THE 'BLIND' DYNAMIC ERROR CORRECTION METHOD – SIMULATION STUDY FOR THE FIRST-AND SECOND-ORDER MEASUREMENT CHANNEL

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Abstract: The results of the simulation study on the differential algorithm of the correction of the dynamic error by the „blind" method are presented in the paper. The study was carried out for measurement channels modelled as first- and second-order systems. The results confirmed the suitability of computer simulation for determining the condition for the practical applicability of the discussed correction method.

Keywords: Simulation, Measurement Dynamical Error Correction

1. Introduction

In cases when where the model of dynamics of measurement channel is known and stationary the dynamical correction problem is solved both theoretically and practically.
The „blind" dynamic error correction may by practically applied when the dynamic properties of sensors or transducers slowly changes over time or under various environmental factors. The method may also be applied when laboratory determination of the coefficients of an equation describing the model of analogue dynamics of a part of the measurement channel is impossible. Possible applications of the dynamic correction method can be as follows:

- Measurement of time-variable temperatures when the coefficient of heat exchange between the medium under study and the temperature sensor depends on the physical properties of the medium;
- Measurement of time-variable high voltage when the dynamic properties of the divider depend on undetermined parasitic capacitances;
- Measurement of highly-variable electrical signals with the use of a low-band measurement amplifier (e.g., measurement of non-sinusoidal currents with a shunt).

The idea behind this method has been known for a long time, but the possibility to use fast real time digital computation allowed for it's practical use.

1.1 Correction method

The method consists in employing two parallel measurement channels to measure the same quantity. To ensure the validity of correction, both measurement channels should have the same gain value and different dynamic properties. Although not meeting these conditions does not make correction impossible, it may however result in the ambiguity of the solution or increase the calculation results. [1,2]
The „blind" method of correction algorithm uses the results of both measurement channels and consists of two stages. The first stage is identification of the dynamic properties of the measurement channels, the second one is the correction itself. In practice, the algorithm can be realised in a signal processor, which requires that the measurement channels are completed with a/d converters. Taking into account the applied identification method, various algorithms implementing the „blind" method can be applied. Three algorithms are described in the literature [2]: an algorithm optimising the conditioning index value, an algorithm based on

relationships among harmonics, and an algorithm based on minimisation of the differential error. Of the afore-mentioned algorithms, the third is applied and described in the paper: an identification algorithm based on parameter optimization of correctors connected in series to both measurement channels, in the way the difference between the results of both measurement channels with correctors are zero.

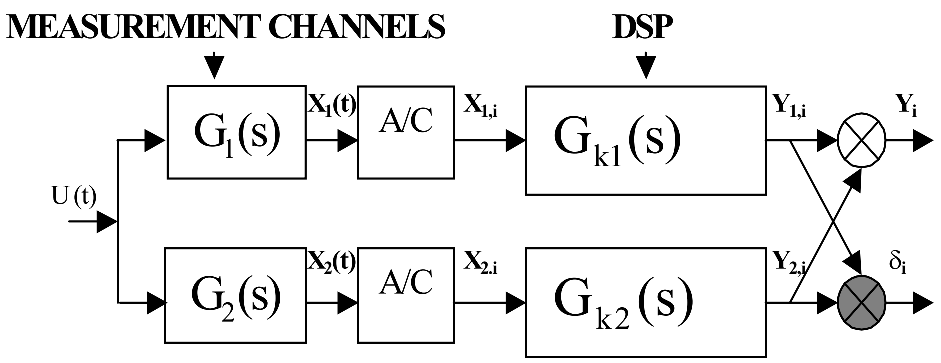

Fig. 1. Schematic diagram of the "blind" dynamic error correction system.

