

# COMBINED MEASUREMENT OF FLOW VELOCITY AND FILLING WITHIN FULLY ELECTROMAGNETIC FLOWMETER FOR OPEN CHANNELS

*Jacek Jakubowski*<sup>1</sup>, *Andrzej Michalski*<sup>1,2</sup>

<sup>1</sup>Electronics Faculty, Military University of Technology, Warsaw, Poland, jjakubowski@wel.wat.edu.pl

<sup>2</sup>Electrical Faculty, Warsaw University of Technology, Warsaw, Poland, anmi@iem.pw.edu.pl

**Abstract** – The paper presents practical aspects of the application of the least squares method as an algorithm for both flow velocity and filling measurements in the case of electromagnetic flowmeters for open channels. The method consists in fitting the flow signal with two waveforms that carry information about the measuring parameters. The basic drawbacks of the method caused by the necessity to perform numerical differentiation as well as by the differences between the signal components and the signal itself are presented together with the efforts to reduce them.

**Keywords:** flow measurement in open channels, LS estimation

## 1. INTRODUCTION

Measurements of flow for open channels play an important role in many monitoring applications just like those for storm water management, wastewater collection systems, billing purposes etc. There are also many scientific efforts taken to model the effect of land development and climate change on aquatic ecosystems as well as for preventing, detecting, evaluating and reducing water pollution. The flowmeters are then used for discharge measurements and to create velocity profiles in rivers and streams. Because of that there is a great need for an accurate and consistent sensors enabled to measure the flow. The flow  $Q$  is defined as the amount of liquid moving through a channel in a period of time. There are lots of methods to find that. Some of them are based on the measurement of filling behind hydraulic structures just like weirs or flumes and then using a theoretical formula of the form  $Q=f(h)$  where  $h$  is the filling. The height of filling can be measured in many ways including pressure sensors [1] or ultrasound transducers. With the use of other methods the flow can be calculated by simple multiplication of two quantities: the cross-sectional area of the channel and the velocity  $v$ . The first can be easily found using the dimensions of the channel and height of filling that can be measured with one of the above techniques. The velocity is usually measured with the use of Doppler effect based on ultrasound [2] or radar technologies [3] or with the use of turbine devices. The above methods have some limitations connected with the necessity of temperature compensation, problems caused by disturbed reflections of ultrasounds from foam and various debris collected by rainwater, inconveniences due to the

moving parts of mechanical devices, especially in environments with vegetation. In some cases costs should also be taken into account. The electromagnetic method is an alternative solution for velocity measurement and is also met in aforementioned applications. The method uses the Faraday's law of electromagnetic induction. According to the law a conductor, moving through a magnetic field, produces a voltage. So such sensors generate artificial magnetic field and an electric voltage  $u_1$  is created in any conductive liquid that moves relative to the field. The voltage is measured by a pair of electrodes and its level is the higher the faster the liquid moves. It is also proportional to the strength of the magnetic induction. The method is very convenient as it does not involve any moving part and provides the measurement of the average velocity. However, to find the flow  $Q$  there is still the necessity to measure the height of filling. The filling is usually obtained with one of the above methods with all of the problems involved. The paper presents our research that carries on the early works by Bonfig [4] and is going to show some practical aspects of the new signal processing used for simultaneous measurement of velocity and filling within the method [5].

## 2. THEORETICAL BACKGROUND

The approach proposed by Bonfig for the height of filling measurement is based on an additional voltage  $u_2$  that may be created in the liquid. The voltage is a direct result of the transformer effect that appears when there is a frame consisted of the electrodes and the surface of the liquid, that is penetrated by time-variant magnetic field  $B(t)$ . The level of the voltage is directly proportional to the rate of change of the field and thus to the derivative of the current  $i'(t)$  driving the coil responsible for the magnetic field at the same time. It is also proportional to the area of the frame, which is perpendicular to the field. The area changes with the height of filling so the voltage can be used as a measure of the latter. One or both of the electrodes should be slightly declined in order to have the possibility of non-zero areas. The general idea of the measurement is depicted in Fig. 1 for two different fillings of the channel.

