Quasi-optimal processing simulation of ultrasonic signals

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Abstract. Magnetostrictive level gauges are widely used for measuring the level of bulk material and liquid medium including petroleum products, which determines the relevance of the measurement techniques and level gauges design improvement examination. The research objective is to modify the optimal signal processing classical methods for measuring the time intervals in the magnetostrictive level gauges by using the digital devices with limited computational resources. The article deals with the modification problems of the digital signal processing optimal algorithms providing the real time measuring devices operation. For addressing the challenges, the methods of numerical simulation and statistical processing of ultrasonic signals are used. Digital signal processing quasi-optimal algorithms for calculating the time intervals based on the use of cross-correlation functions leading to the operations number reduction, are described. The represented results can be applied in the level measurement and medicine for electrocardiograms analysis.

1. Introduction

The devices measuring the petroleum products parameters (volume, level, temperature, density) of the tanks system distributed over a large area, as well as the devices transmitting the information on the measured parameters via radio channel are widely used in industry [1]. Petroleum products level measurement by electronic methods is based on the measured parameter relationship with any physical quantity (conductivity, inductance, capacity) or electrical signal parameter (amplitude, frequency, phase, time shift). When measuring the petroleum products level by the magnetostrictive level gauge, the information on the level is contained in the time interval between the pulses at the piezoelectric transducer output [2]. In radiolocation, radionavigation and communications, the optimal signal processing theory [3] allowing to obtain the best result of the parameters detection, differentiation, estimation, and signals filtering, resolution, identification problems solving by the criterion of the signal-to-noise ratio in the linear systems is used.

The research objective is to modify the classical methods of the optimal signal processing for measuring the time intervals, as well as to simulate quasi-optimal processing and optimize its parameters.

2. Problem statement

The information signal at the piezoelectric transducer output of the magnetostrictive level gauge is pulse in nature. The traditional method of measuring the time interval between the magnetostrictive signals is to measure the time interval between the rectangular pulses obtained when magnetostrictive signals flow through the threshold device (the comparator with the specified threshold). Furthermore,

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magnetostrictive signals form changing and interference introduce errors into the calculated level value or do not allow to calculate the level.

Let us consider the possibilities of modifying the optimal signal processing classical methods while using the practical digital algorithms for measuring the time intervals in the magnetostrictive level gauges. By simulating the quasi-optimal processing systems, their statistical parameters are estimated.

3. Theory

Autonomous magnetostrictive level gauges used for level measuring contain a signal transmission line (metal rod or wire) threaded through the float located on the liquid surface, a piezoelectric receiver, comparator, computer, radio modem, self-contained sensor module, power supply and antenna [3]. Figure 1 shows the flow chart of the autonomous magnetostrictive level gauge.

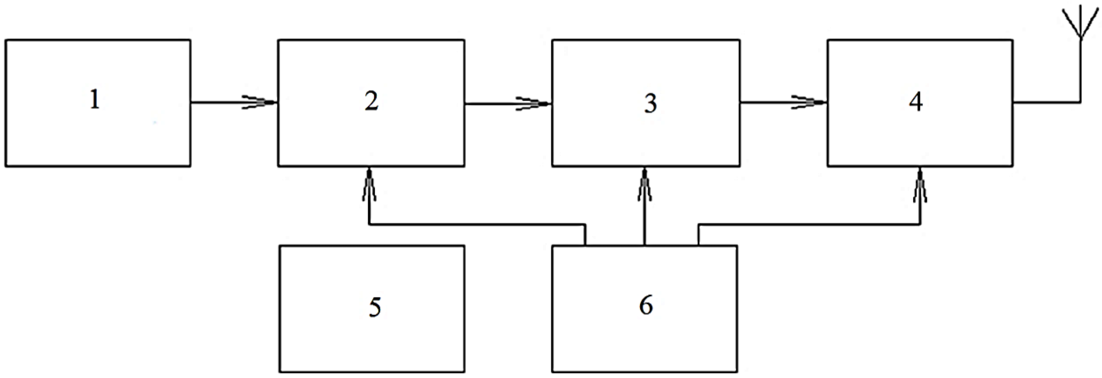

Figure 1. The flow chart of the magnetostrictive level gauge: 1 is piezo receiver; 2 is comparator; 3 is computer; 4 is radio modem; 5 is self-contained sensor module; 6 is power supply.

