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Development of the substitutive circuit for the electromagnetic flowmeter

***Abstract**. The paper presents the results of measurements of the electrical properties of the sensor in the electromagnetic flowmeter. The RC network and its parameters were identified for it. The influence of them on the LS flow velocity estimation in the pulse mode was also examined by simulation. The results showed that using oscillatory excitation gives erroneous results of estimation.*

***Streszczenie.** W artykule przedstawiono wyniki pomiarów własności elektrycznych czujnika w przepływomierzu elektromagnetycznym. Wyznaczono dla niego układ zastępczy RC oraz dokonano identyfikacji parametrów. Przebadano również metodą symulacyjną ich wpływ na estymację LS prędkości przepływu w trybie impulsowym. Wyniki dowodzą, że wykorzystanie pobudzania oscylacyjnego jest źródłem błędów estymacji (**Budowa schematu zastępczego przetwornika elektromagnetycznego**).*

Keywords: electromagnetic flowmeter, synthesis of passive networks, identification of the transfer function, LS estimation.
Słowa kluczowe: przepływomierz elektromagnetyczny, synteza układów pasywnych, identyfikacja transmitancji, estymacja LS.

Introduction

In the field of flow measurements for open channels with the use electromagnetic transducers there is a great need to reduce their energy consumption, especially in the case of distributed monitoring systems where the problem with continuous access to the grid is obvious [1],[2],[3]. The possibility to lower the consumption is given by a simple electronic circuit transferring the energy from the electrochemical battery to the coil in a pulse way. The battery can be then charged by renewable sources of energy. The idea of such a solution is depicted in Figure 1A.

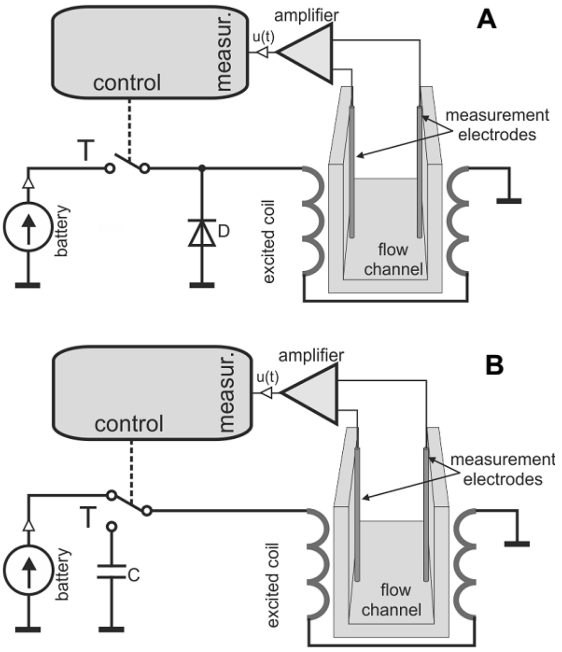

Fig.1. The circuits of pulse excitation of the electromagnetic flowmeter when the energy accumulated in the coil is discharged with the short circuit based on a commutating diode (A) and through an additional capacitor (B)

More detailed description of the circuit as well as the discussion of the proposed algorithm of signal processing are presented in [4]. In that paper the least squares estimation of the flow is demonstrated to be possible with the use of that part of the output signal of the transducer that corresponds to the phase when energy is transferred to the coil. In general, the magnetic field of the coil brings about generation of two voltages (1):

$$u(t) = u_1(t) + u_2(t) = w_1 \cdot i(t) + w_2 \cdot \frac{\mathrm{d}i(t)}{\mathrm{d}t} . \tag{1}$$

The first voltage is caused by the Farady's effect (water as a moving conductor) and is of the shape of the current. The second one is connected with the so called transformer effect and it is proportional to the derivative of the current [5]. Thus the coefficients w_1 and w_2 in (1) are modulated by the flow velocity and the transformer effect. The current waveform corresponding to excitation circuit depicted in Fig. 1A as well as the resulting output voltage signal formed with respect to (1) are presented in Figure 2.

