XVII IMEKO World Congress
Metrology in the 3rd Millennium
June 22–27, 2003, Dubrovnik, Croatia

THE "BLIND" METHOD OF DYNAMIC ERROR CORRECTION FOR THE SECOND ORDER SYSTEM

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Abstract – The paper presents results of simulation investigations of the measuring system, which enables measuring, with very small dynamic error, of rapidly changing signals using inexpensive transducers of not particularly good dynamic performance. Two methods for self-identification of the system sensor parameters are presented. The self-identification is performed using solely the measured signal at the system operating site. The system itself performs the correction of dynamic errors. Therefore the system shows small sensitivity to adverse influence of the operating conditions on the transducers dynamic properties. The investigations have been carried out for the second order, oscillatory and inertial transducers. The presented methods of correction can be applied to measuring of both: periodic and non-periodic signals. The simulation results, presented in a graphical form, illustrate the dependence of the correction effectiveness on the system selected parameters. Created programming tools make possible for testing the system in the neighbourhood of the selected operating point.

Keywords dynamic error, correction, simulation

1. INTRODUCTION

The aim of the simulation investigations was to present examples, which illustrate the methods for "blind" correction of dynamic error, caused by analogue input circuits of the measuring system. The presented correction methods are applied to the transducers modelled as the second order plants: inertial, oscillatory or with critical damping.

The measuring system, of the proposed structure and assumptions, should enable correction of dynamic error, where is no information on values of the zeros and poles of the system input circuits linear model. The order of the model differential equations is the only information used. The distinguishing feature of the investigated method of correction is use of the measured signal for identification of the model coefficients. Thus there is no necessity of applying any special signals for the purpose of identification. The measuring system will itself perform identification at the operation site, using the measured signal. Such a system itself eliminates the influence of changing environmental conditions on its dynamic properties. The identification is carried out simultaneously with the measurement, not disturbing it. In order to have such a feature, the system must contain two independent measuring channels, which measure the same input signal (Fig.1). Moreover, two assumptions have to be fulfilled. The first one concerns identity and linearity of the static characteristics of both measuring channels, the second assumption requires they have no common zeros nor poles. This method of correction has been shown in [1]. Thus the investigations were aimed to determine the range of applicability of the proposed method and estimate the influence of the measuring system and signal parameters on the correction quality. The investigations have been carried out for the system comprising pairs of transducers of the same kind or of different types (e.g. inertial and oscillatory).

Several parameters of the measuring system influence the correction effectiveness, they are: the order of the analogue part model, mutual relationships between the model coefficients, sampling frequency, dynamic behaviour of the measured signal, resolution of A/D converters. Also the properties of algorithms for processing measurement results, such as: the number of samples in the window, degree of the polynomial applied for approximation of the recorded signal, the order of calculated derivative, and the arithmetic employed in calculations for representation of variables, are characteristic for the system, which performs the self-identification and correction. For this reason, investigation of all prospective cases and determination of the system characteristics, which illustrate all possible states of its operation, is not possible. Therefore, the result of the simulation investigations was creation of programming tools, which enable testing the system performance quality

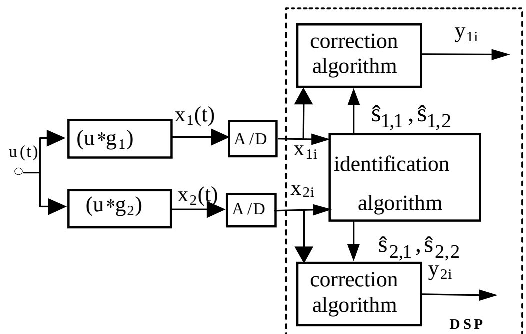

Fig. 1. Block diagram of the system

for the specific operation conditions. Obtained selected results, presented in the form of graphs or contours, are sections of multidimensional characteristics. They allow to investigate quantitatively the influence of changes in the system selected parameters, with other parameters remaining constant, on the system metrological properties.

Due to A/D conversion errors, rounding in arithmetical operations of the executed algorithm and approximations of numerical operations used by the algorithm (e.g. numerical determination of the recorded signal derivative), the final result of correction in one channel differs slightly from the correction results in the second channel. Each of these results is equally probable. Hence the average value of instantaneous results of correction, obtained in both measuring channels for the same time instant, is assumed the final instantaneous value of the corrected signal.

