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CORRECTION OF DYNAMIC ERROR BY THE „BLIND" METHOD. A DIFFERENTIAL ALGORITHM SIMULATION STUDY

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Abstract: The „blind" method of correction algorithm uses the results of two parallel 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. A differential algorithm of identification based on minimisation of the difference between the results of both measurement channels connected with correctors. The paper presents the results of the simulation study on the differential algorithm of the correction of the dynamic error for measurement channels modelled as first- and second-order system. 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 channels.

Keywords: dynamical error correction, simulation

1. INTRODUCTION

The method of dynamic correction of measurement, presented in this paper, can be applied when the dynamic properties of measurement channels are not sufficiently known and using the serial correctors of fixed parameters is not possible. This concerns, therefore, the cases when the dynamic properties of sensors or transducers slowly change in time or under various environmental factors. The method may also be applied when the laboratory determination of the coefficients of the dynamics model equation describing the analogue of a part of the measurement channel is impossible. Potential applications of the dynamic correction method can include, for example, the 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, or the measurement of low highly-variable electrical signals with the use of a low-band measurement amplifier (e.g., measurement of non-sinusoidal currents with a shunt).

The method of dynamic correction, presented in this paper, 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 their dynamic properties should be different. Not meeting these conditions does not make correction making impossible, it may however result in the ambiguity of the solution or increase the calculation results. [1] The correction algorithm is applied to the results of the both measurement channels. It consists of two stages. The first stage is the identification of the dynamic properties of measurement channels, the second one is the correction itself. In practice, this algorithm can be implemented in a signal processor, which requires that the measurement channels be completed with a/d converters. Taking into account the applied method of identification, various correction algorithms can be applied. Three algorithms are described in the literature[2,4]: an algorithm for optimising the condition number value, algorithm based on the relationships among harmonics, and an algorithm based on the minimisation of differential error. Out these algorithms, the third is described in the paper and applied: an algorithm of identification based on the parameter optimisation of correctors connected in series to the both measurement channels in such a way that the difference between the results of both measurement channels with correctors be zero. The algorithm can therefore be called differential or the algorithm of the equivalence of two parallel measurement channels. The dynamic correction method under discussion is also called in the literature the "blind" correction method as it can be applied for correction under unknown dynamic properties of a measurement channel. The idea of the method has been known for many years; its practical application, however, to signal processors was able with the advent of digital techniques implementation.

2. DYNAMIC CORRECTION BY THE METHOD OF EQUIVALENCE OF THE MEASUREMENT BY TWO PARALLEL CHANNELS. CORRECTION DESCRIPTION AND ASSESSMENT CRITERIA

According to the differential algorithm, the dynamic correction method can be performed in a system whose structure is presented in Fig. 1.

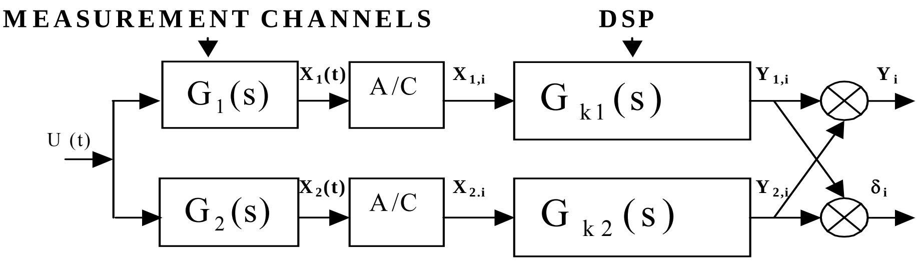

Fig. 1. Diagram of a system implementing dynamic correction by the method of equivalence of measurement by two parallel channels.

Two measurement channels measuring the same output quantity u(t) were used in the system. Dynamic properties of the channels are determined by their transfer functions $G_1(s)$ and $G_2(s)$. Biased with dynamic 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. In the signal processor, these signals are converted 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 the arithmetic average of $y_{1,i}$ and $y_{2,i}$. The difference $y_{1,i} - y_{2,i}$ is the basis for defining an index of the criterion minimised in the corrector parameter optimisation algorithm.