According to this algorithm, the dynamic correction method can be performed in a system whose structure is presented in Fig. 1. Two measurement channels measuring the same output quantity u(t) are used in the system. The dynamic properties of the channels are determined by their transfer functions $G_1(s)$ and $G_2(s)$. Corrupted by errors, the output signals of the analogue channels, denoted $x_1(t)$ and $x_2(t)$, respectively, are converted to digital forms $x_{1,i}$ and $x_{2,i}$ at sampling time instants t_i. The signals are converted in the signal processor by corrector algorithms into the signals $y_{1,i}$ and $y_{2,i}$, which represent the instantaneous values of the quantity measured by the first and the second channel, respectively. Finally, the output quantity y_i is defined at every moment of sampling as an arithmetic average of $y_{1,i}$ and $y_{2,i}$ – $y_i =(y_{1,i} + y_{2,i})/2$. The difference $\delta_i = y_{1,i} - y_{2,i}$ is the basis for defining an index of the criterion minimised in the corrector parameter optimization algorithm.

1.2 Correction assessment criteria

Measurement system dynamic errors with or without correction were estimated initially, using standard norms $||\varepsilon||_1$, $||\varepsilon||_2$ and $||\varepsilon||_\infty$ defined for vector ε with coordinates equal to the instantaneous values of dynamic error at sampling moments. Because the norm $||\varepsilon||_\infty$ introduces assessment criteria more stringent than the previous ones, it was accepted as the sole assessment criterion in all subsequent simulation study.
An index Q for estimating the correction effectiveness was introduced and defined as a quotient of the norm of the dynamic error vector, determined for the faster measurement channel without correction to the value of the norm of the dynamic error vector of the system with correction. The index shows how many times dynamic errors will be decreased upon correction.

$$Q = \min_{k=1,2} \frac{\|\varepsilon_k\|}{\|\varepsilon\|} \tag{1}$$

where: k – channel index, $\varepsilon_k = U(t_i) - X_k(t_i)$, $\varepsilon = U(t_i) - Y_i$

The first stage of the discussed dynamic correction differential algorithm was the identification carried out in this case as an optimum selection of the parameters of the in series correctors, e.g. time constants which according to the “blind” correction rule should be equal to the time constants of the measurement channels corrected. The quality of identification influences essentially on the correction effectiveness. A mean-square type identification quality index, BI, was accepted (2). For example, the BI index for first-order inertia channels is of the following form:

$$BI=\sqrt{(1-a)^2+(1-b)^2}\cdot 100[\%]; \qquad (2)$$

where: a - is the ratio of the time constant of corrector to the measurement channel’s time constant in the first channel, b – the same for the second channel.

2. Simulation study results

Determination of the effectiveness of the correction made and, consequently, determination of the range of the practical applicability of correction to measurement channels with different types of dynamics was the main aim of the simulation study carried out and described in the paper.

2.1. Simulation parameters

The initial simulation study carried out for first-order inertia measurement channels [1] confirmed in general, the suitability of computer simulation for determining the conditions of the practical applicability of the “blind” dynamic correction method, and enabled common simulation methods and parameters to be determined. It was, therefore, accepted as follows:

- measured signal, sinusoidal, undisturbed, of 50 Hz frequency, $T_s = 0.02$ s
- a/d converter is modelled through the quantization operation
- sampling operation is modelled through the simulation step
- operations used in the algorithm realized in DSP are modelled through the adequate operations of a simulation language
- sampling frequency is 40 times greater than the measured signal frequency $f_p = 2$ kHz
- optimization method: Monte Carlo
- optimization criterion: $\|\delta\|_1$
- simulated optimization time is equal to one period of the measured signal.

2.2. Simulation study on first-order inertia measurement channels

The measurement channels are modelled as the first-order transfer functions

$$G_1(s) = \frac{1}{1+sT_1}, \qquad G_2(s) = \frac{1}{1+sT_2} \qquad (3)$$

Correctors were modelled in the following form:

$$G_{k1}(s) = 1 + aT_1 s, \qquad G_{k2}(s) = 1 + bT_2 s \qquad (4)$$

The criterion $\|\delta\|_1$ used during optimization was the function of the coefficients a and b.
A 12-bit word length A/D converter (range: ±1V) was modelled.

