EPJ Web of Conferences 45, 01027 (2013)
DOI: 10.1051/epjconf/20134501027

The Application of EIS and PIV Methods to the Measurement of Aerated Flow

M. Fejfarová[1,a]

[1]Institute of Water Structure, Faculty of Civil Engineering, Brno University of Technology,
602 00 Brno, Veveří 331/95, 541 147 191,

Abstract. The paper describes measurements in the aerated water medium using modern methods PIV (Particle Image Velocimetry) and EIS (Electrical Impedance Spectrometry), which are applied in the Laboratory of Water Management Research (LVV) of the Department of Water Structures (UVST) at the Faculty of Civil Engineering (FAST) of Brno University of Technology (VUT). Measurements of the water medium were carried out for three different aeration intensities at special experimental workplaces. The experiment was focused on the capability of the methods to monitor the air content in the water.

1 Introduction

Basically, the mixture of a fluid (water) and air can form by releasing dissolved air from the fluid (when pressure, temperature or velocity changes) or by sucking air (e.g. leaks in piping systems, spontaneous aeration of flow through water surface, etc.). The investigation of the given two-fluid flow is very difficult, but desirable due to its often negative impacts. For instance, it is known that this undesirable phenomenon largely occurs on chutes of hydro-engineering structures.

On the territory of the Czech Republic (CR), as a consequence of floods, design parameters of hydro-engineering structures (referred to hereinafter as HES) have been totally re-evaluated in recent years in relation to the capacity of hydraulic facilities and the overall safety of HES. A large number of HES operated in the CR have an emergency spillway followed by a stepped chute. This concerns about 16 significant HES equipped with stepped chutes (Broža et al., 2009), which were designed especially at the beginning of the 20th century (e.g. HES Bystricka, HES Luhacovice, HES Frystak, HES Vranov, etc.). Since the mid-20th century, stepped chutes have no longer been designed; only since 1985, interest in them has again strongly increased with the advent of new technologies of construction of gravity dams.

The aeration of water flow in chutes is also favourable for a strong reduction in the risk of the formation of cavitation phenomena and, last but not least, the flow becomes intensively oxygenated, which consequently has a positive effect on the quality of water.

It is obvious that knowledge of the intensity of flow aeration on the given constructions is desirable in relation to their safe operation and also in ensuring the quality of water. The flow of the mixture of air and water, however, is a very complicated problem also from the metrological point of view and the determination of the intensity of water aeration is very difficult. This paper describes possibilities of the application of modern measurement methods EIS and PIV to the given issue.

2 Measurement methods

Within the solution of the project FRVS 1773/2012, modern measurement methods - electrical impedance spectrometry (EIS) (Pařílková, 2008) and Particle Image Velocimetry (PIV), which are used in the Laboratory of Water Management Research of the Department of Water Structures at the Faculty of Civil Engineering of Brno University of Technology (LVV UVST FAST VUT) - are applied to the measurement of aerated flow. These methods are verified for the capability of both recording the aeration of the water medium and monitoring the amount of air in the water medium.

2.1 EIS method

Electrical impedance is a basic property characterizing the AC electrical circuits. It is always greater than or equal to the real electrical resistance R in the circuit. Unreal resistance, i.e. inductance - reactance of inductor XL and capacitance - reactance of capacitor XC, creates variable and therefore frequency - dependent part of the impedance. Electrical impedance is evidently made up of

[a] fejfarova.m@fce.vutbr.cz

real and imaginary parts. Resistance R creates real part and is frequency-independent. Imaginary part is created by reactance X, which is frequency-dependent. Electrical impedance can be expressed by Ohm's equation for AC circuits, i.e. by the ratio of electric voltage phasor U and electric current phasor I

$$Z = \frac{U}{I}\,. \tag{1}$$

Impedance values are, as well as resistance R values in case of DC circuits, expressed in ohms (Ω).

Frequency characteristic of impedance Z can be expressed as a function of complex variable in the algebraic (component) form

$$Z = R + jX\,. \tag{2}$$

Absolute value, i.e. the modulus of the vector of the impedance |Z| is expressed by the formula

$$|Z| = \sqrt{R^2 + X^2} \tag{3}$$

and the phase shift is expressed by the relation

$$\varphi = \mathrm{arctg}\left(\frac{X}{R}\right). \tag{4}$$

2.2 PIV method

Particle Image Velocimetry is a measurement technique enabling information about the instantaneous distribution of velocities in a two-dimensional field in a flowing fluid to be obtained. Velocities are determined from the measured distance which entrained particles will cover in the medium, and from the time which particles will need to do this distance. Particles are either part of the flowing medium (less often), or this flowing medium is seeded with them (in most cases). The system displays and analyses particles which are taken by a planar light section in the flowing medium. A suitably placed light plane is formed by a high-performance laser and a system of optical elements. In order that the stroboscopic effect can occur, which enables the "freezing" of particle motion, the excitation of the light plane is pulsed. The time between pulses is the one that is used for velocity calculation.