The effectiveness of dynamic correction implemented in the system presented in Fig. 1 can be assesses counting how often dynamic errors is decreased upon correction. An index estimating 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.

$$Q = \min_{k=1,2} \frac{\|\varepsilon_k\|}{\|\varepsilon\|}, \quad \text{where k is the channel index} \qquad (1)$$

Dynamic errors of a measurement system with or without correction can be estimated using standard norms $\|\varepsilon\|_1$, $\|\varepsilon\|_2$ and $\|\varepsilon\|_\infty$ defined for vector ε with coordinates equal to the instantaneous values of the dynamic error at sampling moments. Because the norm $\|\varepsilon\|_\infty$ introduces assessment criteria more stringent than the other two, it was accepted as the sole assessment criterion in all further simulation study presented in the paper.

3. DYNAMIC CORRECTION BY THE METHOD OF EQUIVALENCE OF THE MEASUREMENT BY TWO PARALLEL CHANNELS. SIMULATION STUDY

Simulation study was carried for the measurement system presented in Fig. 1. The measurement channels were modelled as first and second-order objects. The main objectives of the study were as follows:

– determining the suitability of the computer simulation method for determining the conditions of practical usability of the presented dynamic correction method;
– determining the effectiveness of the correction performed and, as the consequence, numeric determining of the applicability range of correction (of the same dynamics of both channels) for the measurement channels of different-type dynamics with adjusted corrector form;
– determining the effectiveness of the correction (of the same dynamics of both channels) performed for the measurement channels of different-type dynamics with unadjusted corrector form;
– determining the effectiveness of the correction (different dynamics of both channels) performed for the measurement channels of different-type dynamics.

3.1 Simulation parameters

Initial simulation study carried out for first-order inertia measurement channels [1] confirmed in general the suitability of the computer simulation for determining the conditions of 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;
– a/d converter is modelled through the quantization operation,
– sampling operation is modelled through the simulation time (step),
– operations used in the algorithm implemented in DSP are modelled through the adequate operations of a simulation language;
– sampling frequency is 40 times greater than the measured signal frequency;
– optimisation method: Monte Carlo
– optimisation criterion: $\|\delta\|_1$
– simulated optimisation time is equal to one period of the measured signal.

Simulation study was performed using languages: GODYSPC, SIMULINK and MATLAB.

3.2 Simulation study results for the first- and second order measurement channels with adjusted form of correctors

Table 1

Models of measurement channels	Models of correctors
first-order inertial $G_1(s)=\frac{1}{1+sT_1}$, $G_2(s)=\frac{1}{1+sT_2}$	first-order inertial $G_{k1}(s)=1+aT_1s$, $G_{k2}(s)=1+bT_2s$
second-order inertial with a double time constant $G_1(s)=\frac{1}{1+sT_1}\frac{1}{1+sT_1}$, $G_2(s)=\frac{1}{1+sT_2}\frac{1}{1+sT_2}$	second-order inertial with a double time constant $G_{k1}(s)=(1+aT_1s)(1+aT_1s)$, $G_{k2}(s)=(1+bT_2s)(1+bT_2s)$
second-order inertial with a two time constants $G_1(s)=\frac{1}{1+sT_1}\frac{1}{1+sT_3}$, $G_2(s)=\frac{1}{1+sT_2}\frac{1}{1+sT_4}$	second-order inertial with a two time constants $G_{k1}(s)=\frac{1}{1+aT_1s}\frac{1}{1+cT_3s}$, $G_{k2}(s)=\frac{1}{1+bT_2s}\frac{1}{1+dT_4s}$
second-order oscillation $G_1(s)=\frac{1}{1+s\frac{2z_1}{\omega_{01}}+s^2\frac{1}{\omega_{01}}}$, $G_2(s)=\frac{1}{1+s\frac{2z_2}{\omega_{02}}+s^2\frac{1}{\omega_{02}^2}}$	second-order oscillation $G_{k1}(s)=\frac{1}{1+s\frac{2az_1}{b\omega_{01}}+s^2\frac{1}{b\omega_{01}}}$, $G_{k2}(s)=\frac{1}{1+s\frac{2cz_2}{d\omega_{02}}+s^2\frac{1}{d\omega_{02}^2}}$

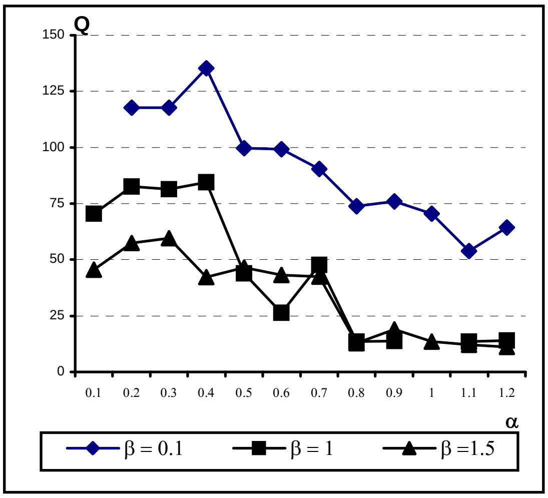

Fig.2 Correction effectiveness index Q in function α for three values β for the first-order inertial measurement channel. Parameters α and β are defined as the ratios of the respective time constants to the period of the input signal.