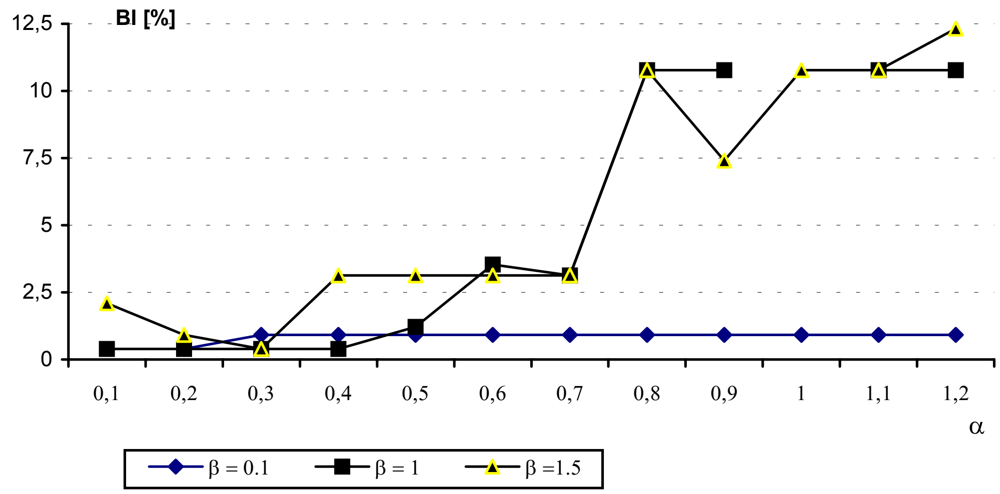

Fig. 2. Quality of identification index BI in function α for three values β for the first-order inertial measurement channel.

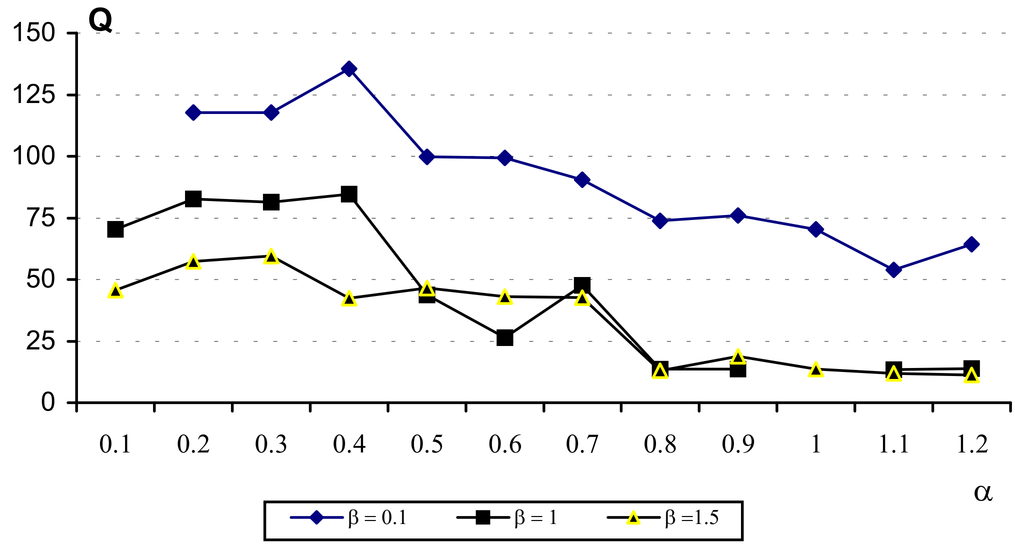

Fig.3. Correction effectiveness index Q in function α for three values β for the first-order inertial measurement channel.

The simulation study results used for determining the relationship between the identification error, BI, correction effectiveness, Q, and time constants of both channels are presented in Fig. 2 through 5. To generalise the conclusions, α denotes in the figures the ratio of the time constant T_1 to the period of the measured signal T_s; analogically β is defined for the time constant T_2. The fundamental conclusion from the study undertaken [3,4] is that for the measurement channels with time constants of the ratio to the period of the measured signal not exceeding 1.5, the dynamic correction by the “blind” method always “improves” i.e. the correction effectiveness is greater than unity.

Moreover, the following conclusions can be drawn:

– The correction effectiveness Q is high (reaches values above 130) when the identification error, BI, is less than 1%. It seems that 3% is the limit value of that error.

