METROLOGY AND MEASUREMENT SYSTEMS
Index 330930, ISSN 0860-8229
www.metrology.pg.gda.pl

FAST FILTRATION METHOD FOR STATIC AUTOMATIC CATCHWEIGHING INSTRUMENTS USING A NONSTATIONARY FILTER

Przemysław Pietrzak

West Pomeranian University of Technology, Faculty of Electrical Engineering, Institute of Control Engineering, 26 Kwietnia 10, 71-126 Szczecin, Poland (✉ pietrzak@zut.edu.pl, +48 91 449 5428*)*

Abstract

The filtration process of measurement signals which occur in industrial weighing systems, decides upon the accuracy of measurement and the duration time of the weighing process alike. The filtration problem gains great meaning in automatic catchweighing instruments whose rate of operation, in case of static weighing, can reach even a hundred weighings per minute. Since output signals from the catchweighing instruments, due to mechanical vibrations and the noise from the environment, are always contaminated with noise, filtration methods which ensure strong attenuation of vibrations and fast transmission of the signal's constant component, should be applied. In this case, filtration methods involving nonstationary filters turn out to be a good solution.
In the paper the filtration method using a discrete nonstationary filter has been discussed. The results of the numerical experiment which was carried out based on the measurement signals recorded on the catchweigher operating in the industrial environment, have been presented. The results obtained using the nonstationary filter have been compared with its stationary equivalent.

Keywords: mass measurement, static automatic weighing, filtration and signal processing, nonstationary filter, time-varying filter.

1. Basic principles of static automatic weighing

According to the OIML R51-1 recommendation an automatic catchweighing instrument (or catchweigher) weighs pre-assembled discrete loads or single loads of loose material [1]. Catchweighers are mostly a part of production lines and they are installed as part of a load transport system. Transported products are consecutively placed on a scale pan and weighed without any intervention of an operator, as schematically shown in Fig. 1.

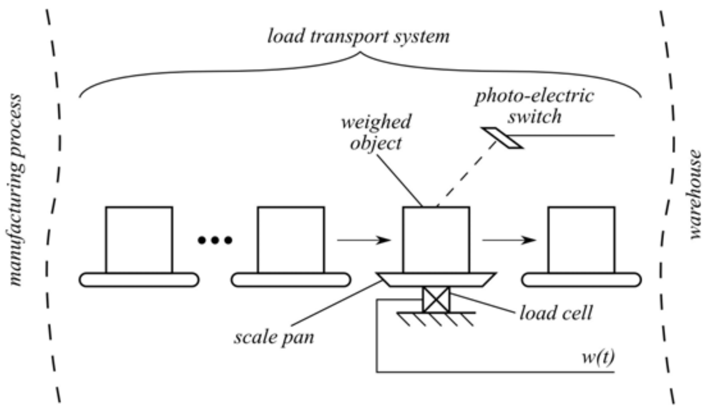

Fig. 1. Static automatic catchweighing instrument.

If the production line after the catchweigher includes a device that sub-divides prepackages of different mass into two or more subgroups according to the measured mass value, then the whole system, *i.e.* the catchweigher and the device, is called the checkweigher which is a more popular name, more often used in the literature.

During static weighing the load transport system should be stopped and the instrument should be in a stable equilibrium, *i.e.* a condition such that the indication of the instrument shows no more than two adjacent values with one of them being the final weight value. The recommendation [1] does not contain a strict guidance for a determination of a stable equilibrium, hence depending on the implementation, particular methods can differ. The criterion used in the paper is based on two parameters: Δt and Δr, called the standstill time and the standstill range respectively. It is assumed that the instrument has reached a stable equilibrium when the condition (1) is satisfied:

$$\left| w(t_k) - w(t) \right| \leq \Delta r \tag{1}$$

for a time period $t - t_k$ greater or equal to the standstill time value:

$$t - t_k \geq \Delta t\,, \tag{2}$$

where $w(t)$ means the indication of the instrument and the time point t_k is the past point in which the absolute difference (1) in relation to the previous indication $w(t_{k\text{-}1})$ has exceeded the standstill range value Δr, what has been shown in Fig. 2.