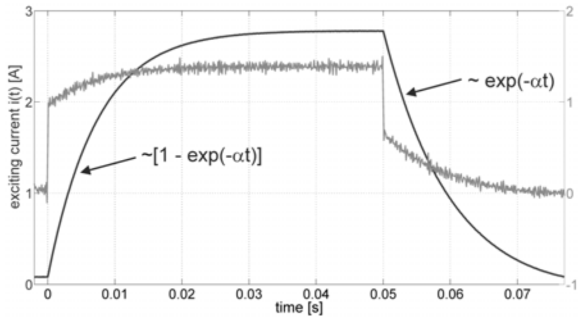

Fig.2. Real waveforms of current and output voltage corresponding to Figure 1A when the battery is turned on during 50ms (the inserted formulas describe the shape of the current when the switch T is on and off)

When the switch T is on, the energy is transferred to the coil and the current waveform is described by the equation:

$$i(t) = \frac{U_B}{R}[1 - \exp(-\alpha t)] , \tag{2}$$

where U_B is the unit step voltage of the battery, R is the overall resistance of the coil circuit and α is its time constant. Processing of the above current according to the equation (1) gives the possibility to find the flow velocity represented by the coefficient w_1 because the resulting voltage takes the form:

$$u(t) = \frac{U_B}{R} \cdot \left[w_1 + \left(w_1 w_2 - w_1\right)\exp\left(-\alpha t\right)\right] . \tag{3}$$

Using the $\exp(-\alpha t)$ function and the LS fitting one can estimate the flow velocity. However, similar processing cannot be performed on the falling edge of the current when the switch T is off because the current changes exponentially (Fig. 2). As the derivative of the exponent is still the exponent, the distinction between the two voltages in (1) is not possible. Hence, in order to take the advantage of the energy accumulated in the magnetic field to perform additional calculations reducing the measurement uncertainty, one should modify the current waveform in such a way that it would differ from the exponent. A potential solution is to use an additional capacitor as depicted in Figure 1B. The capacitor ensures oscillatory discharge of the coil energy. Frequency of the oscillations depends on its capacity. Higher frequencies are useful because the electrochemical noises existing in the method are of "1/f" type. On the other hand, care must be taken as the transformer effect increases with frequency. In practice, the frequency of oscillations shouldn't exceed tens of hertz. However, initial tests of the approach shows that the estimates of the flow velocity obtained in the phase when energy is discharged through the capacitor are systematically lower than estimates obtained in the phase when the energy is transferred to the coil [6]. The difference increases with the frequency of oscillations.

In order to explain the fact and to work out a reliable signal processing method for the pulse mode of excitation, the identification of the transmittance responsible for the modification of the signal generated by the physical phenomena (1) is required. The transmittance is determined by the internal impedance of the pair of electrodes Z_w as well as the input impedance Z_A of the amplifier connected to them. As the electrodes immersed in water form a voltage source, the transmittance can be modeled by the circuit depicted in Figure 3.

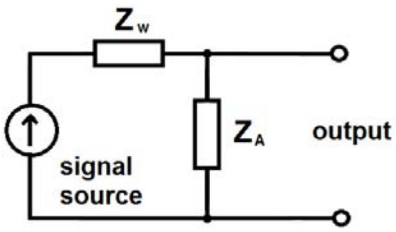

Fig.3. Transmittance modifying the output of the signal source

Thus the main scope of the research presented in the paper was twofold. Firstly – to find out the internal impedance of the transducer in the conditions of real and changing flow parameters, i.e. flow velocity and filling as well as to work out the transmittance of the signal processing path depicted in Figure 3. And secondly – to investigate the process of LS estimation with respect to the transmittance.

Finding the frequency response of the electrodes

The frequency response is the basis for the synthesis of any passive network. In the case of the electromagnetic transducer, the response is described by the whole family of impedances of the electrodes immersed in water for different velocities and fillings in the specified range of frequencies. The impedances were measured with the use of Rohde&Schwarz RLC bridge type HM8018. During the measurements there was a simple contact of the bridge probes with the electrodes. The results of exemplary measurements obtained in the conditions of non-moving water are presented in the Table 1. Similar results were obtained for the cases of moving water.

Table 1. The results of impedance measurement in the conditions of non-moving water for the specified frequencies and heights of filling h (magnitudes and phases of Z_w)

h [cm]	f [kHz]	0,02	0,05	0,1	0,2	0,5	1
2,5	$\lvert Z_w \rvert$ [Ω]	1204	1142	1122	1112	1107	1106
	θ [deg]	-12,9	-6,6	-3,9	-2,2	-1,1	-0,6
3,0	$\lvert Z_w \rvert$ [Ω]	1001	952	936	928	923	923
	θ [deg]	-13,0	-6,7	-3,9	-2,2	-1,1	-0,6
3,7	$\lvert Z_w \rvert$ [Ω]	803	764	752	747	744	744
	θ [deg]	-13,1	-6,6	-3,9	-2,2	-1,0	-0,6
4,6	$\lvert Z_w \rvert$ [Ω]	640	608	598	593	590	590
	θ [deg]	-13,1	-6,6	-3,8	-2,2	-1,0	-0,6

Synthesis of the network for the electrodes

The first step to formulate the structure of the electric circuit is to find the Laplace form of its impedance $Z_w(s)$. The coefficients of the numerator and denominator of the impedance $Z_w(s)$ can be obtained with the use of the least squares approach to find the minimum of the cost function. The function describes the difference between the frequency response coming from the real experiment and the frequency response imposed by the impedance $Z_w(s)$. Appropriate numerical procedures can be found in many numerical environments, e.g. in Matlab. Table 2 presents the impedances found in that way. They correspond to the measurements summarized in Table 1.