– The identification error, BI, depends on the values of the ratio of time constants to the period of the measured signal (α and β), in such a way that if at least one of these ratios is less than 0.7 then BI does not exceed 3% (Fig. 2).
– The correction effectiveness Q depends on the ratios α and β in such a way that the greater value of α or β the smaller Q. Q reaches its maximum for α smaller than 0.5 (Fig. 3). The smaller the time constant related to the period of the measured signal, the better the correction effectiveness. We can say therefore that the best effects can be obtained for the channels with "good" dynamic properties. But: a "good" measurement channel can be corrected effectively with the "blind" method by a "bad" channel (Fig. 5: Q greater than 60) or a "bad" channel can be corrected by another "bad" channel (Fig. 4: Q greater than 10).

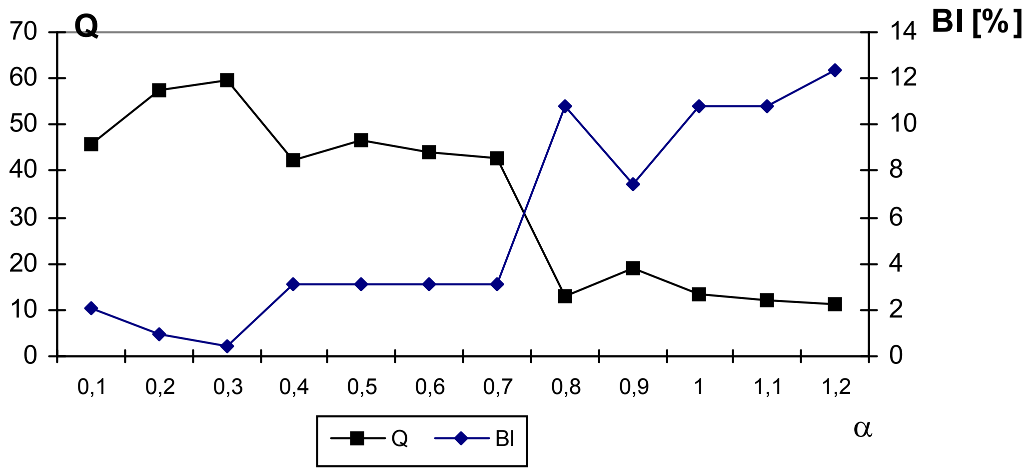

Fig. 4. Correction effectiveness index Q and quality of identification index BI in function α, for β=1.5 for the first-order inertial measurement channel.

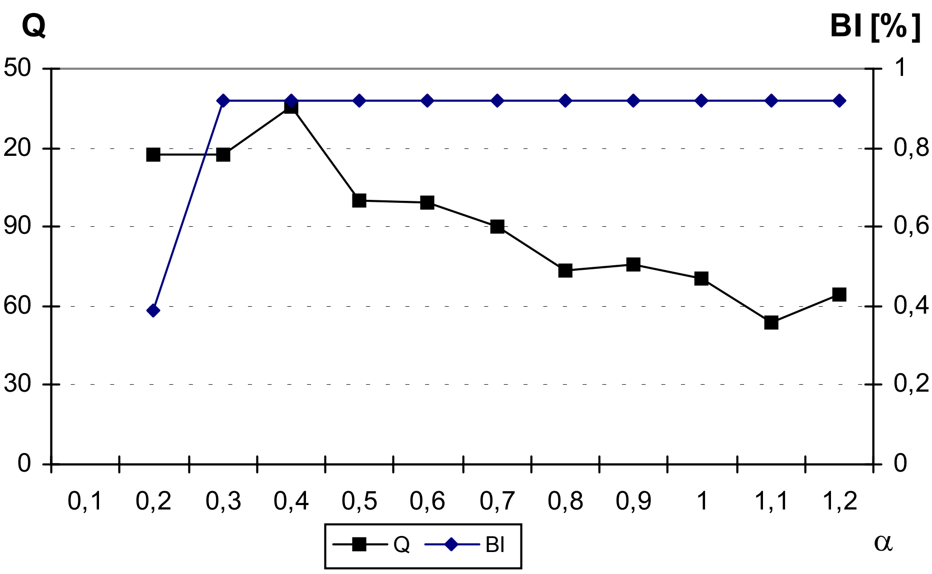

Fig. 5. Correction effectiveness index Q and quality of identification index BI in function α, for β=0.1 for the first-order inertial measurement channel.