The total length *L* of the signal transmission line is calculated [4] according to the following formula (1):

$$L = L_1 + L_2 \tag{1}$$

where L_1 is the length of the submerged section of the signal transmission line, L_2 is the length of the upper part of the signal transmission line.

In the signal transmission lineat the liquid boundary at the moment t_1, the ultrasonic signal is being formed due to the magnetostrictive effect during the interaction of the permanent magnet magnetic field and self-contained sensor module coil pulsed magnetic field with the signal transmission line. The ultrasonic wave travels upwards in the signal transmission lineover the distance L_2 where it is received by the piezo receiver at the time t_2. Furthermore, the ultrasonic wave travels downwards in the signal transmission linefrom the liquid boundary to the distance L_1, where it reaches the signal transmission linelower end at the time t_3, is reflected and travels upwards over the distance$L$, where it is received by the piezoelectric receiver at the time t_4.

The time τ_2 of the ultrasonic wave propagation along the signal transmission line from the liquid surface upwards along the short path is calculated by the formula (2):

$$\tau_2 = t_2 - t_1 \tag{2}$$

The time τ_1 (3) of the ultrasonic wave propagation along the signal transmission line from the liquid surface to the signal transmission line lower end is:

$$\tau_1 = (t_3 - t_1) \tag{3}$$

The time τ_3 (4) of the ultrasonic wave propagation along the signal transmission line from the liquid surface to the signal transmission line upper part along the long path is:

$$\tau_3 = t_4 - t_1 = 2(t_3 - t_1) + t_2 - t_1 = 2\tau_1 + \tau_2 \tag{4}$$

Therefore, the measured time interval τ_m (5) between the pulses received at the piezoelectric receiver input along the short and long paths is calculated by the formula:

$$\tau_m = \tau_3 - \tau_2 = 2\tau_1 \quad (5)$$

The ultrasonic pulses received by the piezo receiver are transmitted to the comparator (figure 1) forming the rectangular pulses used for measuring the time interval and calculating the level.
Let us assume that the signal transmission line is acoustically homogeneous and liquid temperature is constant, subsequently, if the ultrasound is transmitted twicethrough the signal transmission line submerged section, the ultrasound delay (6) is calculated by the following equation:

$$\tau_m = 2 \cdot L_1 / V_1 \quad (6)$$

where V_1 is the sound speed in the signal transmission line lower section.
The calculated value (7) of the liquid level is

$$L_1 = \frac{\tau_m}{2} \cdot V_1 \quad (7)$$

If the signal transmission linebottom end does not touch the tank bottom, the calculated value of the liquid level L_1will not correspond to the actual value. However, there are methods of calculating the actual level value [4].
The signals in the magnetostrictive level gauge are shown in figure 2.

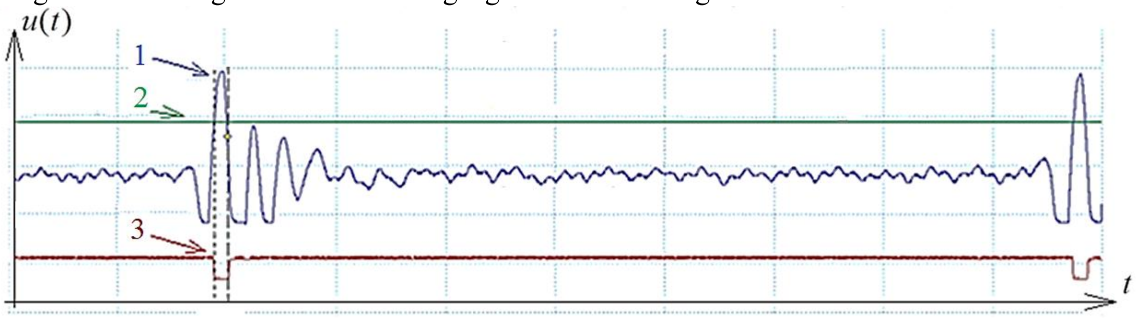

Figure 2. Signals in magnetostrictive level gauge: 1 is piezo receiver output signal; 2 is comparator threshold level; 3 is comparator output signal.