For quantitative evaluation of the correction quality has been introduced the measure Emax, determined as H_∞ norm of the vector of instantaneous values of dynamic error after correction. Also the correction quality index Q, defined as the ratio of the measure of dynamic error, according to the same norm, caused by the faster one of the two analogue channels, to the measure of dynamic error after correction, has been introduced. This index informs how many times the dynamic errors have been reduced.

2. CORRECTION AND IDENTIFICATION METHODS

Two methods for identification of the coefficients of a measuring system analogue part have been proposed. They are intended to be used when measuring any input signal.

The correction procedure, regardless of the identification method used, consists in calculation of the value of an instantaneous correction added to the instantaneous value of sampled signal. Its value is determined as a scalar product of two vectors of dimension conforming to the order of the corrected plant. The first vector contains constant coefficients, which are parameters of the corrector. Their values are results of the identification task. The second vector contains the values of the corresponding order derivatives of recorded signal.

2.1. The difference method

The premise for proposing the first method is the result of theoretical analysis of dynamic properties of the measuring system of proposed structure. A series corrector, of the order according to the order of transducer, has been applied to each measuring channel. It has been proved in former work [1] that the corrector coefficients will be exactly tuned to the transducer model coefficients only, when the output signals in both corrected channels are identical for each time instant.

These signals are also identical with the measured signal, for each time instant. Therefore, the investigated method of identification and correction consists in choosing the correctors' coefficients in order to obtain identical output signals in both channels after completing the correction. The procedure of tuning the correctors' coefficients consists in searching for such their values, for which the output signals matching index attains its minimum.

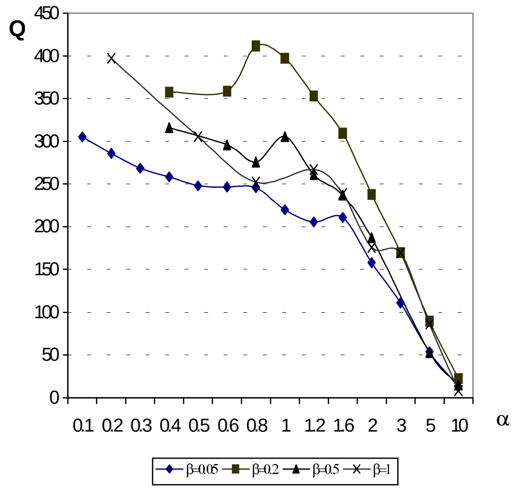

Fig. 2. Correction effectiveness index Q for second-order inertial measurement channels with a double time constant, optimisation of four parameters.

During the simulation the usefulness of basic vector norms H_1, H_2 and H_∞ for determination of the matching index has been tested. These norms are determined for the vector, whose coordinates are the differences in values of output signals in both channels for the instances corresponding with the sampling instances. The investigation has been carried for the sinusoidal signal of frequency 50Hz and amplitude 1V. 24-bit A/D converters of input voltage range ±1V, have been applied in the system. The sampling frequency has been set to 2.5kHz [2].

Time constants for inertial plants in the first channel are denoted $\alpha1$ and $\alpha2$. The values of these coefficients have been determined as the ratio of a given time constant and the period of measured signal. Similarly, time constants for the second channel are denoted $\beta1$ and $\beta2$. The following cases have been taken into consideration in the simulation investigations.

The system employs two channels with double time constants ($\alpha1 = \alpha2=\alpha$ and $\beta1 = \beta2 = \beta$), and only two double parameters of correctors were sought for. In a subsequent case the experiment has been carried out for the system, which contains two channels with double time constants, but four coefficients of correctors have been tuned. The dependence of the correction effectiveness Q versus α at β constant is presented in Fig. 2.

In all investigated cases the correction effectiveness, for the second order inertial channels with double time constant, is very high – above 100, up to the α equal 3. For the plants with double time constant and optimisation of four parameters, when altering in the algorithm the sequence of the optimisation of parameters, different values (differing maximum two times) of the effectiveness have been obtained.