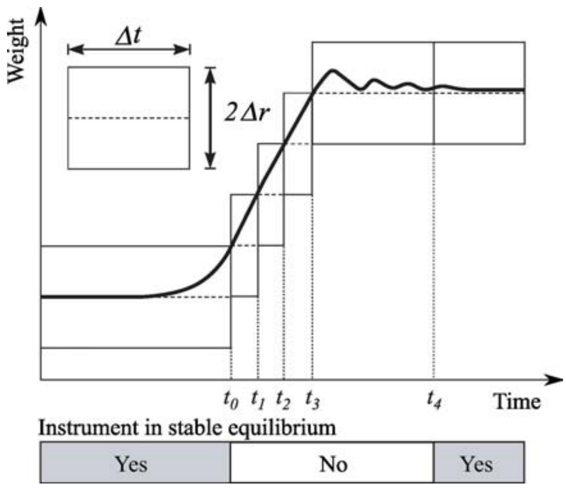

Fig. 2. Criterion for determining the stable equilibrium.

The duration time of a single measurement t_i is the time counted from the beginning of the weighing, *i.e.* from the moment when the product has been put on the scale pan up to a moment in which the conditions (1) and (2) have been satisfied. Thus the length of t_i is related to values of parameters Δt and Δr but also indirectly to the type of the filtration method used. It is because the indication of the instrument $w(t)$ derives from the transducer's signal converted to a digital form and filtered afterwards.

Despite the fact that static catchweighers are in general slower than dynamic ones, their rate of operation can reach even a hundred weighings per minute. With such speed of weighing a constant component of the measured signal is changing rapidly each time when the product is put on and then when it leaves the scale pan after the weighing. Fig. 3 shows changes of the signal's constant component on the example of measured signals recorded on the catchweigher operating in an industrial environment.

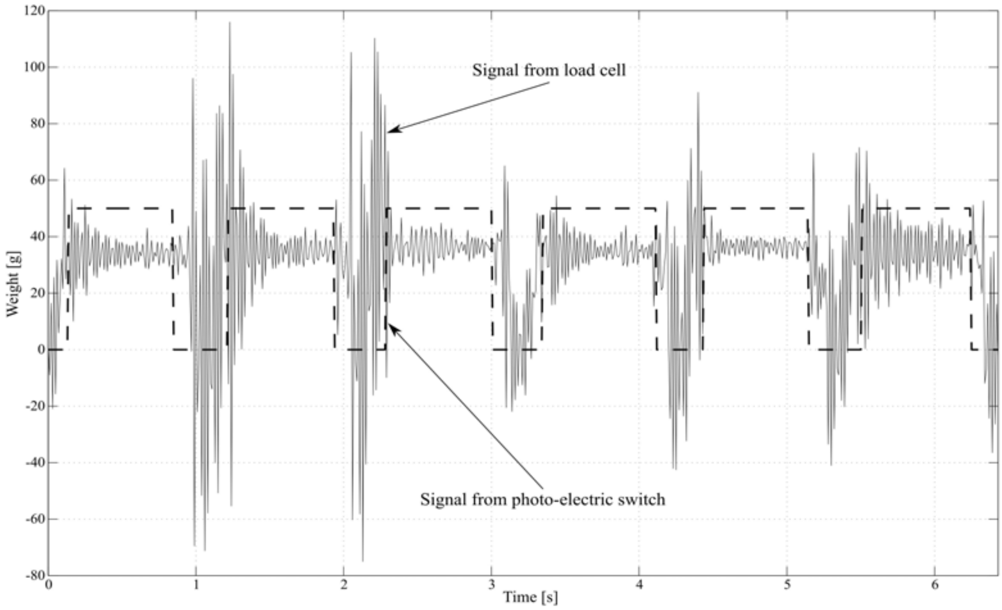

Fig. 3. Time behavior of the catchweigher's measured signals during a weighing process.

Rapid changes of the constant component cause the transient response of the filter to play a dominant role. The duration time of the transient response is inversely proportional to the passband of the filter, *i.e.* the wider the passband of the filter the shorter its transient response. Nevertheless, the passband of the filter is usually tuned in order to assure specific requirements concerning the noise attenuation in a steady state, that is after the expiration of the transient response. For that reason, in fast weighing processes when the noise is in the lower frequency range, classic filters force the user to make a compromise between the duration time of the measurement and its accuracy. Nonstationary filters, which are discussed in the further part of the paper seem to be free from this disadvantage.

It is worth to mention that in case of static weighing, which performs in industrial processes similar to the one presented in Fig. 3, the state in which a weighed object is standing still on the scale pan does not last arbitrarily long – it is directly related to the throughput of the production line. In such situations the load cell's signal cannot reach a stable equilibrium state without using a special instrument, *e.g.* a filter. Due to the fact that this problem is also important in case of dynamic weighing, some methods like Kalman filtering or system identification techniques available for dynamic weighing [2-5] could be also adopted to industrial static weighing applications. Another interesting solution from the domain of filtration methods [6] is based on the discrete FIR filter whose magnitude response is adjusted through down-sampling of the measured data.