As the operation principle of the magnetostrictive level gauge suggests, the comparator output pulses (Figure 2) are the basis for the calculator operation, therefore, they determine the level gaugeaccuracy characteristics. In practice, it was found out that the piezoelectric receiver output signal width and shape depend on the temperature, voltage and other uncontrolled factors causing the time interval errors. There also might besituations when measuring the level is impossible, if one or both measuring pulses at the piezoelectric receiver output do not reach the threshold, or vice versa, the threshold is highly exceeded by false or noise pulses.

The optimal signal processing theory [4-6], according to which a receiver input *x(t)* is exposed to the sum of the useful signal *u(t)* and noise *n(t)* (or only noise *n(t)*), the optimal receiver calculates the correlation integral *z* and then uses the obtained value for making a decision, is known. If the signal parameters are known, and noise is a Gaussian random process with a uniform spectral density (white noise), the correlation integral (8) has the following form:

$$z = \int_0^T x(t) \cdot u(t) dt \quad (8)$$

where *T* is the signal duration.

In fact, the correlation integral is identified using the correlator or a matched filter. The correlator contains a reference signal generator, a multiplier, and an integrator. The multiplier receives the input *x(t)* and reference (desired, expected) *u(t)* signals. The product of the input and reference signals values is integrated until the end of the expected signal [7, 8]. The matched filter is a passive filter with a pulse response characteristic equal to the mirrored reference signal. The common feature of the correlator and matched filter is the equality (with the accuracy of the constant multiplier) of the output voltages at the time T, as well as the fact that the matched filter and correlator maximize the signal-to-noise ratio at their output. The difference is that the correlator is a device with time-varying parameters, while the matched filter is a device with constant parameters, therefore the matched filter is invariant regarding the signal delay and its initial phase, and the correlator is not invariant [9].

If a signal has several measured or unmeasured parameters, the optimal receiver structure changes, but its main body still contains the matched filter or correlator.

For the magnetostrictive level gauge, optimal processing can be implemented by the correlation scheme using the microcontroller, having previously recorded in the microcontroller memory the reference signal N samples received through the sampling interval T_s ($T = N \cdot T_s$). It should be noted that the reference signal implies the signal obtained in the lower position of the self-contained sensor module in the absence of interference at the piezoelectric transducer output [10].

The microcontroller integration (9-10) operation is implemented by summing the samples products of the input and reference signals:

$$z(kT_s) = \sum_{n=1}^{N} x(nT_s) \cdot u[(n-k)T_s] \tag{9}$$

$$T_s \le \frac{1}{2 \cdot f_{\max}} \tag{10}$$

where $f_{\max}$ is the maximum frequency in the magnetostrictive signal spectrum.

The algorithm of optimal correlation processing of digitized ultrasonic signals when using the microcontroller in the measuring device is to calculate the correlation function by summing the ultrasonic signal samples products with the support function samples and to calculate the time interval [11, 12].

4. Experimental results

The similarity of the magnetostrictive signal (Figure 2) with the function sin(x)/x, for which the program of the signal and noise sum simulation and correlating integral calculation was developed, was used to check the possibility of implementing the optimal correlation signal processing algorithms [13, 14]. The parameters of the function *sin(x)/x* are chosen in such a way as to provide the maximum similarity with the real magnetostrictive signal (figure 2), i.e. the main maximum duration is 7 µs, the function duration is 42 µs. When modelling, the sampling period was 12 times less than the width of the function main maximum (580 ns), and the reference signal sample included 64 samples (figure 3a).

