity field, obtained from the *Local hydraulic analysis*, SSC procedure can be performed. Weight vector $\vec{W}$, is replaced with the manufacturer's weight function, similarly as would be the case with full-pipe probes and the Shercliff function. As the available function w is a function of the perpendicular distance to the electrode (x_2), instead of the integration area A, integration line L is defined (Figure 1) and the problem is reduced to:

$$E_{mod} = \int_L w(x_2) \cdot v_1(x_2) dl \qquad (3)$$

Where E_{mod} is now the modelled output from the SSC procedure and v_1 is the streamwise velocity component. Finally, using the ratio of the average, cross sectional velocity V and the E_{mod}, SSC curve can be defined for each EM probe.

Case study

The hydropower system (HPS) of Trebinje is used for the preliminary result presentation. The HPS Trebinje is a complex system of reservoirs, hydropower plants (both conventional and pumped-storage type) and tunnels. Particular interest for this study is in one of the derivational tunnels connecting the two reservoirs, "Fatnicko polje" and "Bileca" (FP-BA tunnel). The tunnel is approximately 14 km long, varying in diameter from 6.4 up to 7.5 m and is used to transfer large quantities of water towards the downstream hydropower plant. Due to the water level variations in the upstream reservoir, flow rate in a tunnel changes during the year from dry conditions (0 m^3/s) to up to 160 m^3/s, while shifting from a free surface flow to a pressurized one. Reynolds number for the max flow rate can reach up to nearly 30 000 000. In order to enable flow metering in mixed flow conditions, four flat and two log-type EM sensors, with two water level gauges were installed on the rim of tunnel cross section placed 45 m from the tunnel entrance (Figure 4, left). Log-type EM sensors were specially designed for this application. They operate as discrete point sensors, but they are out of scope of this paper.

Figure 2. FP-BA tunnel entrance building

RESULTS AND DISCUSSIONS

Firstly, *Global hydraulic analysis* of the system was performed in order to determine boundary conditions for the smaller scale CFD simulations. At this stage, the whole tunnel including entrance building was analysed. Using "In house" 1D numerical models and the previously obtained data: water level, pressure and mean velocity boundary conditions were estimated for the second stage. Also position of the probes was defined at this stage. Due to the constraints posed by the managing company, in terms of the future construction work, the EM probes do not cover the whole flow rate range. Precisely, covered flow rate is between 20 – 160 m^3/s, while smaller flow rates will be measured using the level to flow relations. Secondly, a detailed survey was performed to ensure the accurate topological data for the domain definition of the CFD model. *Local hydraulic analysis* was restricted to first 100 m of the tunnel, measured from the entrance building. In order to avoid computational burden, resulting from the unsteady CFD computations which utilize the Volume of Fluid approach, Rigid Lid concept was used for the modelling of the free surface of the flow. Series of the simulations for the covered flow rate were performed and results were assessed for the SSC procedure.

Local hydraulic analysis has shown that the wall separating two entrance gates of the tunnel, affects the velocity distribution at the cross section where the probes were located. Parts of the cross section where max velocities occur are clearly shifted to the sides as it can be seen on the Figure 3 for the flow rate of $Q = 110\ m^3/s$. Additionally, local geometric features including the probes themselves, also introduce irregularities in the analysed cross section velocity distribution. These results clearly support the idea of the SSC procedure, showing that the true velocity fields can be strongly influenced by the site-specific conditions. Finally, simulations result of velocity fields for each of 4+2 EM probes were combined with their magnetic fields (Fig 4, right), to compute the SSC curves. Presented velocity profiles were sampled along the integration lines shown on Figure 3, for the flow rate of 130

m^3/s.