Regardless of the possibility to measure the height of filling, the magnetic induction is always time-variant with the frequency that usually does not exceed the values of several hertz. There are some reasons for that including the influence of induced eddy currents, reactance of the coil and

various kinds of environmental noises [6]. Taking into account all phenomena connected with the generation of the two voltages together with the conditions depicted in Fig. 1, the resulting signal measured by electrodes should be expressed in the case of no noises and no disturbances as a weighted sum of two components:

$$\begin{aligned} u(t) &= u_1(t) + u_2(t) = a \cdot v \cdot i(t) + b \cdot h \cdot i'(t) = \\ &= w(1) \cdot i(t) + w(2) \cdot i'(t), \end{aligned} \quad (1)$$

where  $i(t)$  is the current driving the coil and parameters  $a$  and  $b$  are constant for a given device. The amplitudes of the components –  $w(1)$  and  $w(2)$  do carry information about the required flow parameters. According to the equation one can use such an excitation described by the current  $i(t)$ , that each of the amplitudes can be easily measured. With the subsequent conditions:  $i'(t) = 0$  and  $i'(t) = \text{const}$ , the value for  $w(1)$  and  $w(2)$  can be found respectively by simple measurements [4]. That means that we should not use voltage but rather current excitations to obtain the above conditions.

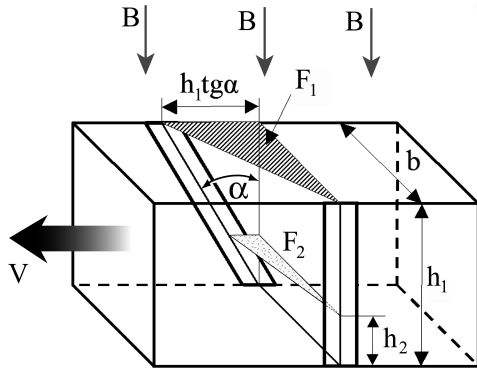


Fig. 1. The idea for the height of filling measurement within the electromagnetic method. The resulting  $u_2(t)$  voltage is proportional to  $b \cdot \text{tg} \alpha \cdot h \cdot B \cdot i'(t)$ .

In contradiction to that our approach is based on the assumption that the waveform of the current is theoretically of any shape and the flow parameters are provided by signal processing algorithms. The first step is to acquire the current driving the coil and then to find its derivative. The second step is the application of the measuring algorithm. The typical method, that can be used, is the least squares method. For discrete time signals the method minimizes two dimensional cost function of the form:

$$\begin{aligned} T_{LS}[w(1), w(2)] &= \\ &= \sum_{n=1}^N \{u(n) - [w(1) \cdot i(n) + w(2) \cdot i'(n)]\}^2. \end{aligned} \quad (2)$$

The solution is theoretically provided by the standard estimator:

$$\mathbf{w} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{u}, \quad (3)$$

where the two-column matrix  $\mathbf{A}$  is constituted in such a way that its first column contains the samples of  $i(t)$  and the

second contains the samples of  $i'(t)$ . The method is very convenient and can be easily extended to estimate the flow parameters in the conditions of low frequency disturbances that dominate in real measurement. The disturbances are caused by the differences between the electrochemical potentials of the fluid and the material the electrodes are made of and can considerably degrade the results of flow measurements. With the LS method the only thing is to support the base with polynomials approximating the disturbances as stated in [5].

### 3. PRACTICAL CONSTRAINTS

Trying to obtain high accuracy of flow measurement with the above method, one can easily note some practical aspects that must certainly influence the results. The first problem that arises is to find the derivative of the current. The procedure for that depends on the waveform of excitation. In the cases, when the signal as a function of time is not exactly known or it is difficult to find, the methods of numerical differentiation should be adopted. Standard methods are based on the Taylor expansion:

$$i(t+h) \cong i(t) + i'(t) \cdot h + \frac{1}{2!} i''(t) \cdot h^2 + \frac{1}{3!} i'''(t) \cdot h^3 \dots \quad (4)$$

from which the derivative can be found as a function of two, three or more signal samples, e.g.:

$$i'(t) = \frac{i(t+h) - i(t)}{h} \quad (5)$$

Such methods are computationally attractive but are ill-posed and generate non-stable solutions in noisy cases as depicted in Fig. 2.