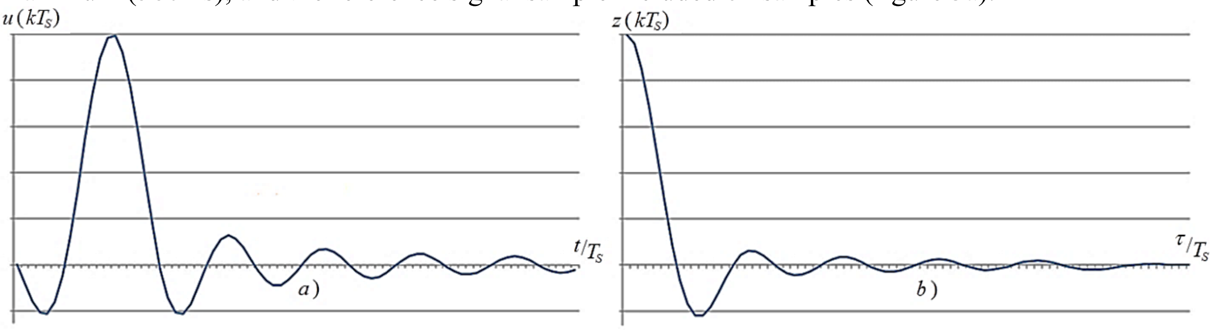

Figure 3. The ultrasonic signal (a) and its correlation function (b) model.

The correlation functions ensemble with a low ratio of the signal power to noise power ($q=P_s/P_n=3$) is represented in figure 4.

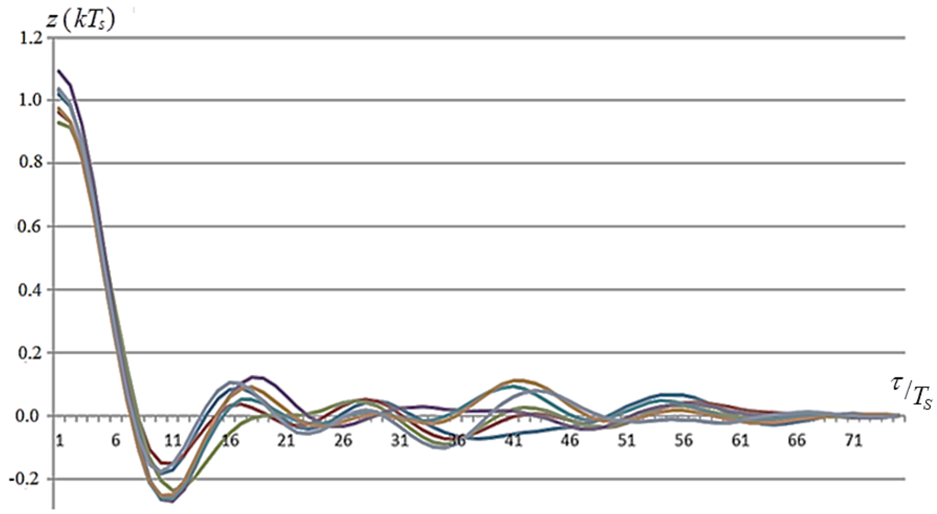

Figure 4. The correlation functions ensemble $z(kT_s)$ at the signal-to-noise ratio of q=3.

The procedure of determining the time shift between the direct and reflected ultrasonic signals is explained in figure 5 a, while the time shift measurement between the correlation function maxima or between the intersection points where the correlation function meets the threshold level (the given dependences correspond to the signal/noise ratio of q=5) is presented in figure 5 b. Since the correlation function (9) has a sampled representation, the time interval measurement error will be determined by the sampling period T_s.