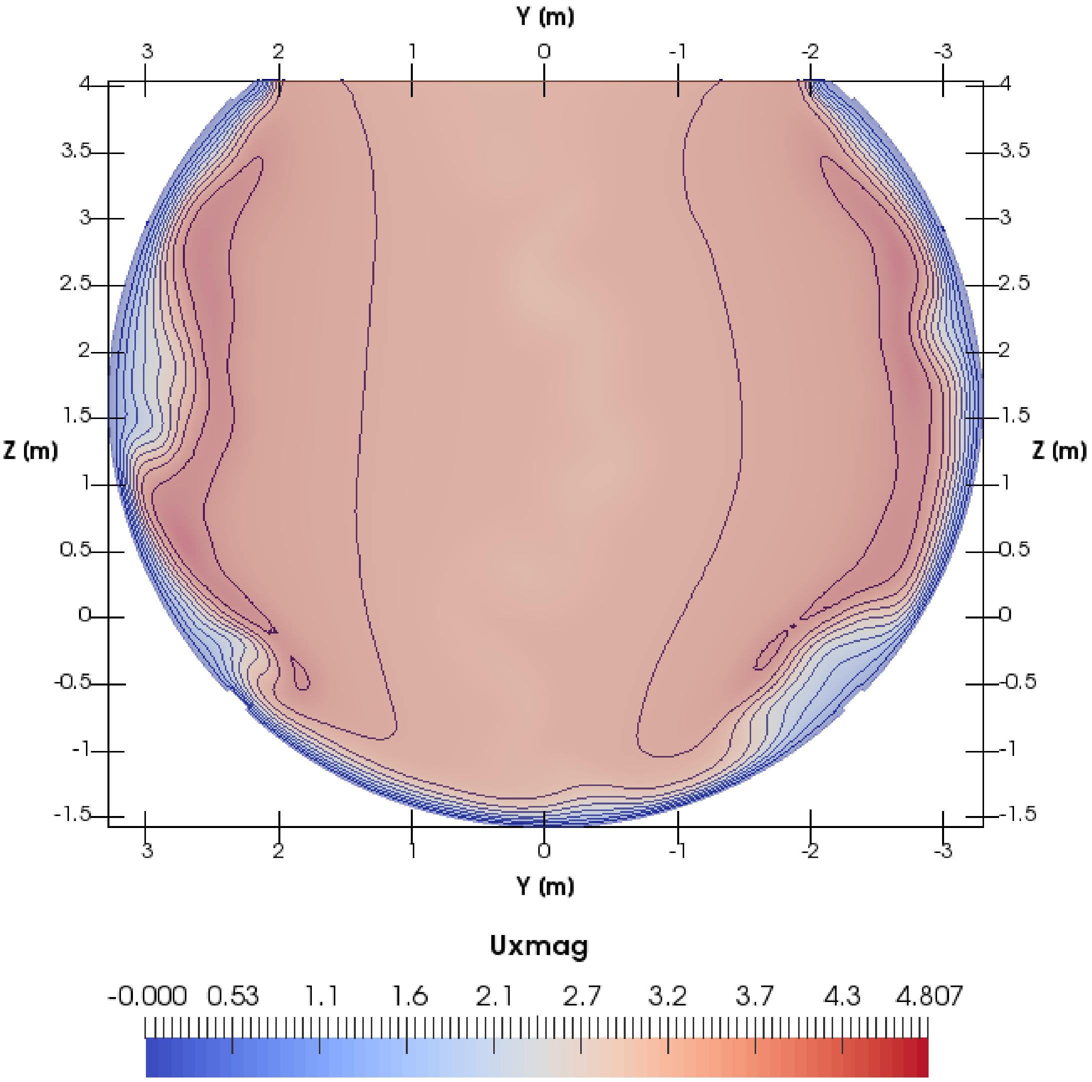

Figure 3. Streamwise velocity distribution for $Q = 110$ m^3/s at the measuring cross section of the FP-BA tunnel