- The applicability range of the "blind" method dynamic correction can be defined through the limit values of the dynamic properties of both channels, ensuring the acceptable correction effectiveness. For example, if we assume that the require correction effectiveness Q is greater than 50 then, based on Figs. 2 through 5, the applicability range of the "blind" method dynamic correction can be determined through the limit values of α and β:
  - ✓ if β equals 0.1 then α can be arbitrary up to 1.2;
  - ✓ if β equals 1 then α cannot exceed 0.5;
  - ✓ if β equals 1.5 then α cannot exceed 0.3.

2.3. Simulation study on double-inertia measurement channels

The measurement channels are modelled as transfer functions:

$$G_1(s) = \frac{1}{1+sT_1}\frac{1}{1+sT_3}, \qquad G_2(s) = \frac{1}{1+sT_2}\frac{1}{1+sT_4} \tag{5}$$

Correctors were modelled in the following form:

$$G_{k1}(s) = (1 + aT_1s)(1 + dT_3s), \qquad G_{k2}(s) = (1 + bT_2s)(1 + gT_4s) \tag{6}$$

The criterion $||\delta||_1$ used during optimization was the function of coefficients a, b, g and d.
The initial simulation study results showed that the minimum length of the a/d converter word is 22 bits. So a 24-bit word length A/D converter (range ±1V) was modelled.
Taking into account the various possible realizations of the measurement channels and methods of optimization algorithm implementations differing in calculation accuracy, the following cases were investigated:
- measurement channels with a double time constant ($T_1 = T_3$ and $T_2 = T_4$), optimization of two parameters
- measurement channels with a double time constant ($T_1 = T_3$ and $T_2 = T_4$), optimization of four parameters
- measurement channels with four time constants and optimization of four parameters.

The results of the simulation study are presented accordingly in Figs. 6, 7 and 8.
The β and α in Figs. 6 and 7 are defined as for first-order channels.
The correction effectiveness for two-inertia channels with double time constants is very high: always over 100 as far as up to 3, and this is clearly better than for first-order channels.
In changing the order of optimised parameters, similar values of identification error were obtained for systems with a double time constant and four-parameter optimization, however, effectiveness values were different (double at maximum). The maximum effectiveness values are presented in Fig. 7.
In Fig. 8, the results of the simulation study on the "blind" method dynamic correction for two-inertia channels at four different optimised time constants are presented. The results refer to the case when the first channel time constants are fixed and constant (α_1= 0.2 and β_1=0.6), and α_2 of the second channel is changing from 0.2 to 10 for three different values of β_2 (0.05, 0.5, 1). The obtained correction effectiveness is even five times smaller than in the case of double time constant channels with four-parameter optimization, but this refers to the particular case under study.

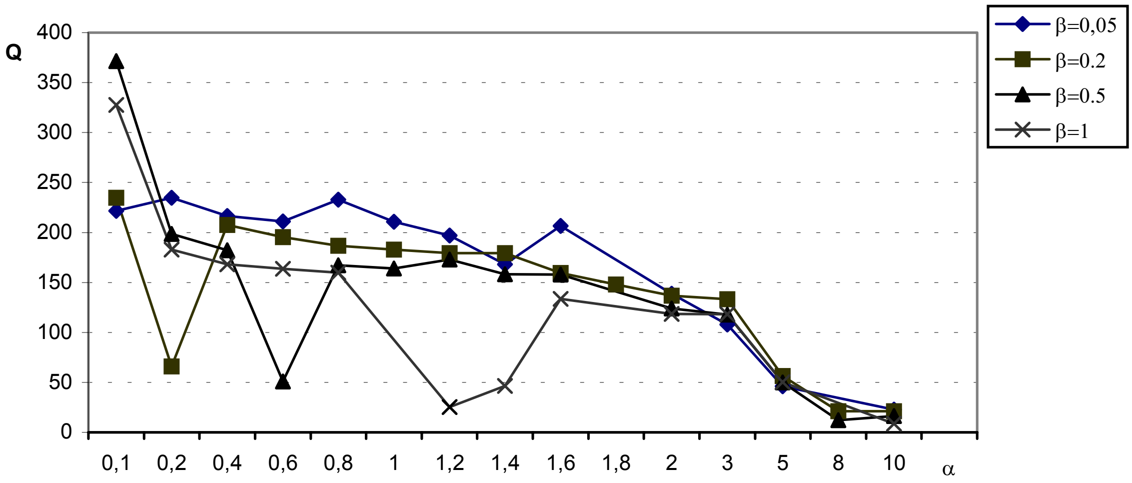

Fig. 6. Correction effectiveness index Q for second-order inertial measurement channels with a double time constant, optimization of two parameters.