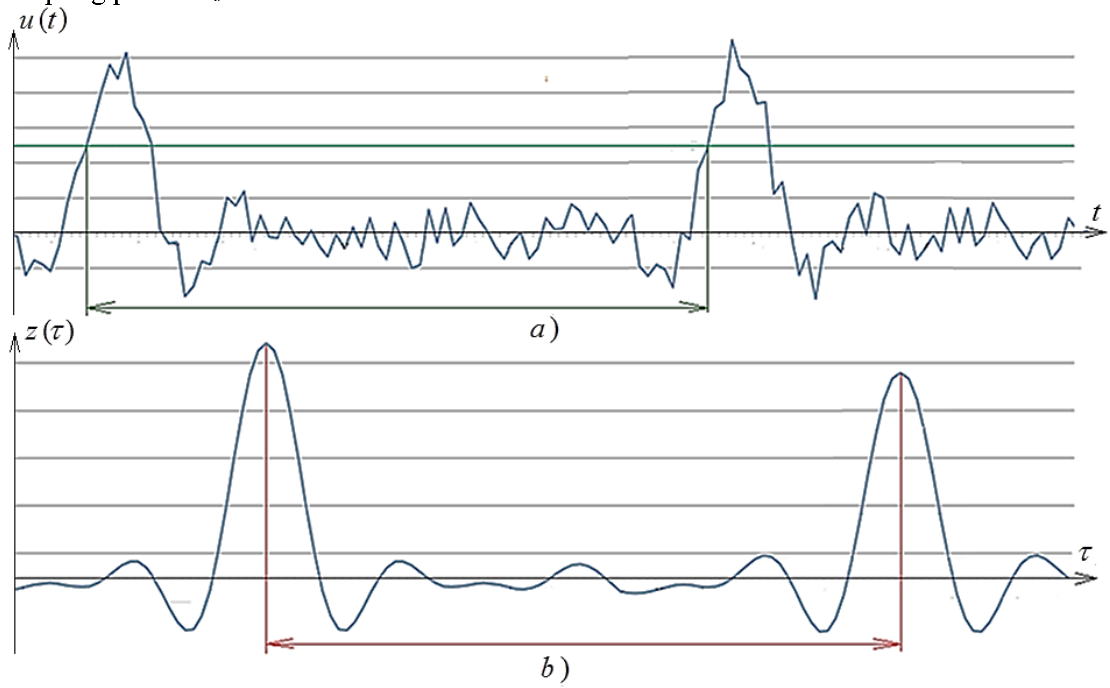

Figure 5. Piezoelectric element output signal (a) and its correlation function (b) at the signal-to-noise ratio of q=5.

When calculating one point of the correlation function (9), N multiplication and Naddition operations are needed, which poses greater requirements of the computing device and does not always allow performing the real-time calculations.

For reducing the number of mathematical operations in order to perform correlation calculations in real time, a discrete version of the modified support function is proposed when calculating the correlation integral (in this case the autocorrelation function is transferred to the cross-correlation one). Sampling is to replace the support function sections between the adjacent zero points of transition to the constant value (figure 6 b), equal to the local extremum (maximum or minimum) [14, 15].

The quasi-optimality of the proposed transformations is ensured by calculating the cross-correlation integral, which parameters differ slightly from the classical correlation integral parameters as confirmed by the statistical modelling results. The restriction of the proposed quasi-optimal processing is the computing device parameters: the number of the arithmetic operations performed, the sampling period of the received signal, and the speed of the microcontroller.

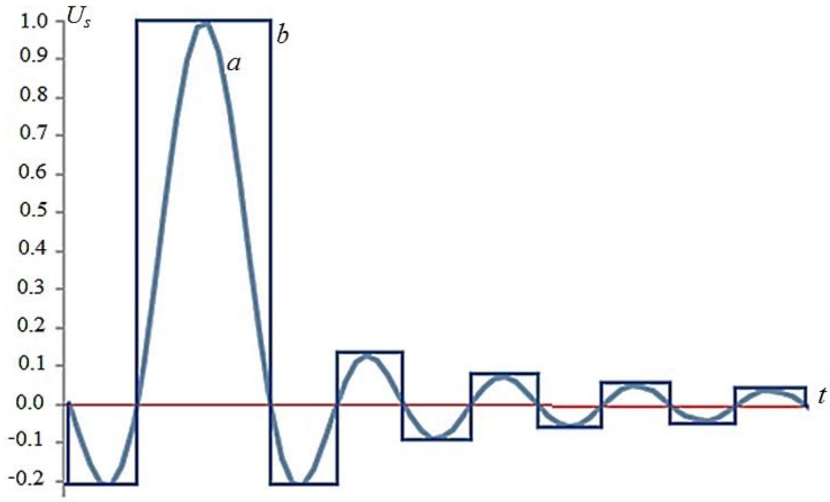

Figure 6. The supporting function U_{s1} (a) replacement by the discrete modification U_{s2} (b).