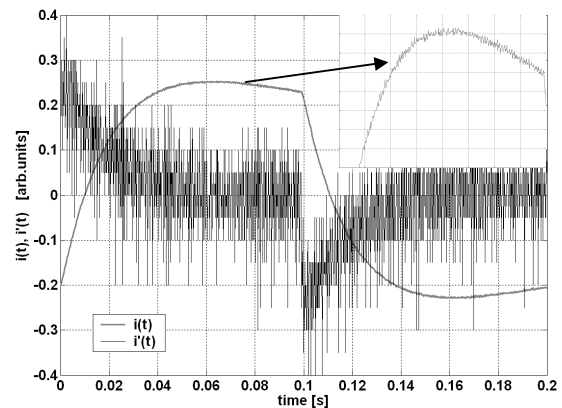


Fig. 2. Results of numerical differentiation according to eq. (5) performed on an exemplary real signal exciting the coil of the electromagnetic flowmeter. The zoomed area shows the noisy waveform of the current  $i(t)$  responsible for not acceptable noise in the derivative.

Similar effects can be observed when another method – differentiation in the frequency domain is applied. The differentiation is then based on the inverse Fourier transform of the spectrum multiplied by  $j\omega$

$$i'(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} j\omega \left( \int_{-\infty}^{+\infty} i(t) e^{-j\omega t} dt \right) e^{j\omega t} d\omega \quad (6)$$

In this case the reason for the non-stable differentiation is the magnification of high frequencies occupied by noise in the waveform  $i(t)$ . The problem to find the derivative is much more simplified when the function describing the processed signal is known or can be easily estimated. An exemplary case is the mono-harmonic waveform of known or calculated amplitude and phase:

$$i(t) = a \sin(\omega t + \varphi) \quad (7)$$

as the derivative can be obtained by simple multiplication and the  $\pi/2$  phase shift:

$$i'(t) = \omega a \cos(\omega t + \varphi). \quad (8)$$

Besides, even with a proper waveform of the derivative estimated, there may also exist the lack of perfect time coincidence between the  $i(t)$  and  $i'(t)$  elements of the base  $\mathbf{A}$  and the voltage signal measured by the electrodes. There are several reasons for that. Some of them depend on the instrumentation. A good example is the kind of sampling. With the use of popular scanning method adopted by most ADC converters, two identical analog signals become slightly different when sampled alternatively and then taken to calculations. The comparison of such resulting discrete-time waveforms is depicted in Fig. 3.

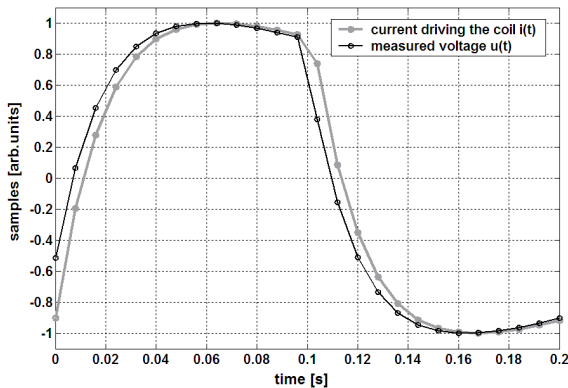


Fig. 3. The effect of scanning sampling of identical signals.