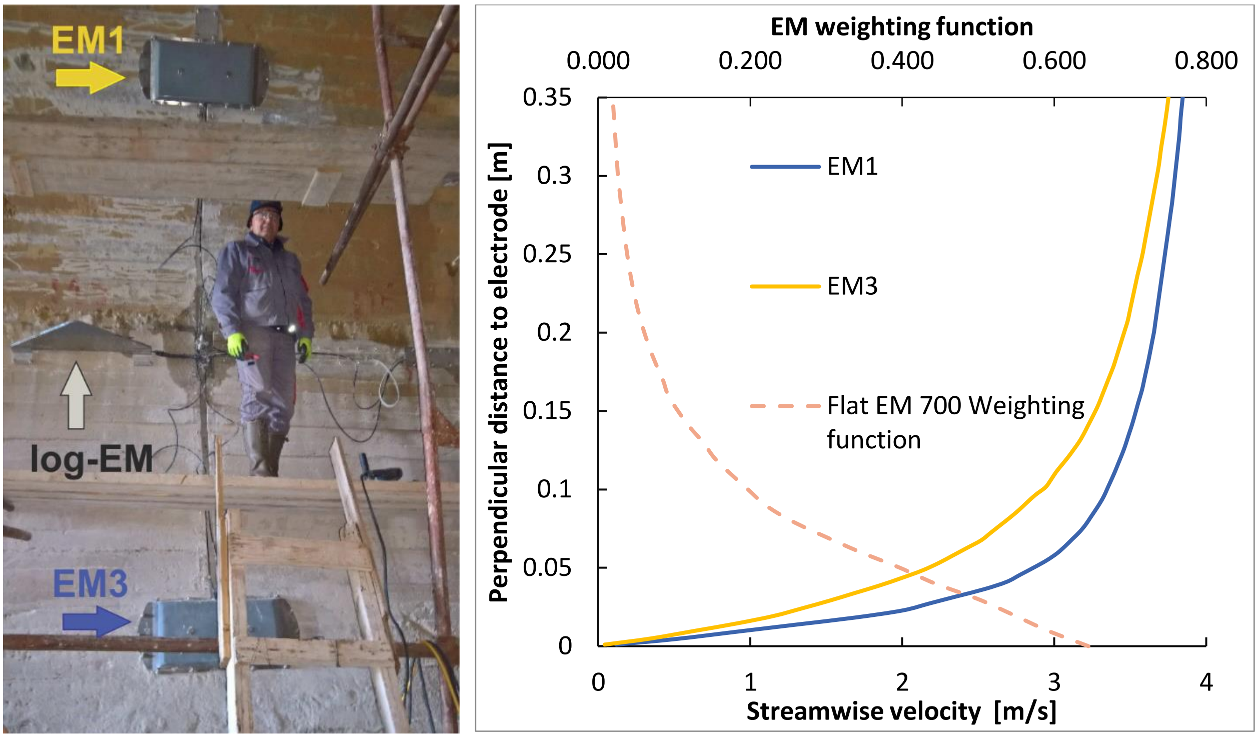

Figure 4. Example application: left) Two flat EM and one log-EM probe on the left side of the derivational tunnel; right) Velocity data obtained from CFD analysis combined with the probes 1D weighting function approximation

Using the equation 3, and the ratio of mean velocity and the modelled output signal, SSC curves for each of the probe were derived. An example curve for the EM3 probe is presented in Figure 5. By employing the SSC curve for each of the four EM probes placed inside the FP-BA tunnel, more profound estimate of the mean velocity can be obtained. Each of the probes will utilize its own SSC curve, thus producing an estimated mean velocity. By combining data from all of the probes, an average can be taken and used for the flow rate computation.

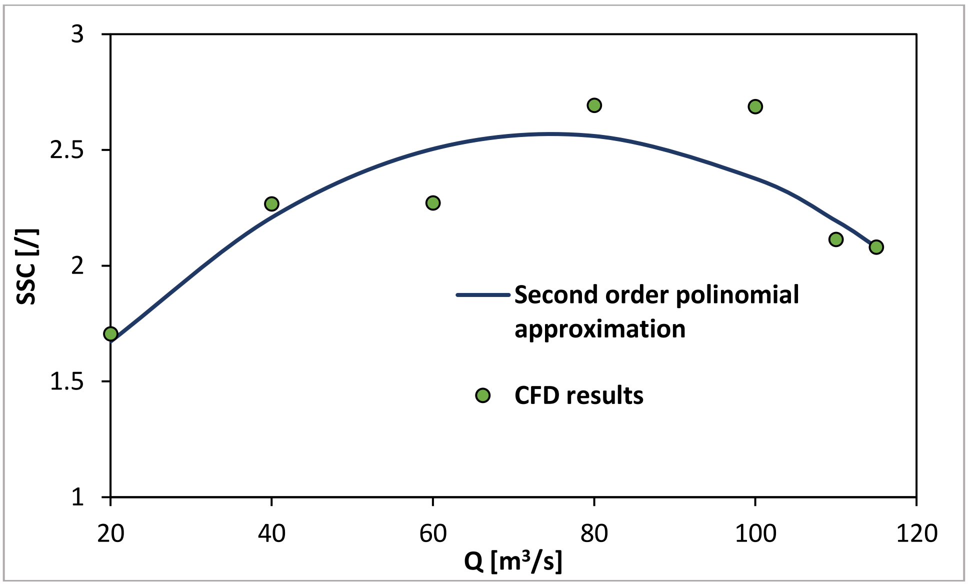

Figure 5. SSC curve for the flat EM3 probe in the FP-BA tunnel entrance building

It can be seen that the difference between the modelled and mean velocity is large in case of the sensor

EM3. This is most likely due to the limited reach of the flat EM probes magnetic field and influence of the local geometry on the velocity field. These results justify the need for the SSC procedure to be employed prior to the flat EM sensor usage. It is important to note, that the reduction of the flow rate bias and uncertainty cannot be directly computed from the presented data in this particular engineering example. Further experimental testing will be performed on the lab flume at the University of Belgrade which will lead to more quantitative results.