The recording system, most often a CCD camera, which is placed with its optical axis perpendicular to the light plane, will display every particle as a pale grain on a dark background. Two images of entrained particles are taken very quickly one after another. Two images taken one after another at the time interval Δt are designated as a double image or a double picture and in further processing they form the basic data set for evaluating flow velocity.

The images are divided into oblong areas which are called investigated areas. For each of these investigated areas, the picture of particles taken by the first image and the picture taken by the second image co-form a substitute vector. It is calculated using cross-correlation analysis (Zubík, 2001).

3 Observed quantities

A Z-meter III device was used in laboratory experiments. It is designed so that the measured real and imaginary components of electrical impedance are depicted in real time on its LCD display.

It is possible from the given components to determine the electrical characteristics of the monitored medium (1), or its physical properties.

In general, the resistance R is defined as the ratio of the electric voltage U to the electric current I that flows between two electrodes (Maryniak, 2003) which are in contact with the measured medium (figure 1).

$$R = \frac{U}{I}\,. \tag{5}$$

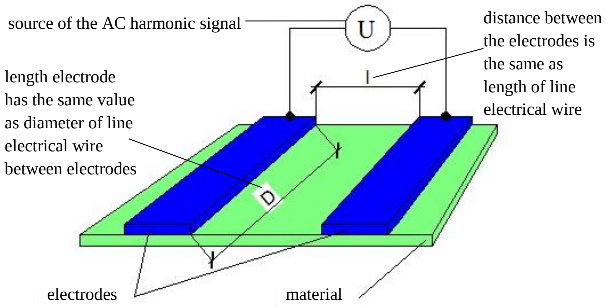


Fig. 1. Basic diagram for measuring resistance (Maryniak, 2003)

The electrical conductance G is the value inverse to the electrical resistance R and is measured in siemens (S) (the basic unit)

$$R = \frac{1}{G}\,. \tag{6}$$

If it is necessary to characterise the property of a studied medium - its capability of conducting an electric current, it is possible to do so by means of the material constant of the so-called electrical resistivity ρ. Electrical resistivity, the unit of which is the ohm-metre (Ω•m) in the SI system, can be expressed by the relation

$$\rho = \frac{R \cdot A}{l} \quad \text{or} \quad \sigma = \frac{1}{\rho} = \frac{G \cdot l}{A}, \tag{7}$$

where A is the cross-sectional area and l is the length of the conductor.

The inverse of resistivity is called electrical conductivity σ. Conductivity is most often measured between the opposite electrodes of a sensor, placed in a medium, and specifies, e.g., the content of dissolved salts in water. The general theory shows, and experiments prove it, that the lower the resistivity, the higher the electrical conductivity of a studied substance, and vice versa (Heaney, 1999), (IES 61 340-5-1, 1998), (wikipedia.org).

In the case of measurement of the aeration of the water medium using the PIV method, velocities of created air bubbles will be monitored and the content of air in the monitored medium will be expressed using software.

4 Aerated medium

A special experimental site was established (Fig. 2), with a vessel of 0.60 m × 0.35 m × 0.05 m in dimensions, made of organic glass 0.01 m thick. In the bottom, the vessel was fitted with an aeration device in which it was possible to set three levels of aeration. On the side walls of the vessel, stainless steel paired point electrodes were installed, spaced *0.03 m* apart, forming sensors of the EIS probe. The electrodes were installed so that their area corresponded with the surface of the internal wall of the vessel. Therefore, it can be stated that non-invasive measurement of the components of electrical impedance in a total of 16 levels was carried out relative to the measured medium represented by aerated water.