Even if we used ADC converters with simultaneous sampling, we could not avoid the discrepancies between propagation times in the signal conditioning circuits for  $i(t)$  and  $u(t)$ . The signal paths for them are different because they are different quantities. Besides, there are differences between signals that depend on the method – the expected inertial behavior of the environment. All that brings about the necessity to modify the cost function by inclusion a delay  $\tau$  representing the overall lack of coincidence between signals:

$$T_{LSM} [w(1), w(2), \tau] = \sum_{n=1}^N \{u(n) - [w(1) \cdot i(n - \tau) + w(2) \cdot i'(n - \tau)]\}^2. \quad (9)$$

As the result, the cost function becomes a function of three variables and the solution (3) is no longer valid.

#### 4. EXPERIMENTS

With respect to the above considerations there is a need for tests to point out the best conditions for numerical differentiation and for tests to verify how much the possible delay between processed signals is significant in real measurements of flow in open channels. In order to do that we have developed a laboratory model of the electromagnetic flowmeter as depicted in Fig. 4.

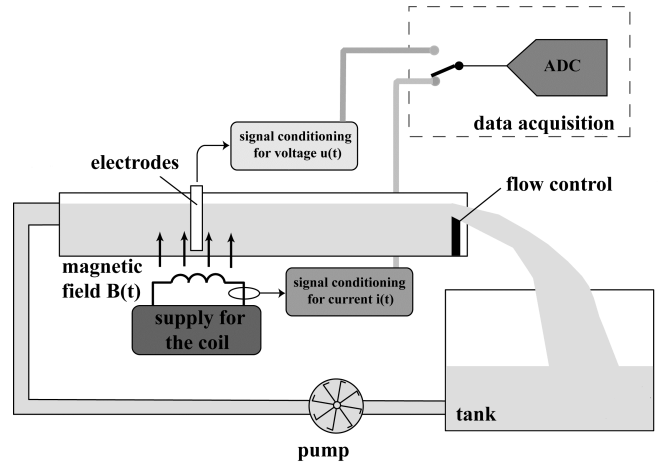


Fig. 4. Schematic diagram of the experimental setup.

The artificial channel of 3m in length was supplied with water in a closed circulation system. We could control the flow parameters with the use of an electric pump and a set of little sluices. In the conditions of the constant volumetric flow, the higher was the level of filling the lower was the velocity and vice-versa. A simple computer measuring system with the scanning sampling DAQ was used to excite the coils with rectangular or arbitrary voltage of frequency 5Hz and to collect the waveforms of the resulting current  $i(t)$  and the induced voltage  $u(t)$ . The electrodes were arranged according to the conditions depicted in Fig. 1.

An obvious way to obtain reliable estimate of differentiation is to improve the quality of the processed signal by one of the de-noising techniques. Discrete wavelet transform can be successfully used because of its excellent properties in reducing high-frequency noise. However, care must be taken as some of the highest frequency signal information is usually also lost during the de-noising process. To make an assessment of the numerical differentiation a quantitative comparison should be made between the accurate derivative  $i'(t)$  and the derivative  $i'_{est}(t)$  estimated upon the noisy signal. The surrogate of the first can be available with the use of polynomials approximating the real current driving the coil. To get the second, an additive white noise can be applied. Thanks to that a simple mean squared criterion:

$$err = \sqrt{\frac{\sum_n [i'(n) - i'_{est}(n)]^2}{\sum_n [i'_{est}(n)]^2}} \quad (10)$$

points out the quality of the numerical differentiation. The results of such assessment in the case of current corresponding to rectangular voltage excitation are presented in Table 1. Wavelet technique based on Daubechies 10 was used to suppress white noise in the case of typical SNR=40dB.

Table 1. The quality of numerical differentiations expressed in the terms of (10) for rectangular voltage excitation.

processed current signal	differentiation according to (5)	differentiation according to (6)
raw signal	1.794	2.292
de-noised signal	0.111	0.157

The waveforms obtained with the wavelet processing are depicted in Fig. 5. One should note the considerable reduction of noise as compared to the corresponding results presented in Fig. 2.