CONCLUSIONS

Flow measurements in mixed conditions can be successfully performed only be a limited number of techniques, like US and EM. In this paper, focus is placed on the flat EM sensors, semi-integrative measurement technique developed for the free surface flows. The main benefits of EM sensors are the possibilities to measure velocities from few millimetres per second up to 10 m/s and operate in both clean and dirty water. An attempt to improve the flat EM flow measurements in mixed flow conditions, through the usage of Site Specific Calibration procedure, is presented. SSC procedure is developed in order to compensate for the site-specific irregularities and allow for the measurements with lower bias and uncertainty. Hydraulic analysis of the flow conditions in the sensor vicinity, as a part of the SSC procedure, is performed in two stages: first the *Global hydraulic analysis* is used to obtain the boundary conditions for the later *Local hydraulic analysis*, in which CFD is used for the prediction of the velocity field distribution. Velocity field data is sampled along the probe’s integration lines and finally combined with the weighting function provided by the manufacturer. Engineering application example of the SSC procedure is presented through the case study of HPS Trebinje. Results show that the modelled output signal differs significantly from the mean velocity, proving that the additional SSC procedure is justified. Further lab testing is planned in order to quantify the reduced flow rate bias and uncertainty.

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REFERENCES

Al-Rabeh, R., Baker, R. (1986) On the Ability to Dry Calibrate an Electromagnetic Flowmeter. *Mechanical Engineering* 203.

Baker, R. (2002) An Introductory Guide to Flow Measurement. John Wiley & Sons.

Beljić, Ž., Ristić, Z., Pejić, D., Prodanović, D., Vujičić V. (2012) *New Construction of Conductive Fluids Velocity Measurement in Point - Using Measurement Over Interval Method, Feasibility Study.* 9th Symposium INDUSTRIAL ELECTRONICS, INDEL2012, Banja Luka, Republic of Srpska, Bosnia and Herzegovina, 142-149.

Bevir, M. (1970) The Theory of Induced Voltage Electromagnetic Flowmeters. *Journal of Fluid Mechanics*, 43(3), 577–590.

Chaudhry, M. H. *(2008). Open-channel flow*. New York, Springer.

Hager, W. (2010) Wastewater Hydraulics: Theory and Practice. Springer Science & Business Media.

Hemp, J., Versteeg, H. (1986) Prediction of Electromagnetic Flowmeter Characteristics. *J. Phys. D: Appl. Phys.*, 19, 1459-1476.

Hilgenstock, A., Ernst, R. (1996) Analysis of installation effects by means of computational fluid dynamics, *Flow Meas. Instrum.* 7, 161–171.

Holm, M., Stang, J., Delsing, J. (1995) Simulation of flow meter calibration factors for various installation effects, *Measurement* 15, 235–244.

Hu, L., Zou, J., Fu, X., Yang, H. Y., Ruan, X. D., Wang, C. Y. (2009) Divisionally analytical solutions of laplace's equations for dry calibration of electromagnetic velocity probes, *Applied Mathematical Modelling* 33 (7), 3130-3150.

Menter, F. R. (1993) Zonal Two Equation K-W Turbulence Models for Aerodynamic Flows. AIAA 93 · 2906

Prodanović D. (2007) *Selecting monitoring equipment*. Data Requirements for Integrated. Urban Water Management. Edited by: Tim Fletcher and Ana Deletić. Taylor & Francis, ISBN 978-0-415-45344-8. 91-102.

Simonović, S. (1990) An expert system for the selection of a suitable method for flow measurement in open channels. *Journal of Hydrology*, 112, 237-256.

Smyth, C. (1971) Derivation of weight functions for the circular and rectangular channel magnetic flowmeters, by means of Green's theorem and conformal mapping, *J. Phys. E: Sci. Inst.* 4(1), 29-34.

Steinbock, J., Weissenbrunner, A., Juling, M., Lederer, T., Thamsen, P. U. (2016) Uncertainty Evaluation for Velocity – Area Methods. *Flow Measurement and Instrumentation* 48, 51–56.

Watral, Z., Jakubowski, J., Michalski, A. (2015) Electromagnetic Flow Meters for Open Channels : Current State and Development Prospects. *Flow Measurement and Instrumentation,* 42 (4), 16–25.

Wilcox, D. C., (2006) Turbulence Modeling for CFD, 3rd edition, DCW Industries, Inc., La Canada CA.

Weissenbrunner, A., Fiebach, A., Schmelter, S., Bär, M., Thamsen, P. U., Lederer, T. (2016) Simulation-Based Determination of Systematic Errors of Flow Meters due to Uncertain in Flow Conditions. *Flow Measurement and Instrumentation,* 52, 25–39.