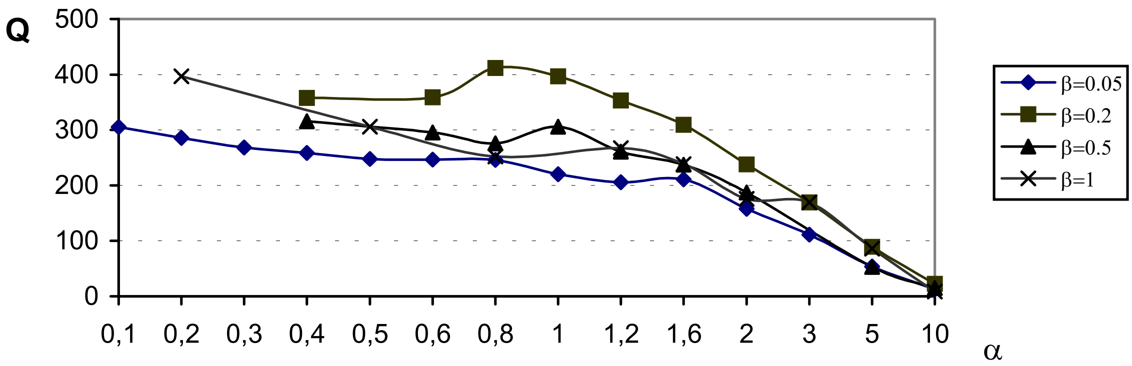

Fig. 7. Correction effectiveness index Q for second-order inertial measurement channels with a double time constant, optimization of four parameters.

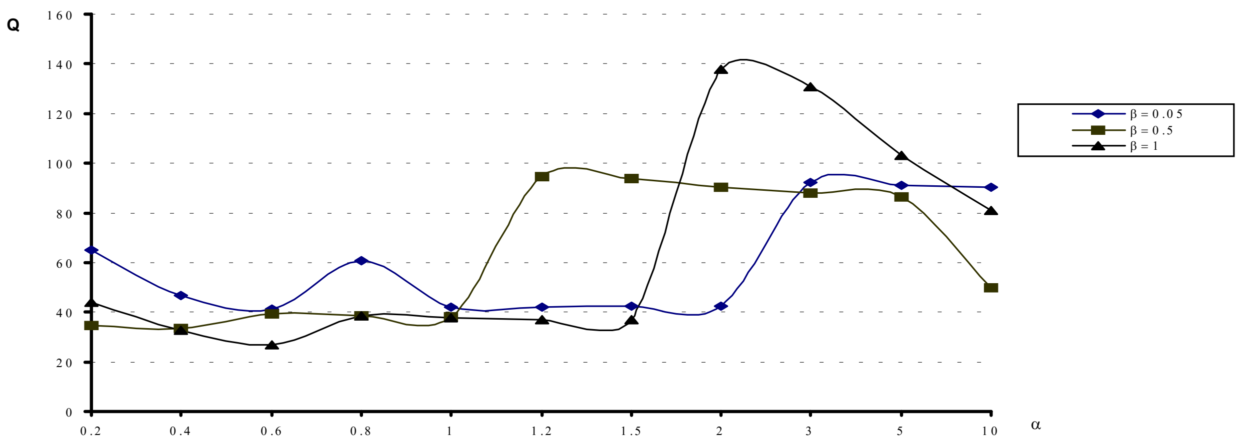

Fig. 8. Correction effectiveness index Q for second-order inertial measurement channels with four time constants and optimization of four parameters.