During transfer (11) to the modified support function (12), the number of operations is reduced by more than 6 times due to the multiplication operations grouping:

$$z(kT_s) = \sum_{n=1}^{64} u_{s1}[(n-k)T_s] \cdot x(nT_s) \tag{11}$$

$$z^{'}(kT_s) = \sum_{m=1}^{10} u_{s2}[(m-k)T_s] \cdot \sum_{n=1}^{N_m} x(nT_s) \tag{12}$$

where m is the interval number of the modified discrete support function U_{s2},
N_m is the number of time samples in the m-th interval of the modified sampled support function,
$\sum_{n=1}^{N_m} x(nT_s)$ is the sequence sum of the samples falling into the mth interval of the modified discrete support function.

The autocorrelation function of the *sinx/x* original signal model and cross-correlation function of the signal *sinx/x* with a discrete modified reference signal are shown for comparison in figure 7.

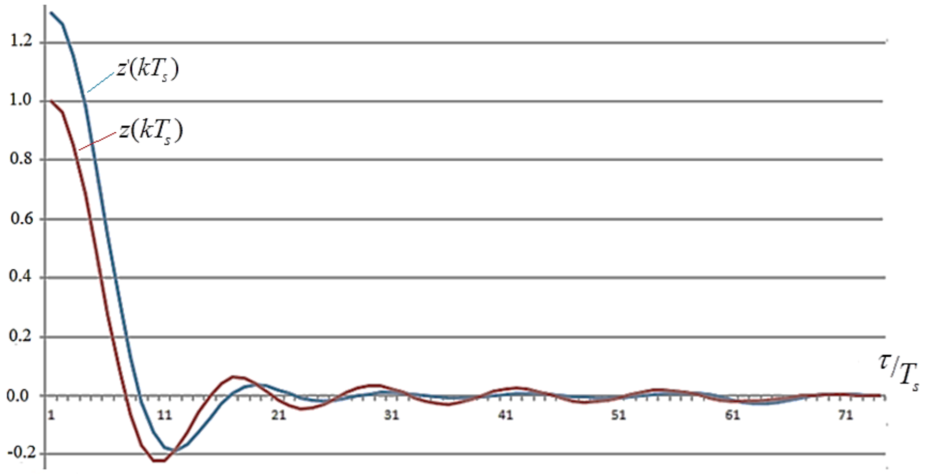

Figure 7. The autocorrelation (red line) and cross-correlation (blue line) functions.

The cross-correlation function structure is largely similar to the initial autocorrelation function, except the level (by 31 %) and width (by 15 %) increase of the main maximum and a slight decrease in the side lobes level.

The cross-correlation functions ensemble at the low ratio of the signal power to noise power (P_s/P_n=3) is represented in figure 8.