Typical results obtained are presented in Fig. 2.

The following conclusions can be drawn from the obtained results of the simulation:

– The minimum word length of the a/d converter applied in the correction system is 12 bits for first-order channels and 22 bits for second-order channels. In the study, 13 and 24 bits, respectively, were applied.
– For first-order channels, the correction effectiveness Q depends on the values of time constants of both measurement channels. The smaller the ratio of the time constant to the period of the measured signal, the better the correction effectiveness (not greater than 150). It can therefore be said 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 or a "bad" channel can be corrected by another "bad" channel [1].
– The correction effectiveness of two-inertia measurement channels with double time constants is very high and is at least 2.5 times higher than that for first-order channels and reaches the value of 400 at optimising both two and four parameters. The correction effectiveness of two-inertia measurement channels with two different time constants is no more that five times lower than that for channels with double time constants at optimising four parameters. Special attention should be paid to high value of effectiveness obtained in the case when for one channel the ratio of the time constant to the period of the measured signal is large (between 1.5 and 4). So a dynamically „very bad" two-inertia measurement channel may be corrected even better, in wider range of time constants, than it was possible for the first-order channels. [3,4]
– The correction effectiveness of second-order oscillation measurement channels is at least 2.5 times lower than for two-inertia channels with two different time constants. Similarly, the best correction effects are obtained for the channels with large dynamic errors. The ambiguity of trends and, especially, different behaviour of channels with prevailing phase error and of channels with prevailing amplitude error, causes that the presented correction method may be of

The study was performed for cases presented in Table 1. It was accepted that the practical applicability range of the dynamic correction by the two parallel channels equivalence method can be determined through limit values of the dynamic properties of both channels ensuring the acceptable correction effectiveness.

practical application for oscillation channels only in the sense of the best case choice for a particular measurement channel under correction. [3]

The results presented confirmed that the dynamic correction method is efficient under preservation of input conditions: known and unchanged model form for both channels, the same gain and different dynamic properties. However, its practical application requires answering the further questions: How the correction effectiveness value will be affected by disturbances, and could the correction be really carried out "blindly", i.e., not knowing *a priori* the order of a measurement channel.

3.3 Simulation study results for the first- and second order measurement channels with unadjusted form of correctors' dynamics

Because in this study the models of measurement channels and correctors of different type occurred, it turned out to be necessary to repeat first the study for first order using a 24-bit a/d converter.

The obtained results confirmed the above presented conclusions for the first-order channels where the maximum values of the effectiveness increased triple. It was possible therefore to extend the range of the applicable possible dynamic properties (time constants) for which the correction is satisfactory.

In the study presented cases were considered where the mathematical form of the measurement channels is not known while the models of the applied correctors are known. Choosing corrector models was based on the criterion of identification error minimisation. Accepting an assumption that this model depends also on the number of the identified (in the optimisation procedure) parameters, two forms of corrector models were chosen: the first-order model and the inertial second-order one with double time constant. To be able to compare the results obtained in the study on the "mixed" models with the results obtained previously for known models of measurement channels, a study was performed for the cases listed in Table 2.

Table 2

Models of measurement channels	Models of correctors
first-order inertial $G_1(s) = \frac{1}{1+sT_1}$, $G_2(s) = \frac{1}{1+sT_2}$	second-order inertial with a double time constant $G_{k1}(s) = (1+aT_1s)(1+aT_1s)$, $G_{k2}(s) = (1+bT_2s)(1+bT_2s)$
second-order inertial with a double time constant $G_1(s) = \frac{1}{1+sT_1}\frac{1}{1+sT_1}$, $G_2(s) = \frac{1}{1+sT_2}\frac{1}{1+sT_2}$	first-order inertial $G_{k1}(s) = 1+aT_1s$, $G_{k2}(s) = 1+bT_2s$
second-order inertial with a two time constants $G_1(s) = \frac{1}{1+sT_1}\frac{1}{1+sT_3}$, $G_2(s) = \frac{1}{1+sT_2}\frac{1}{1+sT_4}$	first-order inertial $G_{k1}(s) = 1+aT_1s$, $G_{k2}(s) = 1+bT_2s$ second-order inertial with a double time constant $G_{k1}(s) = (1+aT_1s)(1+aT_1s)$, $G_{k2}(s) = (1+bT_2s)(1+bT_2s)$
second-order oscillation $G_1(s) = \frac{1}{1+s\frac{2z_1}{\omega_{01}}+s^2\frac{1}{\omega_{01}}}$, $G_2(s) = \frac{1}{1+s\frac{2z_2}{\omega_{02}}+s^2\frac{1}{\omega_{02}^2}}$	first-order inertial $G_{k1}(s) = 1+aT_1s$, $G_{k2}(s) = 1+bT_2s$ second-order inertial with a double time constant $G_{k1}(s) = (1+aT_1s)(1+aT_1s)$, $G_{k2}(s) = (1+bT_2s)(1+bT_2s)$