Fig. 3 shows the dependence of Q versus $\alpha2$ for the system containing plants with two different time constants in each channel. The results are pertaining to the case, where time constants in the first channel are fixed ($\alpha1$= 0.2 and $\beta1$=0.6) and in the second one $\alpha2$ changes from 0.2 to 10, for three different values of $\beta2$ (0.05, 0.5, 1). The obtained effectiveness of correction is even five times smaller than in

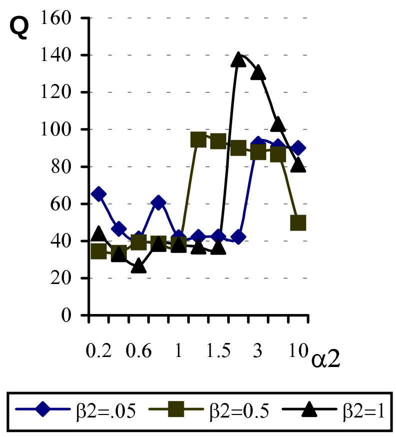

Fig. 3. Correction effectiveness index Q for second-order inertial measurement channels with a with four time constants and optimisation of four parameters, parameters of second channel: $\alpha 1= 0.2$ and $\beta 1=0.6$

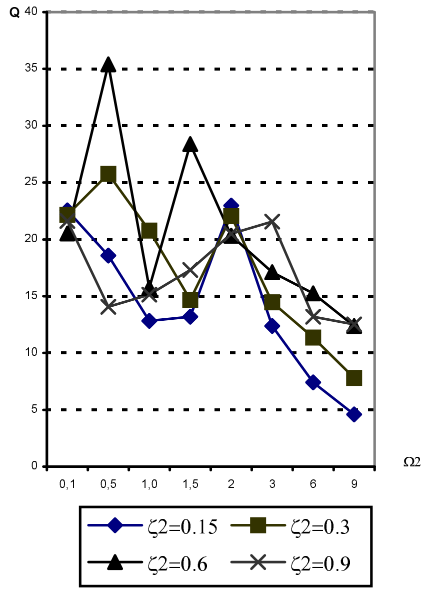

Fig. 4. Correction effectiveness index Q for second-order oscillation measurement channels in function damping $\xi 2$ for various values $\Omega 2$ for one channel; parameters of second channel: $\Omega 1=1$, $\xi 1=0.6$

the case of channels with double time constants, with optimisation of four parameters, but it pertains to the specific case.

Summarising the obtained results of simulation investigations, it can be ascertained, that the effectiveness of the dynamic "blind" correction, obtained for the second order inertial plants is fully satisfactory, despite of numerical errors occurring (the errors of double differentiation). The lack of influence of increased numerical errors on the obtained effectiveness values can result from the principle of the correction method – optimisation on the basis of the difference error.

Computational errors can compensate themselves if they occur simultaneously in both channels. The value of correction effectiveness Q in an obvious way depends on dynamic parameters of the corrected measuring channels. A particular attention should be paid to the high values of effectiveness obtained in the case when the ratio of the time constant to the measured signal period (α) in one channel is large (1.5 ÷5). Thus the second order inertial measuring channel, dynamically "very bad", can be very well corrected over a wide range of changes in time constants.

The correction effectiveness for the second order inertial channels with a double time constant, is very high when optimising two, as well as four parameters.

The correction effectiveness for the second order inertial channels with two time constants is five times smaller than in the case of channels with double time constants and optimisation of four parameters. This may be caused by a smaller accuracy of numerical calculations in the algorithm of parametric optimisation.

Very high values of the correction effectiveness are obtained for channels with large dynamic errors. It has been noted that increasing the sampling frequency increases the "sensitivity" of extreme obtained values of the correction effectiveness Q.

Investigations have been also carried out for the system comprising oscillatory transducers. The dependence of the correction effectiveness on the free oscillations pulsation of the second channel, at the other transducers parameters fixed (free oscillations pulsation of the first channel and damping in the first and second channels), for an example system is shown in Fig. 4. The dimensionless parameter Ω is defined as the ratio of a corresponding free oscillation pulsation to the signal pulsation. In the investigated cases the correction effectiveness for the second order oscillatory channels is at least two times smaller than for the second order inertial plants with two different time constants.

The best accuracy of the optimisation process ensures the Monte Carlo method; its only disadvantage, as compared to other methods available in languages GODYS PC and SIMULINK, is long time of calculations.