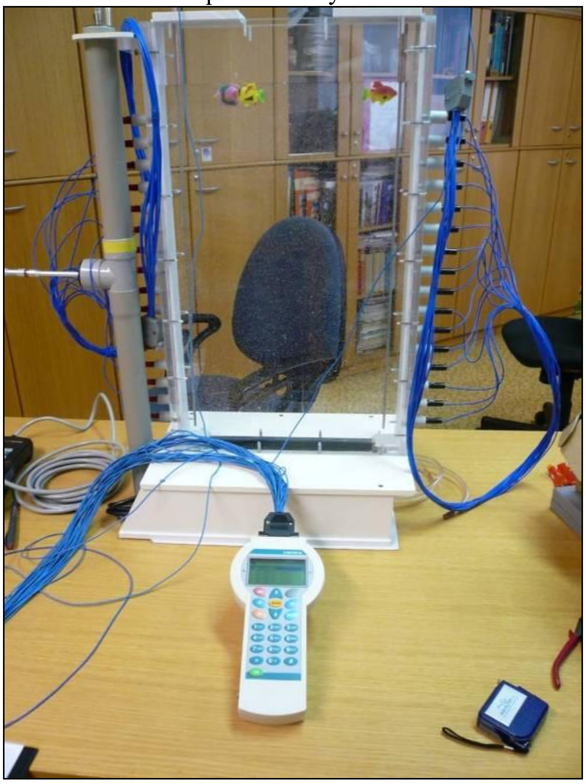


Fig. 2. Experimental site - aerated water: a) Experimental site with a Z-meter III

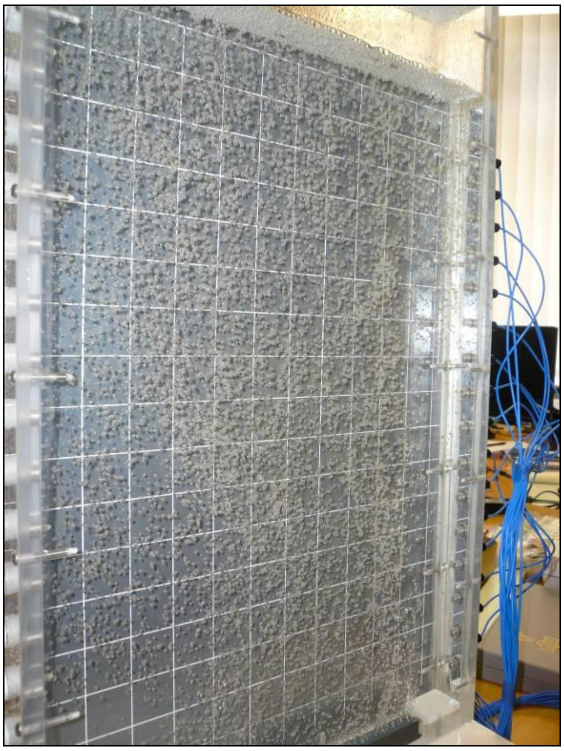


Fig. 2. Experimental site - aerated water: b) Aerated water medium

The first, initial, measurement was made as soon as the vessel had been filled with water to the level $h = 0.50\ m$. Subsequently, the water in the vessel was aerated over a period of 10 minutes, using an aquarium air pump of a low capacity, and after the end of aeration, the measurement of electrical impedance was made again. The measurement of electrical impedance further took place after aeration by an air pump of a higher capacity and also after the simultaneous connection of both the air pumps (time intervals are given in the legend of Figures. 4, 5 and 6). During the experiment, the constant air temperature $t = 19.5\ °C$ and the relative air humidity $\upsilon = 48\%$ were maintained in the room, in which the experimental workplace was sited.