Typical results obtained are presented in Fig. 3

The following conclusions can be drawn from the obtained results:

- the correction effectiveness is always reduced when the corrector model form is not adjusted to the measurement channel model;
- for measurement channels modelled as the first-order inertial objects, connecting second-order inertial correctors with double time constant reduces the correction effectiveness from 15 to 60 times. This also means that the system itself does not detect the order of the measurement channel. Similar study made for comparison for the correctors modelled as second-order with two different time constants gave similar results;
- for measurement channels modelled as the second-order inertial objects with double time constant, the first-order inertial correctors reduced the effectiveness from 20 to 100 times, depending on the dynamic parameters of the channels;
- for measurement channels modelled as the second-order inertial objects with two different time constants, the first-order inertial correctors reduced the effectiveness from 30 to 70 times, depending on the dynamic parameters of the channels, and the second-order correctors with double time constant reduced the effectiveness from 5 to 40 times;
- for second-order oscillation measurement channels, the correction under unadjusted correctors is practically impossible;

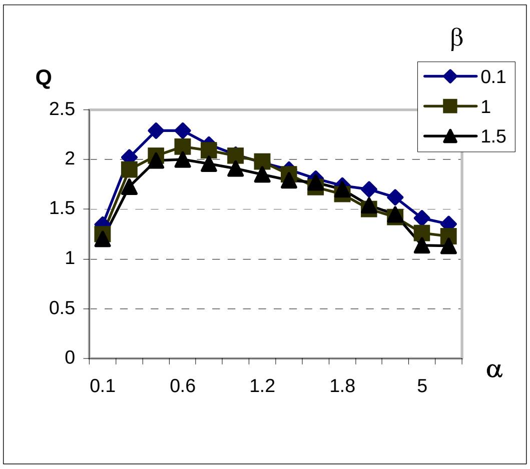

Fig.3 Correction effectiveness index Q in function α for three values β for the first-order inertial measurement channel and corrector - second order inertial with double time constant

– out of two correctors used in the study on correctors, better results were obtained for the second-order inertial corrector with double time constant;
– however, comparing the obtained results with the simulation study on the presented correction method for adjusted correctors with input signals with imposed disturbance of up to 5% of the amplitude, it was shown that they shown similar level of correction effectiveness reduction.

3.4 Simulation study results for the first- and second order measurement channels when the dynamics characteristics of the both channels are different

In the study presented cases were considered when a model form of the corrected measurement channel is unknown but it is known and assumed the form of the second parallel measurement channel, and the forms of corrector models are adjusted to it. Out of possible model forms of the corrected measurement channel two were accepted as the most possible: first- and second-order with two different time constants. For measurement channel modelled as inertial first-order, two model forms of the second channel and the second-order inertial correctors were used: with double time constant and with two different time constants. For measurement channel modelled as inertial second-order with two different time constants, two model forms of the second channel and correctors were used: inertial first-order and two-inertial with double time constant. Second-order oscillation models were not investigated.

The cases under study are listed in Table 3. Also the values of α and β are presented there. Parameters α and β are defined as the ratios of the respective time constants to the period of the signal under study.