2. Discrete nonstationary filter

The idea of varying parameters in continuous-time systems has been developing since the second half of the 20th century. In [7] Zadeh proposed the concept of a general transfer function for discussing continuous time-varying systems. The basic properties of the continuous linear time-varying systems realizable as a differential equation have been investigated in [8]. Nonstationarity of the filter can be achieved by changing in time the values of coefficients describing the linear differential equation of a system [9]. In [10] the author discusses a continuous time-varying phase-compensated Chebyshev filter and suggests its application to filtration of rectangular signals with additive noise. A time-varying filter has been also proposed to compensate the dynamic response of the load cell in [11] where authors have assumed that both the influence of the transient component and measurement noise can be minimized using a time-varying low-pass filter. In [12], time-varying filtration has been applied during the zeroing or weighing stage of the automatic gravimetric filling instrument's working cycle in order to increase its rate of operation.

The relationship determining the change in time of the coefficients is called a varying function of the system. An equation of the discrete nonstationary filter has been derived from the equation of its continuous-time equivalent. Considering the lack of overshoot in the step response, a critically damped low-pass filter has been selected. In analogue technique the filter can be realized as a series connection of first-order elements. Taking into account spectral assumptions concerning the 3 dB decrease of the frequency response module by the cut-off frequency ω_c, the equation of a single element takes the form:

$$\frac{\alpha_n}{\omega_c}\frac{dy(t)}{dt} + y(t) = u(t), \tag{3}$$

where: $\alpha_n = \sqrt{\sqrt[n]{2} - 1}$, n means the filter order, $y(t)$ represents the output signal and $u(t)$ the input signal. A difference equation corresponding to equation (3) can be obtained using numerical integration according to the trapezoidal rule, similarly as in the case of bilinear transform [13]. As a result, after all necessary calculations, one can obtain the difference equation (4):

$$y(k) + (2a - 1)y(k-1) = a(u(k) + u(k-1)), \text{ for } k = 0, \Delta, 2\Delta, 3\Delta, \ldots, \tag{4}$$

where:

$$a = \frac{\omega_c}{\omega_c + \frac{2\alpha_n}{\Delta}} \tag{5}$$

and Δ is the integration step which is also equal to the sampling period. The equation (4) can be directly implemented in logic circuits in so-called Direct-Form I [13] or as a numerical routine in a microprocessor system. Filters of higher order can be naturally obtained by connecting systems (4) in series.

2.1. Varying function and selection of its parameters

The varying function applied in the filter is based on changing in time the value of the cut-off frequency ω_c from the expression (5) defined as follows:

$$\widetilde{\omega}_c(k) = \omega_c + (\omega_0 - \omega_c)e^{-\left(\frac{k}{\kappa}\right)^2}. \tag{6}$$

Exemplary shapes of the function (6) for three different values of the parameter κ have been shown in Fig. 4. An initial instant for a varying procedure is always the moment when a weighed product is put on the scale pan. At that time, that is at the beginning of the measurement, the cut-off frequency of the filter ω_c is changing from a certain initial value ω_0 down to the stationary value ω_c at a speed rate depending on the value of the parameter κ. For time k greater or equal to approximately 3κ the value of the function (6) is almost equal to ω_c and the filter acts like a stationary critically-damped low-pass filter. The varying function defined according to the expression (6) allows to widen the passband of the filter during the initial stage of the measurement and keeping the required level of noise attenuation at the final stage.

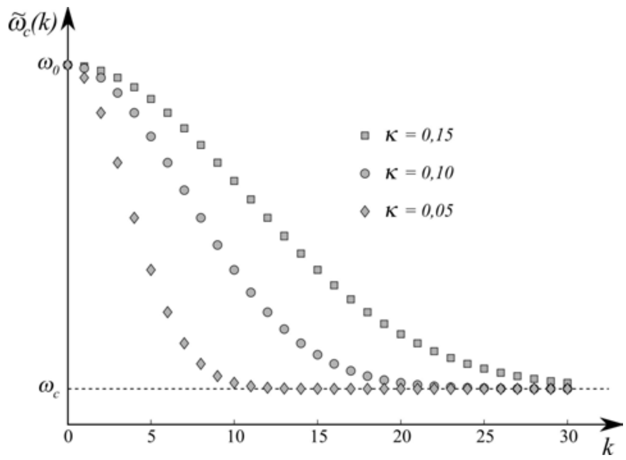

Fig. 4. Exemplary shapes of the function (6).