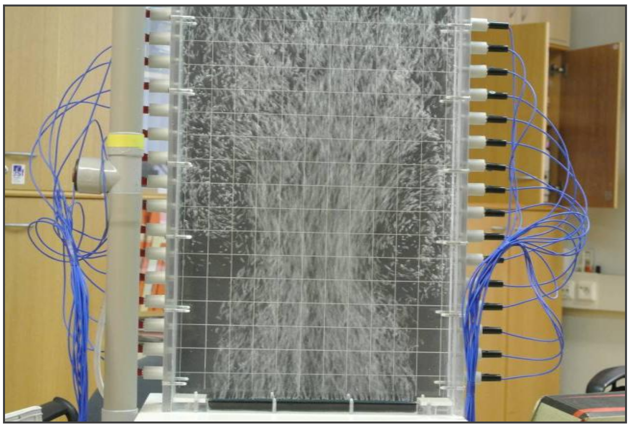


Fig. 3. View of air distribution in the water medium

5 Selected results

The aerated medium and its changes at individual depths and time intervals were evaluated using resistivity ρ (7) and the modulus of electrical impedance (3). During the experiment, the time stability of the output signal was also monitored in conjunction with the repeatability of measurement and the reproducibility of its results. On each EIS probe, 10 values of the real and imaginary components of electrical impedance were measured at a certain time interval, of which a value characterising each level was determined by the arithmetic average. figure 4 shows the evaluation of changes in electrical impedance and resistivity for each level of mounted EIS probes; it is evident that the values of electrical impedance/resistivity grow with the increasing intensity of aeration of the medium. The evaluated graphs (figures. 5 and 6) show that as soon as the water becomes aerated, the moduli of electrical impedance and resistivity of the medium display high values, i.e. the medium is a poorer electric conductor. With the decreasing content of air at the individual levels, the electrical conductivity of the monitored medium increases because the properties of water again appear dominant. Measurement was also carried out using rod probes made of stainless steel (Fig. 2a), the diameter of the rods was *0.004 m* and their length *0.700 m*. The results are given in Fig. 7, in which the graphic relationship of electrical impedance and resistivity with time is plotted. Again, it is evident that with the increasing content of water in the water medium, the values of electrical impedance/resistivity rise, i.e. the capability of the medium to conduct the electric current decreases. Specifically, the change in electrical impedance is evident there when repeating measurements, i.e. how the medium changes during tenths of a second.

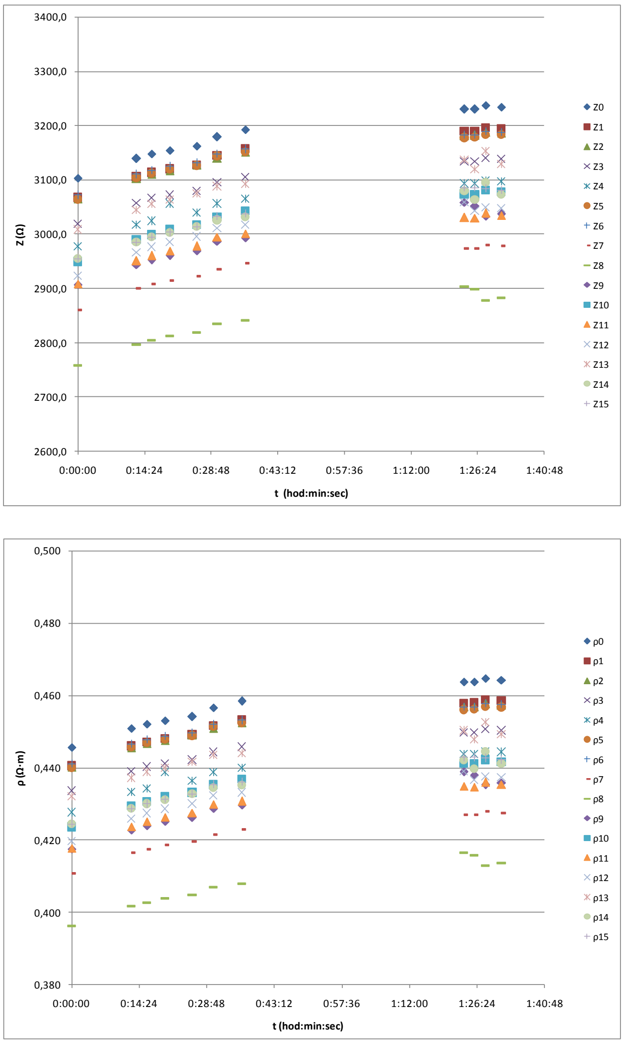
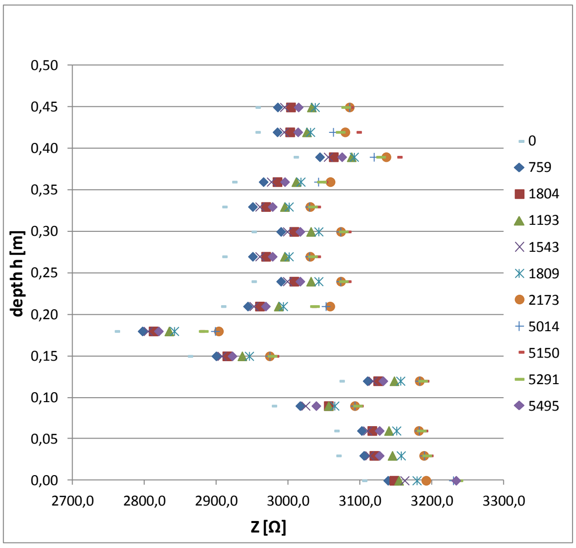


Fig. 4. Pattern of electrical impedance and resistivity at the individual levels and with time



