Using CFD and real-magnetic field of EM probes to improve the accuracy of flow measurements in mixed flow conditions

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Abstract: Flow measurement in mixed flow conditions is a challenging task, which can be performed only by few techniques like ultrasonic and electromagnetic. Usually despite the flowmeter's special design, the systematic uncertainty of flow rate remains high. In order to overcome this issue, additional site-specific calibration procedure for flat EM sensors is presented in this paper. Procedure includes both a hydraulic and magnetic field analysis. Concept of its application in the engineering practice example are presented.

Keywords: electromagnetic flowmeters; CFD; mixed flow

Introduction

An accurate sewer flow data is important for the management and modelling of the urban drainage systems. Different applications and environment conditions require different measuring techniques, which can significantly vary in terms of accuracy, cost and robustness (Prodanović, 2007). In most storm and wastewater network systems the flow is a mixture of free surface and pressurized flow (mixed flow conditions). In both cases the installed flowmeter needs to operate with specified accuracy.

For the mixed flow conditions, most often used flow measuring devices are the ultrasonic (US) transit-time or Doppler profiling devices and electromagnetic (EM) flowmeters. An attempt to address the accuracy 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, their main advantage is the possibility to measure velocities from few millimetres per second up to 10 m/s and possibility to work both in clean water (but not distilled!) and dirty water with lot of sediments. Watral *et al.* (2015) gave historical overview with numerous applications and design possibilities, clearly pointing out the adventages of EM method.

The major drawback of the flat EM flowmeter is limited, in terms of the size, magnetic field and hence the integration (or measuring) zone, which is often a fraction of the "wet" cross section. One solution is to increase the number of used EM sensors, but the velocity irregularities are still the issue. To improve the accuracy of single or multiple-sensor EM flow meter, the paper suggests the Site-Specific Calibration (SSC) procedure. The methodology is still under the development but the first results presented in this paper are promising.

Material and Methods

Flat Electromagnetic 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). Originating 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:

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

where A is the integration zone of the EM sensor (Figure 1), $\vec{B}$ is the magnetic induction and $\vec{j}$ 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 $\vec{W}$.

In the research presented here, flat type EM flowmeters designed by Svet Instrumenata for the free surface and mixed flow conditions, were used. 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 zone 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 condition for "ideal" flowmeter is not satisfied ($curl(\vec{B} \times \vec{j}) = 0$), velocity distribution will have significant effect on the flow rate data.

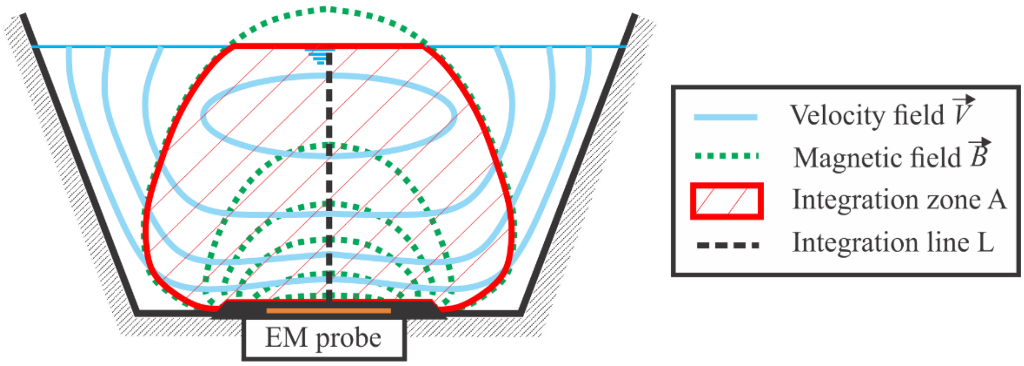

Figure 1. An example of velocity and one flat EM magnetic field distribution in an open channel

Analytical derivation of the appropriate weighting function (e.g. Hu et al. 2009) in this case is complicated, thus magnetic field should be measured to derive weighting functions for the particular flat EM probe (e.g. Al-Rabeh & Baker, 1986). Since the functions have not been formulated yet, 1D manufacturer's approximation of the 3D weighting function is used in presented example.

Site-Specific Calibration procedure

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 systematic uncertainty. Each EM sensor is calibrated in towing tank, where the velocity around the probe is constant, different from the local velocity pattern at the planned measurement position. Motivation for the SSC procedure is based on the premise that true velocity field is a necessity for flow rate measurements with low systematic error in mixed flow conditions. Using CFD, as an established tool, it is possible to predict the true velocity field and calculate the deviation from the field used during the calibration of EM sensor, for all mixed flow conditions, and for each used EM sensor. Here, URANS turbulence modelling strategy was utilized and the governing equations were solved using the open-source toolbox, OpenFOAM.

In the presented example, weight vector $\vec{W}$, is replaced with the 1D 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 zone A, integration line L is defined (Figure 1) and the problem is reduced to:

$$E_{mod} = \int_L w(x_2) \cdot v_1(x_2) dl \quad (2)$$

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 flow measuring device installed in derivational tunnel connecting the two reservoirs "Fatnicko polje" and "Bileca" (the hydropower system of Trebinje, Republic of Srpska) is used for the preliminary result presentation. The tunnel is 14 km long, varying in diameter from 6.4 up to 7.5 m. 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) up to 160 m^3/s, shifting from a free surface flow to a pressurized one. In order to enable flow rate measurements in the derivational tunnel, four flat and two log-type EM sensors (Fig 2, left), with two water level gauges were installed 45 m from the tunnel's entrance. Firstly, large scale hydraulic analysis of the system was performed in order to determine boundary conditions for the smaller scale CFD simulations. Secondly, a detailed survey was performed to ensure the accurate topological data for the domain definition of the CFD model. Finally, simulations results were assessed and used for the SSC procedure for each EM probe.