In this way the filtration process, carried out using the filter (4) with the varying function defined through expressions (5) and (6), becomes a cyclic procedure and follows a pre-determined scheme. The procedure is determined by the three parameters ω_c, ω_0 and κ and their values should be carefully chosen in order to increase the rate of operation of the checkweigher and maintain the measurement's accuracy at the same time.

The selection of the parameters has been performed through repeated filtration of the recorded signal containing a series of weighings. For every weighing in the registered signal the duration time t_i, defined as in Section 1, and the weighing error e_i have been calculated. During this numerical experiment the parameters of the function (6) were being changed using the grid search method in the rectangular area $\Omega_0 \times \mathrm{K}$ defined as follows:

$$\Omega_0 = \left\{ \omega_m \in \langle \omega_a, \omega_b \rangle : \quad \omega_m = \frac{m\omega_k + \omega_p(100-m)}{100} \right\}, \text{ for } m = 0,\ldots,100 \tag{7}$$

and

$$\mathrm{K} = \left\{ \kappa_n \in \langle \kappa_a, \kappa_b \rangle : \quad \kappa_n = \frac{n\kappa_k + \kappa_p(100-n)}{100} \right\}, \text{ for } n = 0,\ldots,100 \tag{8}$$

by certain values: ω_a, ω_b, κ_a, κ_b. The parameter ω_c in separate experiments had a constant value. Hereby for each node $(\omega_0, \kappa) \in \Omega_0 \times \mathrm{K}$ of the grid, a sequence of time values t_i and a sequence of error values e_i have been assigned. The experiment has been carried out for the values of the parameter ω_c from the set $\Omega_c = 2\Pi \cdot \{1 \cdot 10^{-k}, 2 \cdot 10^{-k}, 5 \cdot 10^{-k}\}$, for $k = 1,2,3$ and for systems of the 1st to 6th order.

3. Results of the experiment

The discussed results have been worked out based on signals recorded on the catchweigher operating in an industrial environment with a nominal load equal to 150 g. The average mass of the weighed product was 35 g and the rate of operation was approximately 60 weighings per minute. During the registration process the signal from the load cell and the signal from the photo-electric switch have been acquired. Both signals have been sampled at a sampling frequency equal to 100 Hz. The photo-electric switch enables the detection of the condition in which the weighted product is being put on or when it is being taken off the scale pan. These conditions correspond to the rising and falling edge of the photo-electric switch signal respectively, what can be seen in Figs 3 and 6. Altogether the complete registration includes the weighing process of 200 products. At the end, each of the products has been re-weighed on a reference scale in order to determine the values of weighing errors. The errors have been calculated using reference measurements according to the expression (9):

$$e_i = \hat{w}_i - w_i, \tag{9}$$

where: $\hat{w}_i$ is the measurement's result obtained in the experiment and w_i is the result from the reference scale.

Based on the registered signals, using the method described in Section 2 by $\omega_a = \omega_c$, $\omega_b = 100\Pi$, $\kappa_a = 0.01$, $\kappa_b = 0.5$, the numerical experiment has been carried out. The duration time t_i of the *i*-th weighing has been determined with the standstill time value Δt equal to 100 ms and the standstill range value Δr equal to 0.05 g. For every node $(\omega_0, \kappa) \in \Omega_0 \times \mathrm{K}$ of the grid a 200-element sequence of t_i and e_i has been obtained, and to each sequence its mean value (*i.e.* $\bar{t}$, $\bar{e}$) and its standard deviation (*i.e.* σ_t, σ_e) have been assigned. As a result, for nine different values of the parameter $\omega_c \in \Omega_c$ and for six different system orders, a set of 54 surfaces, spanned on the grid $\Omega_0 \times \mathrm{K}$, has been obtained. As the optimal solution a set of three parameters of the function (6) and the system order, minimizing the mean duration time of the weighing $\bar{t}$ subject to the mean value of the errors $\bar{e}$, which should not exceed 0.05 g, and standard deviation of errors σ_e, which should not exceed 0.168 g, according to the requirements for instrument in accuracy class XIII(1) [1], has been chosen.

Among all obtained surfaces the best solution has been found by ω_c = 4Π·10^{-3} rad/s for the second-order system. The surface which contains the optimal point, is shown in Fig. 5.