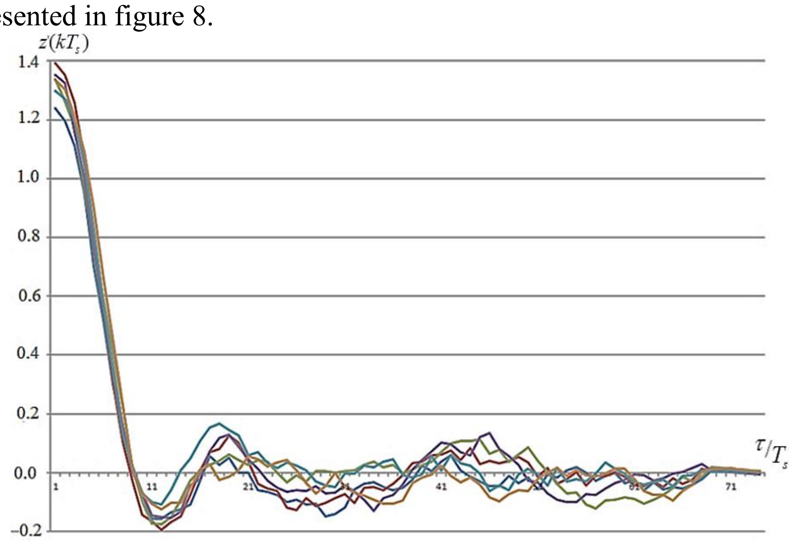

Figure 8. The cross-correlation functions $z'(kT_s)$ ensemble at the signal-to-noise ratio of q=3.

Cross-correlation (figure 8) and autocorrelation (figure 4) signal functions ensemble comparing at the same signal-to-noise ratio does not reveal significant differences in noise immunity.

The next step in minimizing the number of mathematical operations was to examine the nature of the correlation properties change when quantizing the reference signal samples: the coefficients values of the modified reference function were replaced by the nearest values 2^{-k}. The purpose of the transformation was to replace the product of the current signal reference and the reference function value by the grid shift of the signal sample. Under the given transformations, each operation of multiplying the current signal value by the scaling factor of 0.5 is replaced by shifting the binary number grid by one order (figure 9).

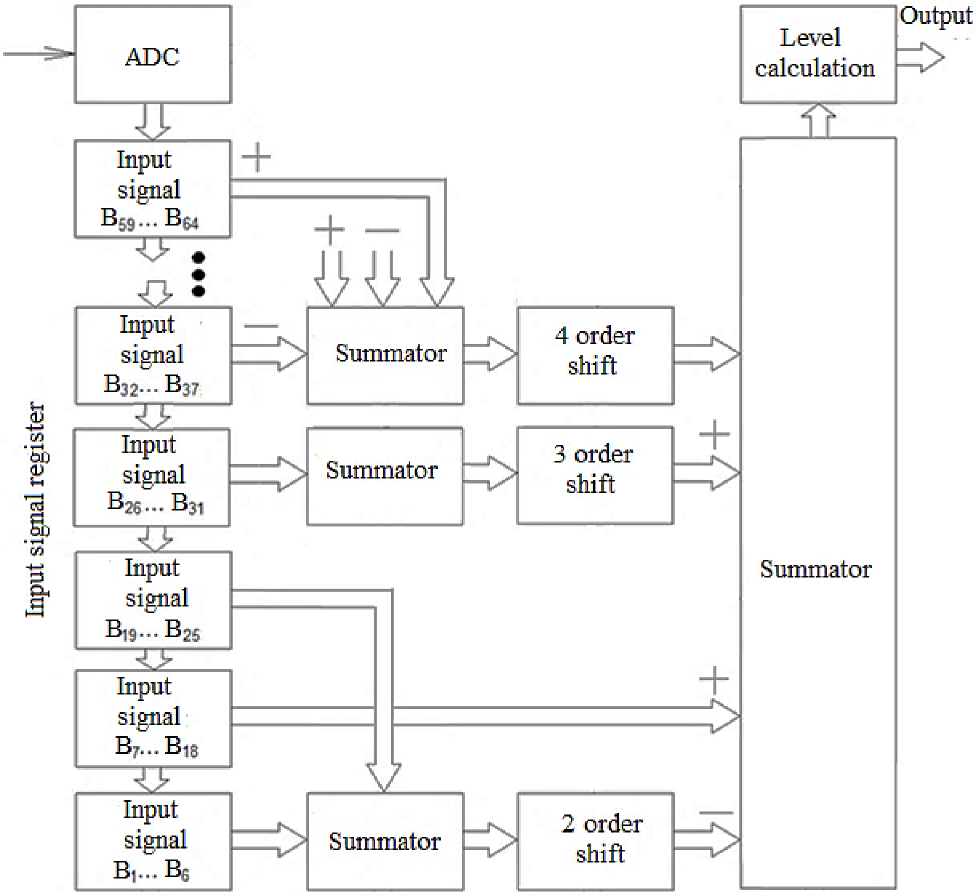

Figure 9. The level calculation algorithm by using the cross-correlation function for the quantized modified discrete reference function (ADC - analog-to-digital converter).