Table 2. The impedances $Z_w(s)$ of electrodes immersed in water in the terms of the Laplace transform for different heights of filling and non-moving water

h [cm]	$Z_w(s)$
2.5	$\dfrac{1105s^2+4.033\cdot 10^5 s+1.204\cdot 10^7}{s^2+318.6s+1972}$
3.0	$\dfrac{922.5s^2+2.996\cdot 10^5 s+7.4\cdot 10^6}{s^2+278.9s+324.7}$
3.7	$\dfrac{742.9s^2+2.219\cdot 10^5 s+5.164\cdot 10^6}{s^2+254.5s+2.008\cdot 10^5}$
4.6	$\dfrac{589.6s^2+2.152\cdot 10^5 s+6.472\cdot 10^6}{s^2+319.5s+1862}$

It was assumed that both the degrees of the numerator and denominator polynomials of the impedances $Z_w(s)$ equal 2, i.e. they are impedances of the type described by (4):

$$Z_w(s)=\frac{as^2+bs+c}{s^2+ds+e}\,, \tag{4}$$

where the coefficients a, b, c, d and e change with the flow parameter. Increasing the degrees didn't contribute to significant improvement in the fit between the derived impedances $Z_w(s)$ and experimental frequency responses. The quality of the fit is presented in Figure 4, where the magnitudes of the impedances collected in Table 2 are compared with the results of measurements performed by the RLC bridge and shown in Table 1. The magnitudes were obtained by substituting s in equation (4) with $j\omega$. The scheme of the substitutive circuit representing the internal passive network of the electrodes was derived with the Cauer method on the basis of the Laplace impedance $Z_w(s)$. The scheme is presented in Figure 5. The parameters of the derived network strongly depend on the flow conditions. Exemplary values of the parameters, corresponding to the cases of experimental data presented in the Tables 1 and 2, are given in the Table 3.

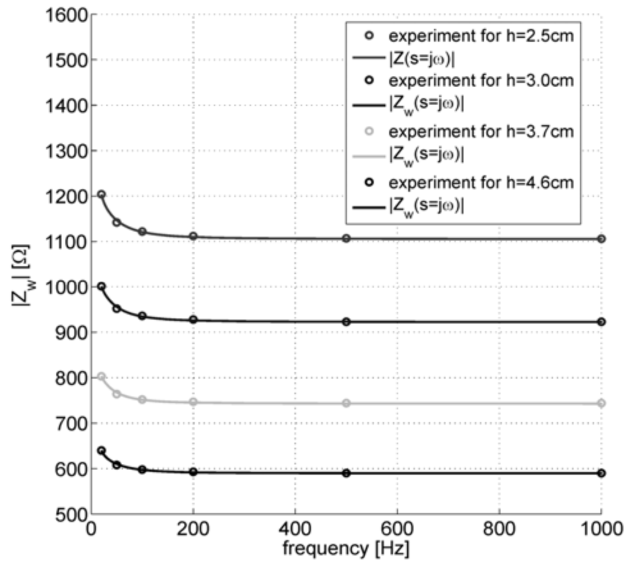

Fig.4. Comparison of the experimental data with the values offered by the synthesis method (on the Tables 1 and 2)

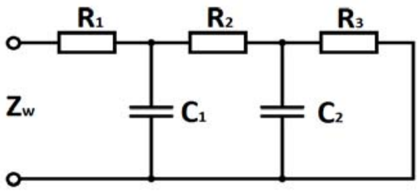

Fig.5. Substitute circuit of the two electrodes immersed in water

Table 3. The parameters of the substitutive circuit depicted in Figure 4 with respect to the height of filling for the case of non-moving water