Results and Conclusions

In the presented results, manufacturer's 1D weighting function field approximation was used and combined with velocity profiles sampled along perpendicular integration lines (Fig 2, right). Using eq. (2) an example SSC curve for the EM3 probe was computed (Figure 3).

It can be seen that the difference between the modelled and mean velocity is large in case of the sensor EM3 (SSC > 1.5). Also, Fig. 2, right, gives clear picture of the velocity differences "seen" by EM1 and EM3. It is assumed that both the limited approach reach and local geometry influenced 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 systematic uncertainty of the flow rate 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. Also, used 1D manufacturer's weight function is planned to be replaced by the function derived from true measured 3D measured magnetic field.

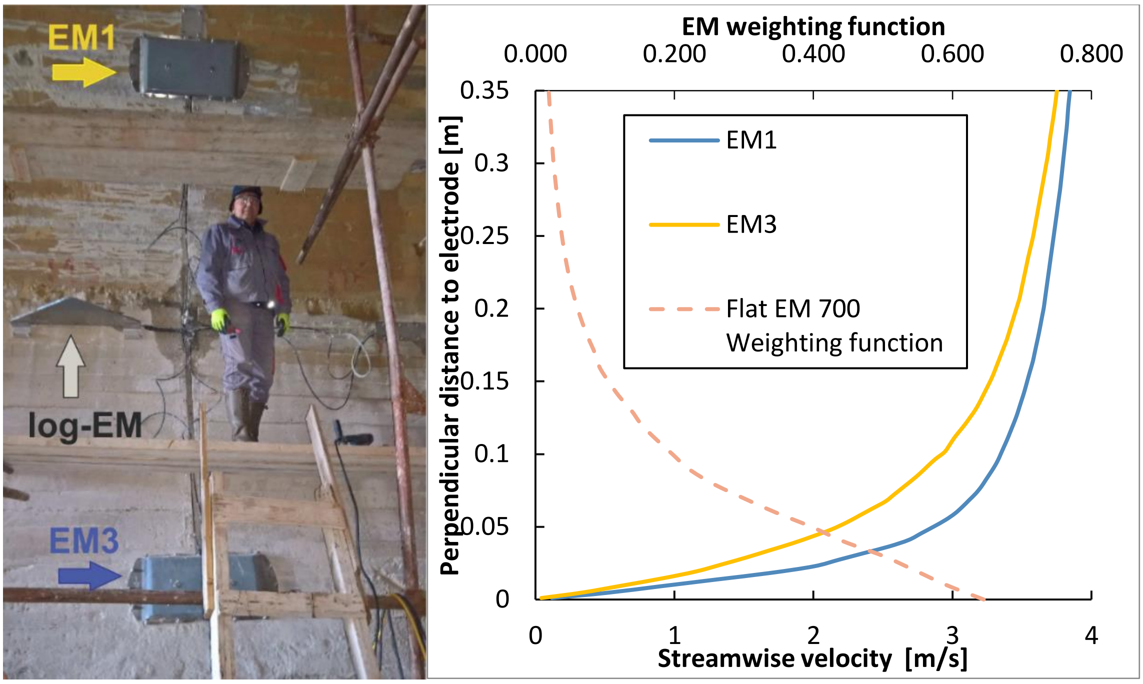

Figure 2. Example application: left) Two flat EM and one log-EM probe on the left side of the derivational tunnel; right) Velocity data obtained from CFD analysis combined with the probes 1D weighting function approximation

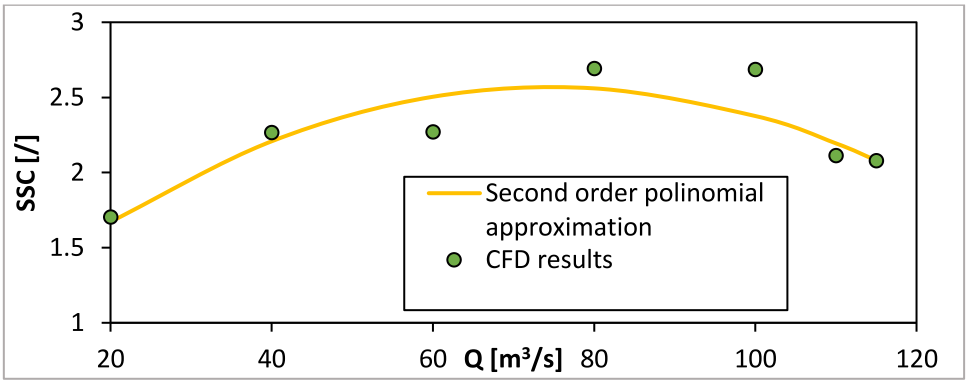

Figure 3. SSC curve for the flat EM3 probe in the FP-BA tunnel entrance building

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