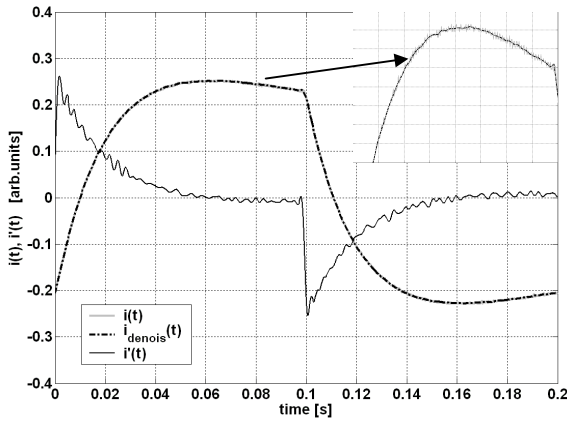


Fig. 5. Results of numerical differentiation after preprocessing the real current signal with the use of wavelet de-noising. The zoomed area shows the original (gray line) and de-noised current signal (black dotted line).

It should be also mentioned that with the mono-harmonic excitation, when the Fourier transform was used to find the amplitude and phase of the noisy current, the value of  $err$  for the differentiation according to (8) was only  $6 \cdot 10^{-4}$ . Unfortunately, having done a simple analysis of the equation (9) one can easily conclude that mono-harmonic excitation (7) should not be applied at all. A basis  $\mathbf{A}$  that is composed of the sine and cosine functions is a complete basis for any signal of the form  $i(t) = asin(\omega t + \varphi)$  and any delay will be treated as a change in the parameters. As the result the voltage rectangular excitation was used in further experiments.

To verify the overall effect of the expected delay there should be the access to the non-disturbed versions of the waveforms. We got them using averaging over single periods acquired during long term data acquisition in steady

flow conditions. Additionally, we used special spongy stabilizers to hold the laminar flow.

Results of the verification for an exemplary flow  $Q=0.75dm^3/s$  and a height of filling  $h=9cm$  are depicted in Fig. 6. The acquired waveforms that can be treated as noise free thanks to the above efforts, are compared with waveforms obtained as a result of synthesis after LS estimation of  $w(1)$  and  $w(2)$ . One should notice the waveforms of error as well as the difference between estimated parameters in the case of pure LS estimation according to (3) and in the case of LS estimation supported by polynomial approximation. The results prove that the influence of the examined delay on estimation is significant – the polynomial intended for nothing but the approximation of disturbances started to work causing estimation errors.

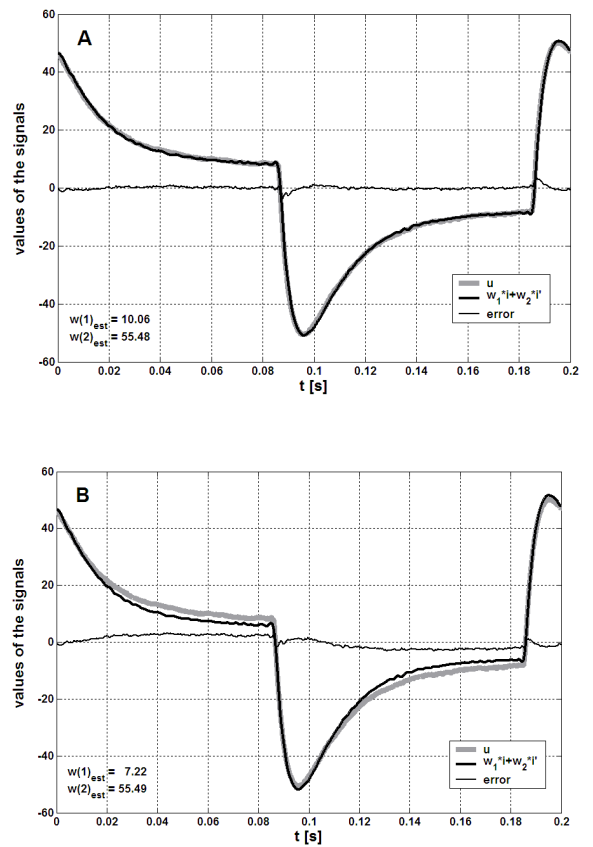


Fig. 6. Comparison of real flow signals (the gray lines) with signals synthesized after the use of the classic LS method (the black thick lines): A – the pure LS case, B – LS with Chebyshev degree 6 polynomial support.