h [cm]	2.5	3.0	3.7	4.6
R1 [Ω]	$1.1\cdot10^{3}$	$9.2\cdot10^{2}$	$7.4\cdot10^{2}$	$5.9\cdot10^{2}$
R2 [Ω]	$4.1\cdot10^{2}$	$3.8\cdot10^{2}$	$3.4\cdot10^{2}$	$2.3\cdot10^{2}$
R3 [Ω]	$4.6\cdot10^{3}$	$2.1\cdot10^{4}$	$2.6\cdot10^{11}$	$2.7\cdot10^{3}$
C1[F]	$1.9\cdot10^{-5}$	$2.4\cdot10^{-5}$	$3.0\cdot10^{-5}$	$3.7\cdot10^{-5}$
C2[F]	$1.4\cdot10^{-5}$	$1.6\cdot10^{-5}$	$1.9\cdot10^{-5}$	$2.5\cdot10^{-5}$

Identification of the transfer function

There is an impedance Z_A in the Figure 3 representing instrumentation amplifier connected to the electrodes. The role of the amplifier is at least twofold. Firstly, it is required to increase the level of the signal from micro volts, as depicted in Figure 2, to volts in order to fit it to the range of the ADC converter. Secondly, it should attenuate the electromagnetic interferences arising when the magnetic field is switched on. Because of the latter, the input of the amplifier should be equipped with a capacitor forming the RFI filter. Assuming that its capacity is C_A and the input resistance of the instrumentation amplifier is high enough, the transmittance depicted in Figure 3 can be described by the following equation using the same symbols as in (4):

$$(5)\ H(s)=\frac{s^2+d\cdot s+e}{C_A\cdot a\cdot s^3+(C_A\cdot b+1)\cdot s^2+(C_A\cdot c+d)\cdot s+e}.$$

The above transmittance formally describes a low pass filter with frequency response dependent on the flow parameters. Exemplary responses of the filters corresponding to two impedances from Table 2, first for the height of filling 4.6 cm and the second 2.5 cm are depicted in Figure 6.

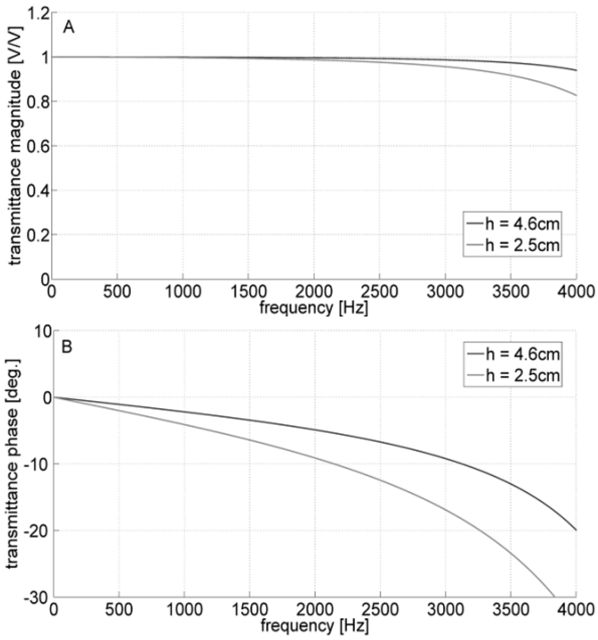

Fig.6. Magnitude (A) and phase (B) of the transmittance depicted in Figure 3, corresponding to 2 heights of filling

It can be seen that the magnitudes of the transmittances are almost constant and equal to one in the range of several hundreds of hertz. The range can be treated as useful from the practical point of view because of the acceptable level of the transformer effect existing when the energy in the coil is discharged in the oscillatory manner. Such magnitude doesn't modify the amplitudes of the signals generated according to the Faraday's law. In contradiction to that the phase response indicates that there must be a certain shift in the time domain. The shift brings about obvious discrepancies between the generated signal and the signal acquired for calculations.

Examination of the LS estimation

The signal modification introduced by the transmittance (5) causes a certain problem with the usage of the fundamental least squares algorithm for the needs of estimation. The phase of the transmittance depends on local and unknown flow parameters. Using the LS algorithm one has to assume that the voltage, generated by the physical phenomena according to (1), is the same as the voltage acquired for calculations. However, simulations of the processing involved by the filter described with the transmittance (5) show something quite different. Figure 7 presents the comparison of the two voltages and one can easily observe a certain shift between them. The waveforms were obtained in the case of non-moving water, the height of filling was 4.6 cm and the frequency of oscillations was 150 Hz. The observed shift makes the results returned by the LS method in the process of minimization of the cost function inappropriate. Numerical experiments show that the level of errors depends on the kind of the energy transfer. During the phase when the energy is applied to the coil, there is exponential growth of the current. When the energy is discharged through the additional capacitor, the current changes in the oscillatory way. The results of simulations arranged to estimate the flow velocity $\hat{w}_1$ on the basis of the signal modified by the transmittance (5) are presented in Tables 4 and 5 for both of the phases.