The general conclusion from the presented simulation investigations is, that the applied method for correction of dynamic error is effective in all investigated cases, because its effectiveness is greater than unity. The best results of tuning the correctors' coefficients have been obtained using the norm H_1 as the matching index.

In the final assessment of this version of the identification and correction method, it should be stated that it is most suitable to the correction of a formerly recorded signal. The procedure of finding the minimum is complex and time-consuming. For this reason it can be difficult to be implemented on a signal processor.

2.2. Algebraization method

The second method of identification is based solely on the assumption, that both channels are measuring the same input signal. Therefore, it is possible to create a differential equation, which connects the instantaneous values of dynamically uncorrected output signals of transducers with the derivatives of these signals. In such equation, coefficients of the transducer model dynamic behaviour are unknown. Such equation can be created for each sampling instant. Hence a redundant system of algebraic equations results. The number of equations to be selected from the system should equal the number of the model coefficients sought for. A condition number of the equations system has been assumed the criterion of selection. When the condition number is approaching unity, the matrix associated with the system of equations assumes the diagonal form. Therefore, the solution of such a system of equations is the least susceptible to numerical errors.

In order to create these equations it is necessary to determine the derivative of recorded signal. The method of determination of the instantaneous value of a derivative consists in approximation of samples, acquired in a rectangular window of length N, by means of a polynomial of a degree not less than the order of determined derivative. Once this polynomial is analytically differentiated, the value of its derivative is determined for the centre of a window. The obtained result is taken as the instantaneous value of the recorded signal derivative.

On the basis of numerous simulations it was established, that the ramp signal is the best test signal, representing actual conditions of measurement. A correction, using the unit step function as a standard test signal, is an easy case for theoretical analysis. However, it does not represent an actual measured signal, which rate of rise is, as a rule, finite. The unit step test signal can be considered as a limit case of a ramp signal, which rise-time approaches zero. When applying a ramp function as a test signal, it has been proved, that, if the rate-of-rise of this signal majorizes the absolute value of actual (measured) signal, the final errors, after correction of the actual signal, will not be greater than for the ramp signal.

In the investigated system an m-bit (m=24) A/D converter of input voltage range ±Umax has been modelled. Investigations have been carried out for an assumed sampling period Ts=1s. Other time-parameters of the system (e.g. time constants, pulsation of free oscillations, a signal rise-time or frequency) have been determined with respect to this unit and expressed as dimensionless values. This way, the obtained results are general and easy to convert to parameters of real problem, as in design of classical analogue filters for the unity bandwidth. A ramp signal rising from 0V to Umax=10V in time equal 100 sampling periods, has been applied as the test signal.

Example results of simulation for the second order inertial plants [3], when measuring a linearly rising signal are presented in Fig.5. In this example two time constants have been set for one channel TI1=12 and TI2=67. Time constants of the other channel are altered from 1 to 100. Condition numbers for the selected systems of equations attains very large values, even reaching 10000, for large changes of the second channel time constants values (the intensely shaded area). Such a large value of the condition number means high sensitivity of the obtained solution to numerical errors. In these cases, the errors determined as Emax after applying the correction are much greater than 0.1 V (also the intensely shaded area). For such mutual relations of time constants in both channels, the correction effectiveness Q attains small values, about 10 or even less (white area). The reason for wrong condition number of the equation system can be small differences in output signals of analogue channels. The areas where the correction results are unsatisfactory are distinctly overlapping with the areas where the second assumption, which decides on adequate formulation of the problem, is not fulfilled. Such areas of changes in the model coefficients of both channels can be regarded as forbidden

Obtained correction effectiveness exceeds a value of 100 only for small areas, which determine recommended values of time constants. For these cases the condition number attains values about 1000. The correction errors are smaller and attain values at the level of 0.04 V.