Summarizing the obtained results of the simulation study, it can be stated that the correction effectiveness of the "blind" method dynamic correction obtained for two-inertia systems is quite satisfactory despite larger numerical errors (also double differentiation errors). The lack of influence of the enlarged numerical errors on the obtained effectiveness values may follow from using the 24-bit a/d converter and also from the correction method rule itself (optimization based on differential error) as calculation errors can counterbalance. The value of correction effectiveness Q depends clearly on the dynamic parameters of the measurement channels under correction. However, special attention should be paid to the high effectiveness values obtained when for one channel, the ratio of time constant to the period of the measured signal (α) is large (between 1.5 and 5). So a „very bad" dynamically, two-inertia measurement channel may be even better corrected , in wider range of time constants, than it was possible for first-order systems.

2.4. Simulation study on second-order oscillation measurement channels

The measurement channels are modelled as transfer functions :

$$G_1(s) = \frac{1}{1 + s\frac{2z_1}{\omega_{01}} + s^2\frac{1}{\omega_{01}}}, \qquad G_2(s) = \frac{1}{1 + s\frac{2z_2}{\omega_{02}} + s^2\frac{1}{\omega_{02}^2}} \tag{7}$$

where: $\omega_0 = 2\pi f_0$ – natural frequency,
z – damping factor

Correctors were modelled in the following form:

$$G_{k1}(s) = 1 + sa\frac{2z_1}{\omega_{01}} + s^2 b\frac{1}{\omega_{01}}, \qquad G_{k2}(s) = 1 + sd\frac{2z_2}{\omega_{02}} + s^2 g\frac{1}{\omega_{02}} \tag{8}$$

The criterion $\|\delta\|_1$ used during optimization was the function of coefficients a, b, g and d.
A ±1V, 24-bit word length A/D converted was modelled.
The possible variability of the four parameters dictated a method for the simulation study similar to that of the two-inertia channels. The dynamic properties of the one channel were fixed, whilst the properties of the second one were changed. Additionally, as in previous investigations, the parameter, the natural frequency, was referred to the measured signal pulsation - ω_s. Parameter –omega1- is defined as the ratio of a pulsation ω_{01} to ω_s and parameter –omega2- is defined as the ratio of a pulsation ω_{02} to ω_s . In Figs. 9 and 10, the results of the simulation study for two cases are presented. The first case (Fig. 9) refers to a channel with fixed parameters: omega1 = 1, z1 = 0.6, while the second case (Fig.10) refers to a channel with parameters: omega1 = 2, z1 = 0.15. Such a choice results from an observation on the results of the simulation study that the channels with a large phase error can be corrected differently, as can the channels with a large amplitude error. The results presented were obtained for a sampling frequency of 2.5 kHz. It was noted that increasing the sampling frequency increases the "sensitivity" of the obtained extreme values of the effectiveness Q.
Based on the obtained results, it can be stated that the "blind" method dynamic correction for oscillation channels is effective within a wide range of measurement channel parameters and the highest values of the effectiveness Q are similar as for two-inertia channel with four-

parameter optimization. Similarly, the best effects are obtained for the channels with large dynamic errors.

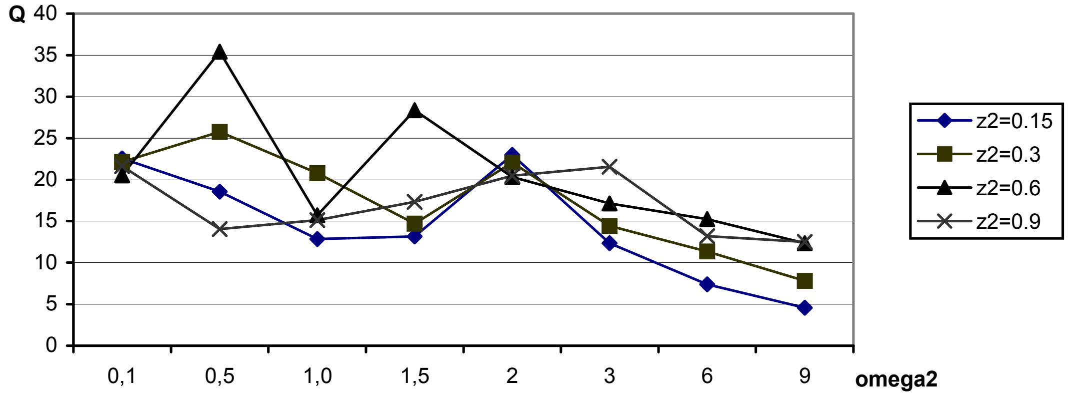

Fig. 9. Correction effectiveness index Q for second-order oscillation measurement channels in function damping factor z2 for various values omega2 for one channel; parameters of second channel: omega1=1, z1=0.6.