During the simulations, the amplitudes of the components carrying the information about the flow velocity and about the transformer effect prior the above modification, i.e. w_1 and w_2 in eq. (1), were assumed to take integer values from 0 to 4. Values in the subsequent rows should be equal to the value w_1 presented in the 1st column.The frequency of oscillations was set to 150 Hz. The value of the capacity corresponding to the input of the real amplifier was 10 nF.

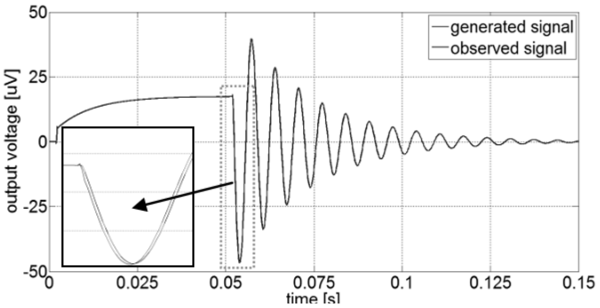

Fig.7. Illustration of the influence of the transmittance (5) on the signal observed at the output of the transducer. The phase difference is visible in the zoomed area on the left

Table 4. The results of the flow velocity estimation when the energy is absorbed by the coil for various combinations of w_1 and w_2.

w_2 / w_1	0	1	2	3	4
0	0.00	$-0.07\cdot10^{-3}$	$-0.14\cdot10^{-3}$	$-0.22\cdot10^{-3}$	$-0.29\cdot10^{-3}$
1	0.99	0.99	0.99	0.99	0.99
2	1.99	1.99	1.99	1.99	1.99
3	2.99	2.99	2.99	2.99	2.99
4	3.99	3.99	3.99	3.99	3.99

As it can be easily seen (Table 5), the case when the energy is discharged through the capacitor is more sensitive to the phase shift observed in Fig. 6B. It is the case when the dumped oscillatory waveform is used for calculations in the LS method. The method finds the coefficients of the linear combination of dumped sine and cosine basis functions in order to minimize the cost function. Thanks to the nature of the basis, the perfect approximation of the input signal is possible, regardless of its phase shift introduced by the identified transmittance. Unfortunately, the coefficients of the linear combination don't respond to the real flow parameter.

Table 5. The results of the flow velocity estimation when the energy is transferred from the coil for various combinations of w_1 and w_2.

w_2 / w_1	0	1	2	3	4
0	0.00	-0.03	-0.05	-0.08	-0.11
1	0.99	0.97	0.95	0.92	0.89
2	1.99	1.97	1.95	1.92	1.89
3	2.99	2.97	2.95	2.92	2.89
4	3.99	3.97	3.95	3.92	3.89

The identified transmittance of the signal processing path let also use simulations to explain the decrease of the flow velocity estimate with the frequency of the oscillations. The decrease is observed in real experiments [5]. The comparison of the estimated values of flow velocities $\hat{w}_1$ calculated in the range from 30 Hz to 130 Hz for both phases of the energy transfer is presented in the Table 6 for the case w_1 = 3. The results show that the transmittance imposed by the internal network also disturbs the estimation and the error indeed increases with the frequency of oscillations.

Table 6. Estimation of the flow velocity $\hat{w}_1$ when the oscillation frequency f increases ("phase 1" corresponds to the exponential waveform of the current, whereas "phase 2" means using the oscillations). The real value of w1 was 3

f [Hz]	30	50	70	90	110	130
phase 1	2.99	2.99	2.99	2.99	2.99	2.99
phase 2	2.97	2.95	2.90	2.85	2.78	2.69

Conclusion

The paper presents the results of measurements of the electrical properties of the sensor in the electromagnetic flowmeter and discusses the influence of them on the flow velocity estimation in the pulse mode. The RC network and its parameters representing two electrodes immersed in water were identified. The parameters strongly depend on the actual flow conditions. Moreover, it turned out that the network together with the input of the measuring amplifier form a filter-like circuit that can modify the signal induced on the electrodes according to the Faraday's law. The results of simulations showed that there is an inevitable error in the estimation of the flow parameters, especially when the current responsible for the magnetic field is of the oscillatory origin. The reason for that is the phase response of the above filter. Presented material explains the results published earlier and as such gives the possibility to develop further modifications of the excitation circuit.

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