Fig. 6 shows the example result obtained for the measuring system comprising two oscillatory II-order plants [4]. For one channel the free oscillations pulsation $\omega 1= 0.3$ and damping $\zeta 1=0.15$ have been set. The areas of changes in the second channel model coefficients ($\omega 2$, $\zeta 2$), for which the correction efficiency, obtained for a ramp signal,

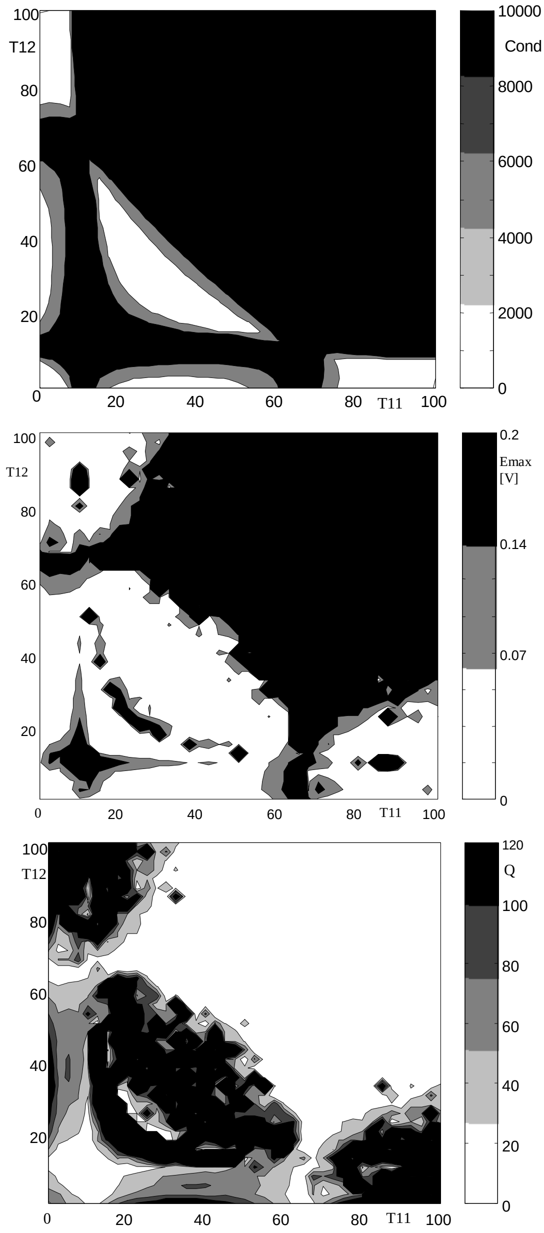

Fig. 5. Condition number **cond**, maximum error **Emax** and correction effectiveness **Q** for double inertial channels vs. time constants of the first channel TI1, TI2 for fixed time constants of the second channel: T21=12, T22=67

exceeds 100, are also small, similarly as for inertial plants.

The condition number of created equations attains very small values, around several tens, as compared to the previous case. It is very advantageous feature, because the solutions of algebraic equations used for identification are very little sensitive to inaccuracy in determination of their coefficients. The index Emax attains the values about 0.001 V for the same test signal as in the previous case.

This feature results from a diversified shape of the response of the two analogue channels.

On the created contours, which show the dependence of the correction effectiveness and condition number on coefficients of the channels models, a distinctive, but small forbidden area is present. It exhibits very large value of the condition number, very small effectiveness and large correction errors. A centre of such area is the point where the coefficients of both channel models are equal. It is the case, for which the second assumption is not fulfilled.

In a subsequent variant of the identification and correction method has been employed the system, which contains two second order plants: an inertial plant, with dual time constant T1=T2=12, and an oscillatory one Fig.7. The premise for investigating the system of such a structure is that the second assumption concerning the correct formulation of the correction problem is inherently fulfilled. The poles of the transmittance of one channel are real and negative. The transmittance of the other channel has a conjugate pair of complex poles. Thus no forbidden areas occur in the domains of coefficients of these channels models. The created system of equations has always the unique solution.

In the investigated cases, the condition number values were of one order of magnitude greater than for two oscillatory channels. An increased value of the condition