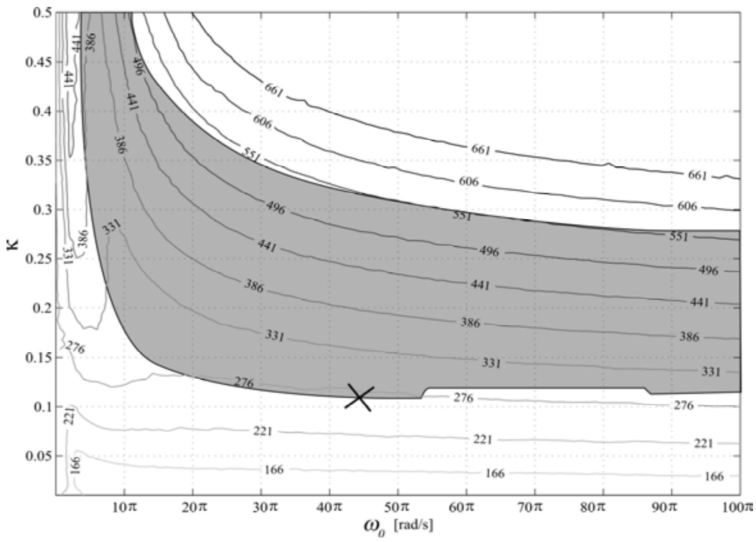

Fig. 5. Contour lines of the function $\bar{t} = f(\omega_0, \kappa)$ and the area restricting standard deviation of the errors σ_e to 0.168 g value, for a second-order system, by ω_c = 4Π·10^{-3} rad/s.

The optimal point is marked with the black cross and the grey strip denotes an area where for each point belonging to it the standard deviation of measurement errors is less or equal to 0.168 g. It can be noticed that the optimal point is located at the edge of the area and the surface of mean duration time of the weighing $\bar{t}$ is decreasing smoothly in the direction from the upper-right to the lower-left corner. Although the value of the mean time $\bar{t}$ is constantly falling when the value of parameter κ becomes smaller, in this case the filter output is settled far away from the final weight value. For points located above the upper bound of the stripe the filter output reaches the level around the final weight value very fast, however, the response of the filter is characterized by significant oscillations.

A similar experiment has been carried out for the discrete stationary critically damped low-pass filter but in this case only for two parameters, *i.e.* system order and the cut-off frequency ω_c. The optimal points for both experiments have been given in Table 1.

Table 1. The results of numerical experiments for stationary and nonstationary filters.

Filter type	$\bar{t}$ **[ms]**	σ_t **[ms]**	$\bar{e}$ **[g]**	σ_e **[g]**
Stationary, 4th order, ω_c=6,8Π	333	46	-0.015	0.06
Nonstationary, 2nd order, ω_c=4Π·10^{-3}, ω_0=44,4Π, κ=0,11	269	22	0	0.095

The filtration results using the filters from Table 1 have been shown in Fig. 6. The varying procedure is started at each rising edge of the photo-electric switch signal. A high level of the logic signals placed in the lower part of the figure corresponds to achieving the stable equilibrium condition for the standstill time Δt equal to 100 ms and the standstill range value Δr equal to 0.05 g. At the beginning of the weighing process both filters start with zero initial conditions. However, after the first weighing each next measurement carried out with the nonstationary filter begins from a value close to the value obtained during the previous measurement. It is because the cut-off frequency of the nonstationary filter after approximately 0.33 s reaches its stationary, still a very low value. This behavior does not influence the accuracy of the measurement, because the parameters of the function (6) have been chosen in a way to guarantee reaching the final weight value for the initial conditions from a wide range around the final weight value.