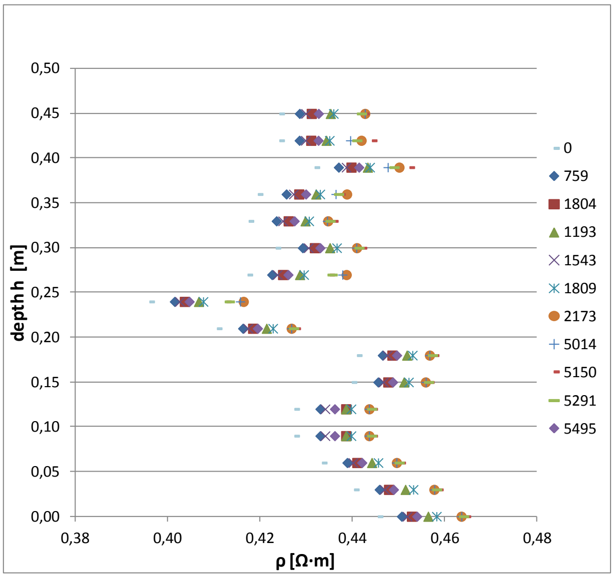


Fig. 5. Pattern of electrical impedance and resistivity as the depth of the aerated medium increases

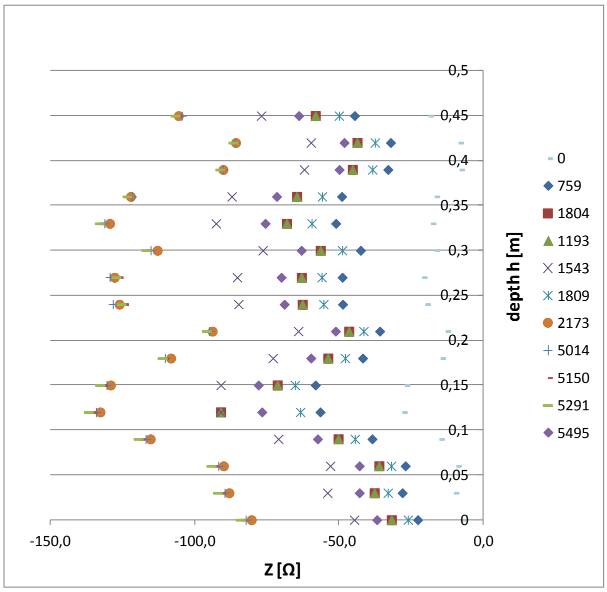


Fig. 6. Pattern of reactance (the imaginary component of electrical impedance) as the depth of aerated flow increases

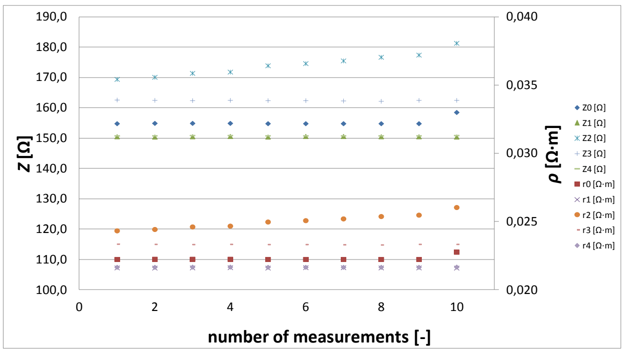


Fig. 7. Pattern of electrical impedance and resistivity with time on a rod probe

6 Conclusion

Laboratory experiments have been carried out using a Z-meter III device when verifying the suitability of the EIS method for the measurement of the aerated water medium. The experiments performed have shown both the possibility and suitability of using the EIS method for laboratory measurements configured in the given way, including the Z-meter III apparatus. Advantages of the verified apparatus are the possibility of a wide range of construction and the configuration of measuring sensors.

Within the solution of the project FRVS 1773/2012, the PIV method is also verified, which is used in the LVV (UVST, FAST, VUT). Pilot measurements are now carried out in the LVV (UVST, FAST, VUT); it is necessary to make other measurements for data processing.

7 Acknowledgements

The presented results have been obtained under the financial support of the Ministry of Education, Youth and Sports of the Czech Republic when undertaking the international project E!4981 (a part of the Czech investigator, OE 10002) in an EUREKA programme and in the FRVS (Universities Development Fund) project 1773/2012.

Thanks are due to the project E!4981 “The Automated System for Analysis of Selected Characteristics and Processes in a Porous Environment Using the EIS Method”, and to the FRVS project “Verification of Modern Methods for Measurement of the Density Fields of Aerated Flows”.

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