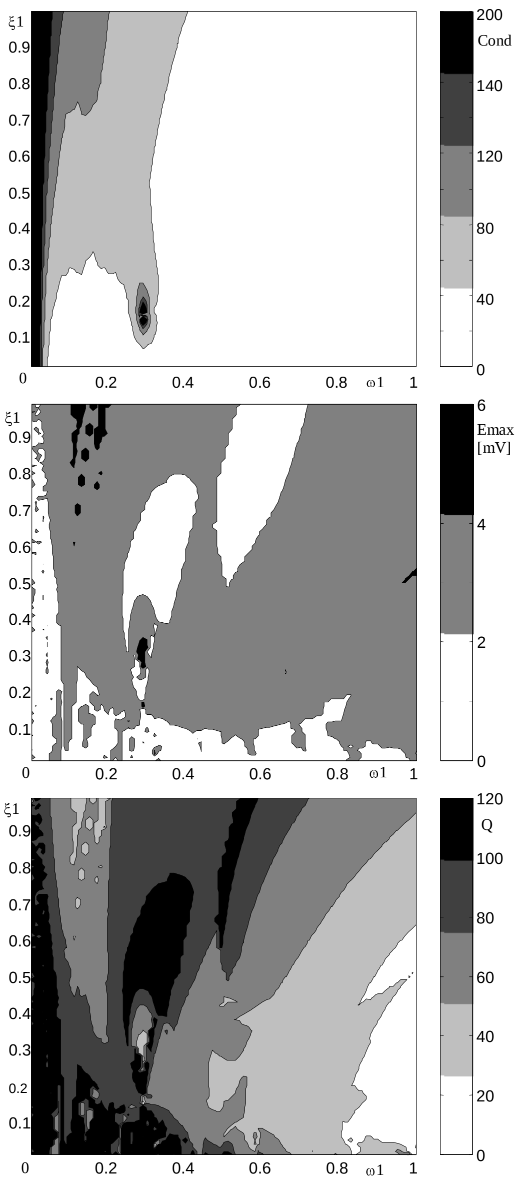

Fig. 6. Condition number **cond**, maximum error **Emax** and correction effectiveness **Q** for double oscillatory channels vs. function of damping ξ1 and pulsation ω1of the first channel; for fixed parameters of the second channel: ω2=0.3, ξ2=0.15

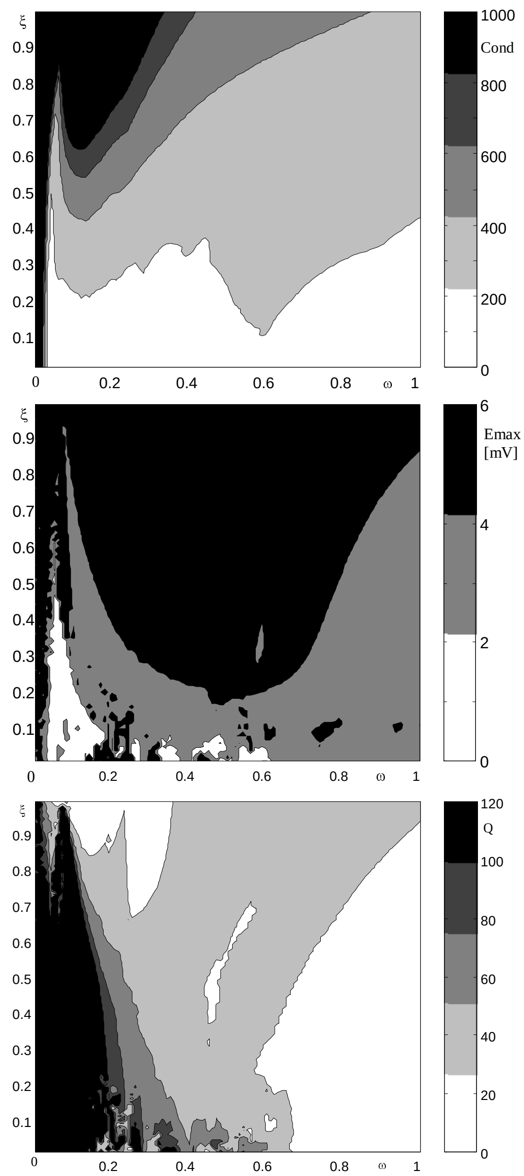

Fig. 7. Condition number **cond**, maximum error **Emax** and correction effectiveness **Q** for mixed channels (inertial and oscillatory) vs. function of damping ξ and pulsation ω of the first channel; for double time constant of the second channel T1=T2=12

number results only from the numerical properties of the selected equations systems. Hence the sensitivity to inaccuracy in determination of the equations coefficients is much greater. Also a certain area occurs in the domain of the second channel coefficients, for which the correction effectiveness exceeds 100 and condition number attains values close to 100. For this area the maximum correction error Emax, attains two times greater values than for the system, which comprises two oscillatory plants.