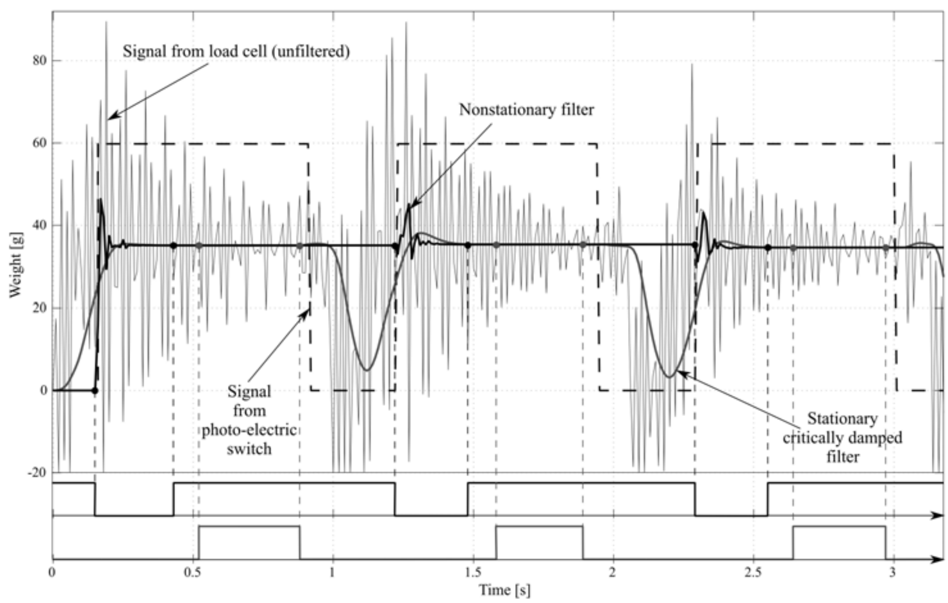

Fig. 6. Comparison of the filtration results.

4. Conclusions

The filtration method discussed in the paper is characterized by a shorter mean value of the duration time of the weighing $\bar{t}$ comparing to the stationary critically damped low-pass filter. In both cases the accuracy of the measurement was comparable. It is worth to underline that besides the lower value of $\bar{t}$ the obtained result for the nonstationary filter is also characterized by a lower value of the standard deviation of the duration time of the weighings σ_t. In this case, to guarantee achieving a stable equilibrium condition for each weighing from the series of measurements, it is needed to extend the time devoted to the measurement even by $3\sigma_t$ – on the understanding that the random variable t_i has the normal distribution.

Considering the inverse problem, it can be noticed that by extension of the value $\bar{t}$ the measurement's accuracy can be increased. It can be achieved by moving the optimal point from the edge of the grey strip from Fig. 5 towards the minimum σ_t value. In this case, both filters would have a comparable value of the mean duration time of the weighing, however, the nonstationary filter would be characterized by an increased accuracy.

Acknowledgements

This scientific work has being financed from a science fund in the years 2008-2010 as research project # N515 298735.

References

[1] International Recommendation OIML R51-1. Automatic catchweighing instruments. Part1: Metrological and technical requirements – Test. 2006.

[2] M. Niedźwiedzki, A. Wasilewski: "Application of adaptive filtering to dynamic weighing of vehicles". *Control Eng. Practice*, vol. 4, no. 5, 1996, pp. 635-644.

[3] M. Niedźwiedzki: *Identification of time-varying processes*. J. Wiley & Sons Ltd., 2000.

[4] P. Burnos, J. Gajda, P. Piwowar, R. Sroka, M. Stencel, T. Żegleń: "Accurate weighing of moving vehicles". *Metrol. Meas. Syst.*, vol. XIV, no. 4, 2007, pp. 507-516.

[5] M. Halimic, W. Balachandran: "Kalman filter for dynamic weighing system". *IEEE Symposium on Industral Electronics*, Athens, July 1995, pp. 787-791.

[6] R. Tasaki, T. Yamazaki, H. Ohnishi, M. Kobayashi, S. Kurosu: "Continuous weighing on a multi-stage conveyor belt with FIR filter". *Measurement,* vol. 40, no. 7-8, August-October 2007, pp. 791-796.

[7] L.A. Zadeh: "Frequency analysis of variable networks". *Proc. IRE,* vol. 38, 1950, pp. 291-299.

[8] H. D'Angelo: *Linear time-varying systems*. Allyn and Bacon, Boston, 1970.

[9] R. Kaszyński: "The properties of parametric filter of signal constant component". *Metrol. Meas. Syst.*, vol. V, no. 4, 1998, pp. 303-313.

[10] J. Piskorowski: "A new concept of phase-compensated continuous-time Chebyshev filters". *Signal Processing*, vol. 88, no. 3, March 2008, pp. 437-447.

[11] J. Piskorowski, T. Barciński: "Dynamic compensation of load cell response: A time-varying approach". *Mechanical Systems and Signal Processing*, vol. 22, no. 7, October 2008, pp. 1696-1704.

[12] P. Pietrzak: "The conception of fast filtration of weighing signals using parametric filters". *PAK*, vol. 53, no. 9, 2007, pp. 134-137. (in Polish)

[13] A.V. Oppenheim, R.W. Schafer: *Digital signal processing*. Prentice-Hall, Inc.: Englewood Cliffs, NJ, 1975.