Table 3

Model of first measurement channel	Models of second measurement channel and both of correctors
first-order inertial $G_1(s)=\frac{1}{1+sT_1}$, β=0.1, 1.0, 2.0	second-order inertial with a double time constant $G_2(s)=\frac{1}{1+sT_2}\frac{1}{1+sT_2}$, $\alpha = 0.1 - 5.0$ $G_{k1}(s)=(1+aT_1s)(1+aT_1s)$, $G_{k2}(s)=(1+bT_2s)(1+bT_2s)$
	second-order inertial with a two time constants $G_2(s)=\frac{1}{1+sT_2}\frac{1}{1+sT_4}$, $\alpha_2 = 0.1, 1.0$ $\beta_2 = 0.1 - 5.0$ $G_{k1}(s)=(1+aT_1s)(1+aT_3s)$, $G_{k2}(s)=(1+bT_2s)(1+bT_4s)$
second-order inertial with a two time constants $G_1(s)=\frac{1}{1+sT_1}\frac{1}{1+sT_3}$, $\alpha = 0.2$, $\beta = 0.6$	first-order inertial $G_2(s)=\frac{1}{1+sT_2}$, $\alpha_2 = 0.1$ - 5 $G_{k1}(s)=1+aT_1s$, $G_{k2}(s)=1+bT_2s$
	second-order inertial with a double time constant $G_2(s)=\frac{1}{1+sT_2}\frac{1}{1+sT_2}$, $\alpha_2 = 0.1$ - 5 $G_{k1}(s)=(1+aT_1s)(1+aT_1s)$, $G_{k2}(s)=(1+bT_2s)(1+bT_2s)$

Typical results obtained are presented in Fig. 4.

The following conclusions can be drawn from the obtained results:

– the correction effectiveness is always reduced when the corrector model form is not adjusted to the measurement channel model;
– for measurement channels modelled as the first-order inertial objects, connecting a second channel and correctors in the form of second-order inertial objects with double time constant reduces the correction effectiveness from 8 to 30 times;
– for measurement channels modelled as the first-order inertial objects, connecting a second channel and correctors in the form of second-order inertial objects with two different time constants reduces the correction effectiveness from 2 to 7 times compared with the full adjustment. This results from the fact that in most cases the system itself

has detected that the corrected channel is modelled as a first-order object. So, a case of two parallel channels of different orders with correctors adjusted in series has occurred;

- for measurement channels modelled as the second-order inertial objects with two different time constants, connecting a second channel and correctors in the form of the first-order inertial objects reduces the correction effectiveness from 20 to 40 times, compared with the full adjustment;
- for measurement channels modelled as the second-order inertial objects with two different time constants, connecting a second channel and correctors in the form of the second-order inertial objects with double time constant reduces the correction effectiveness from 6 to 15 times compared with the full adjustment.

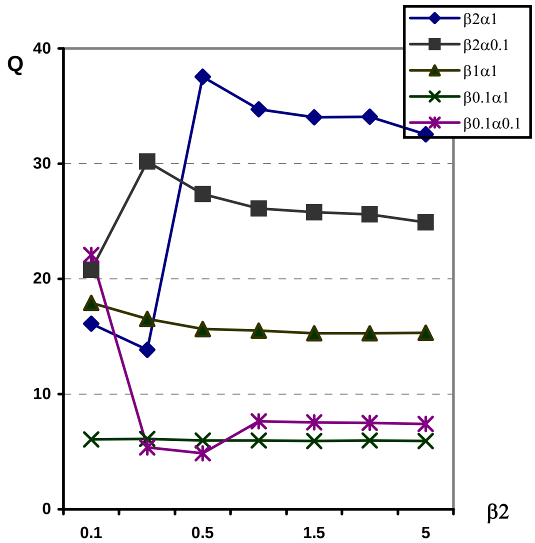

Fig.4 Correction effectiveness index Q for the first-order inertial measurement channel (three value of β) ; second channel - second-order inertial with a two time constants (two value of α in function β2)

4. CONCLUSIONS

Summarising the simulation results, it can be stated that the effectiveness of the "blind" correction method depends both on the level of the dynamics of both corrected measurement channels and the ratio of the parameters of this dynamics to the parameters of the dynamics of the measured quantities. For most investigated cases, the correction effectiveness was greater than unity. When the dynamics of both measurement channels and correctors were adjusted then the correction effectiveness reached the value of near 500. It is promising for practical application that for different form of dynamics high correction effectiveness for dynamically "bad" measurement channels was found using a second, also "bad" channel. The forms of the corrector model, and the forms of the second parallel channel unadjusted to the form of the measurement channel under correction always reduces the correction effectiveness. This means that the studied correction method will be of practical application only in such cases when the model forms of both measurement channels are known while the dynamics parameters of these models change slowly in time.

The presented results of the study that covered many cases have shown that the computer simulation method is the only tool for determining the condition of the practical usability of the "blind" dynamic error correction method.

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