From the presented examples it follows that, the best results of correction can be obtained when using oscillatory plants. In this case the errors after correction are the smallest. Also the smallest is the susceptibility of the obtained results to numerical errors. However, the forbidden areas occur in the domain of changes in the values of the coefficients of these plant models. When designing a real measuring system it should be ensured that the expected range of changes of these coefficients must not overlap the forbidden areas.

Other combinations of the transducers types (oscillatory with inertial or two inertial) are acceptable, but also in a limited area of permissible changes of their parameters. When applying these pairs of transducers, the correction results can contain greater errors.

Similarly as in the previous method, the resolution of A/D converters must increase at lest to 22 bits. Use of A/D converters of lower resolution does not ensure satisfactory results of self-identification and correction of dynamic error caused by the second order plants.

3. CONCLUDING REMARKS

Two contradictory goals are associated with the identification task. If the system is required to perform the correction with high accuracy then time must be provided for the precise identification to be carried out. If the correction result has to be obtained quickly, its low accuracy has to be accepted in the initial phase after turning-on the system. Improving the correction accuracy is possible in a longer term.

The effectiveness of correction depends mainly on time-rate of change of the measured signal with respect to the dynamic features of measuring channels. If dynamic errors, without the correction, in both channels are large, then applying one of the presented methods will significantly reduce these errors. The simulation investigations shown that using two inexpensive transducers, of not particularly good dynamic performance, for measuring time-varying signals it is possible to obtain the measurement results with very small dynamic error. It is sometimes impossible to obtain such a small value of the dynamic error, even using very fast and expensive measuring transducers.

In case when at least one channel of good dynamic features is used, the dynamic features of the whole system will improve, however the improvement is not significant.

The scope of practical applicability of the "blind" correction method can be determined by the limit values of dynamic features of both channels, which ensure the acceptable effectiveness of correction. Intervals of the permissible changes in the dynamic features of transducers can be mutually supplementary, depending on the identification method applied.

The proposed measuring system is distinguished by the very small number (limited to the necessary minimum) of analogue elements. The very good dynamic performance of the system results from the applied methods and numerical algorithms, not from dynamic features of analogue input circuits. Such a system is flexible and easy to match to specific measuring tasks. The matching consists mainly in the alterations in software, not in restructuring the hardware.

The results obtained from simulation investigations concerning the second order inertial channels are the premise for formulation of next investigation task. The task of correction of the second order inertial plant, by means of the matched corrector, also of the second order, increases the dimension of the identification task because of the increased number of the parameters sought for. A reduction of the task dimension by using the first order correctors can be proposed. The proposed structure does not yield unique analytical solution. It is however interesting to investigate the problem if the investigated method of self-identification has a unique solution in numerical terms and the obtained correction results are acceptable.

Simulation investigations are the effective tool for determining the conditions of practical applicability of the dynamic error "blind" correction method for the specific measuring system. The obtained results are valuable indication for construction of a laboratory set-up, which enable experimental verification of the investigated correction methods. A good conformity of simulation and experimental results has been obtained for the first order plants using the method of algebraization. Unfortunately, the already used laboratory set-up has been supplied with 12-bit A/D converters. Thus a new one have to be constructed, using the converters of much higher resolution.

REFERENCES

[1] J. Nabielec, "An Outlook on the DSP Dynamic Error Blind Correction of the Analog Part of the Measurement Channel", *16th IEEE Instrum. Meas Techn.y Conf.*, May 24-26,1999, Venice, Italy, vol. 2, pp. 709 – 712.

[2] J. Nalepa „The 'Blind' Dynamic Error Correction Method – Simulation Study For the First-and Second-Order Measurement Channel" , *Meas. Science Review – Journal of Institute of Meas. Science* Slovak Academy of Sciences, Bratislava 2002, vol. 2, Sec. 1 pp. 33-42

[3] J. Nabielec, "'Blind' correction of the measurement dynamic error-simulation investigation of the second-order system". Proc. 12 IMEKO TC4 Inter. Symp., Part 1, Sept. 25-27, 2002, Zagreb, Croatia, pp.205-208.

[4] J. Nabielec, "'Blind' correction of the measurement dynamic error-Simulation Investigations of the oscillatory system", *Proce, 8 IEEE Inter. Conf. Methods and Models in Automation and Robotics,*. Szczecin, Poland, 2-5 Sept. 2002 pp. 1287-1290.

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