Formal solution with respect to the delay can be obviously achieved by means of optimization process for the cost function (9). However, we have tested a simpler method that converts the function of three variables into the function of one variable  $\tau$  by replacing  $w(1)$  and  $w(2)$  with their counterparts described by the typical LS solution. The effects can be observed in Fig. 7. The resulting cost function reaches its minimum for the delay at which the estimation seems to be done properly – the synthesized waveforms cover the acquired ones and the parameters representing

flow are almost the same. However, the modified cost function has some local minima and to find the global minimum we had to penetrate the whole  $\tau$  domain. Besides, the analyzed signals are discrete time signals and to find the exact delay precisely, high oversampling or interpolation must be used. The results presented in the paper were obtained with the sampling frequency of 2.56kHz and interpolation that increased the number of samples 10 times.

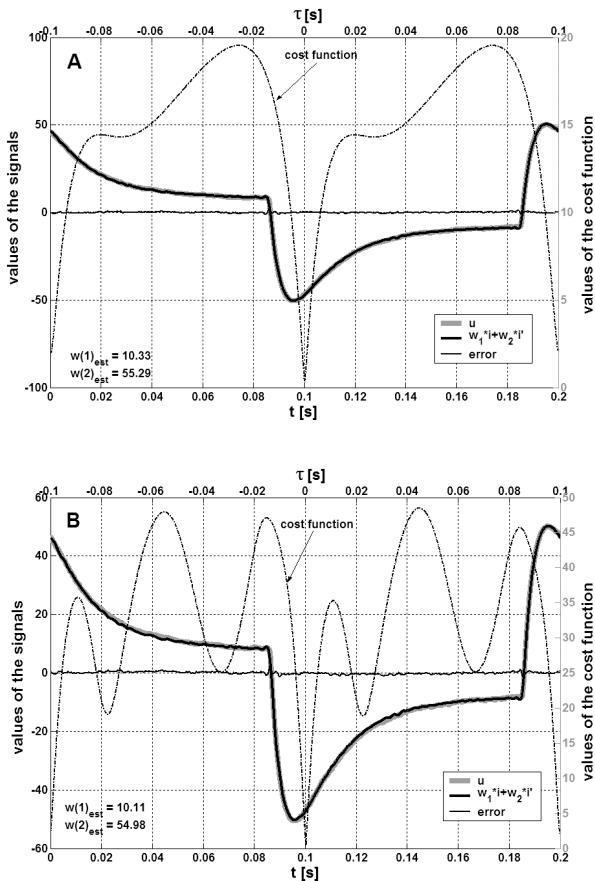


Fig. 5. The effects of taking into account the delay between acquired waveforms. There are separate axes for the waveforms (left and bottom) and for the cost function (top and right).

## 5. CONCLUSIONS

The novelty of the presented material lies in the examination of the least squares method as the measuring algorithm of the electromagnetic flowmeter for open channel where the height of filling varies. In particular the method is based on the processing of a noisy current signal

to obtain differentiation and requires some regularization to obtain a reliable estimate. Discrete wavelet transform can be used as an effective technique to suppress the noise. Moreover, the examinations confirmed the existence of a delay between acquired signals and their influence on the flow parameters. In this context mono-harmonic excitation appeared to be useless as the sine function with its derivative constitute a complete base for any harmonic signal, including signal with a delay caused by electronics or the method. In contrast to that, examinations with the current signal corresponding to the rectangular voltage excitation show that taking into account the delay enables the least squares approach to be effective for simultaneous estimation of flow parameters within one, fully electromagnetic method. Application of polynomial approximation of existing low frequency disturbances becomes effective. Thanks to that there is no need to support typical electromagnetic velocity measurement with additional methods to find the height of filling and eventually – the volumetric flow.

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