The ambiguity of trends and, especially, the different behaviour of channels with a prevailing phase error and a different one for channels with a prevailing amplitude error, results in the fact that the presented correction method may be of practical application, only in the sense of the best choice for a particular measurement channel under correction. This can be seen especially in the case presented in Fig. 10 where the best effectiveness is reached for a single particular pair of parameters.

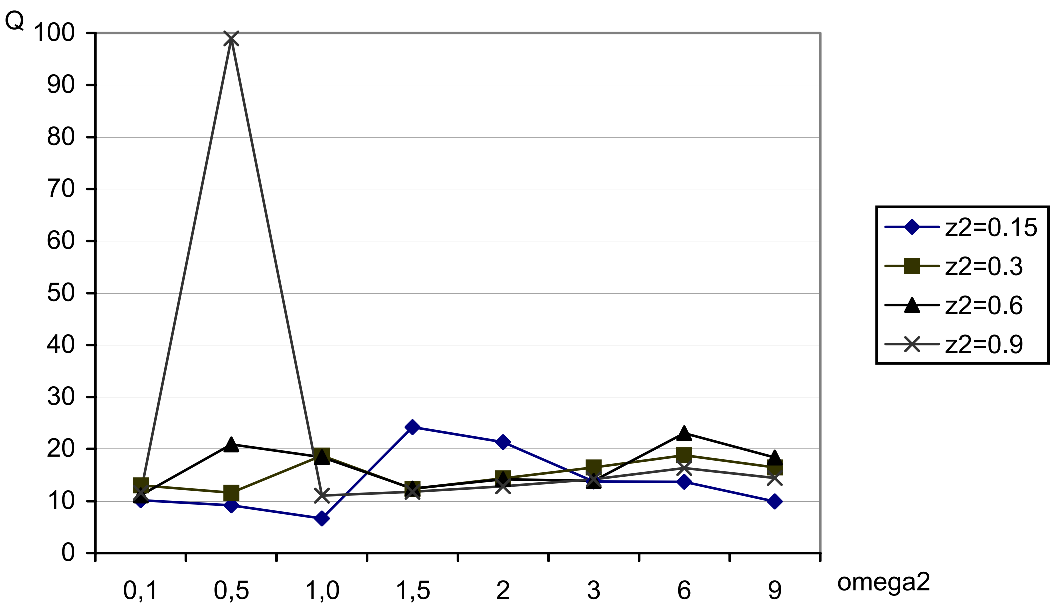

Fig.10. Correction effectiveness index Q for second-order oscillation measurement channels in function damping factor z2 for various values omega2 for one channel; parameters of second channel: omega1=2, z1=0.1.

3. Summary and conclusions

The results of the simulation study on the differential algorithm of the dynamic correction error by the „blind" method for the models of first- and second-order measurement channels are presented in the paper. The results presented concerned one type of measured signal only, but the initial study for other signal types were made as well [3].
A general conclusion drawn from the presented simulation results is that the applied method for the dynamic error correction is always effective. The correction effectiveness depends on the values of the dynamic parameters of the modelled measurement channels and on numerical errors. An advantage of the presented differential algorithm is the possibility of compensating certain numerical errors and also of compensating disturbances if they occur in inputs of both channels simultaneously. Whereas even small disturbances occurring after analogue parts of measurement channels always heavily reduce the correction effectiveness.
The accuracy of the practical application of the presented „blind" method correction algorithm depends primarily on:
- the resolution of the employed a/d converter;
- sampling frequency;
- applied method of numerical differentiation;
- applied method of parameter optimization.

Summarizing: A simulation study similar to that presented in the paper, can be an effective instrument to determine conditions for the practical applicability of the dynamic error correction by the „blind" method for a particular measurement channel.

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