The structure of the cross correlation function during quantization of the reference signal coefficients has remained virtually unchanged as compared with the autocorrelation function: the main maximum is larger by 2 dB (positive effect), the side lobes level is smaller by 3-11 dB (positive effect), the main maximum width is larger by 15 % (insignificant negative effect). The processing algorithm changing impacts on the noise immunity (normalized process dispersion at the output of the processing system), which is represented in figure 10, implying that the proposed modification of the support function during cross-correlation processing degrades the signal-to-noise ratio at the correlator output (from 3 to 5 dB).

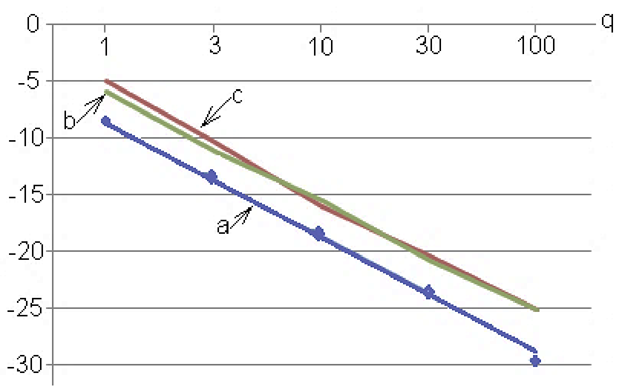

Figure 10. The dependence of the dispersion ratio at the correlator output to the signal energy (in dB) on the signal-to-noise ratio: (a) is in autocorrelation processing, (b) is in cross-correlation processing with a discrete modified reference signal, and (c) is in cross-correlation processing with a discrete quantized modified reference signal.

Thus, the time interval measuring algorithm in the level gauge, which is resistant to changing the pulses shape and interference level, is proposed. The digitized signal values from the output of the level gauge piezoelectric transducer are fed to the shifting register with taps after each word (a delay of one sampling interval). The adjacent samples groups are summed, then the sums are multiplied by the weighting coefficients. It is implemented by the digit-by-digit number shift followed by re-summing (some values have the changed signs in relation to the initial ones) [16].

5. Conclusions

- When using the traditional methods,the time interval measurement error in magnetostrictive level gauges depends on the temperature, supply voltages and other uncontrolled factors, which may result in the accidents.
- The optimal processing application of the acoustic signals based on the microcontroller makes it possible to reduce the measurement errors of the petroleum products level and to increase the measurement accuracy.
- Correlation processing classical methods of the digital acoustic signals require a large number of operations (for N samples of the reference signal, the calculation of one point of the correlation function requires performing N addition operations and N multiplication operations), which is difficult to implement in real time and leads to the increase in the power consumed by the microcontroller.
- Applying the proposed acoustic signals cross-correlation processing on the basis of the modified discrete support function and quantized modified discrete reference function reduces the number of the operations performed (for N samples of the reference signal, calculating one point of the cross-correlation function requires performing N addition operations and shift operations without multiplication operations) while maintaining the energy and accuracy parameters (in quantizing the reference signal coefficients, as compared with the autocorrelation function, the cross-correlation function has the main maximum increased by 2 dB, main maximum width increased by 15%, side lobe level lower by 3-11 dB when the signal-to-noise ratio degrades from 3 to 5 dB)
- The represented results can be applied in the level measurement and medicine for electrocardiograms analysis [17, 18].

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References

[1] Dyomko A I, Semenov O Yu and Dyomko I A 2019 RF Patent No 191611 (14 August 2019)
[2] Semenov O Yu and Dyomko A I 2019 *AIP Conf. Proc. (Omsk)* (Melville, NY: AIP Publishing) **2141** pp 050010-1-050010-10
[3] Dyomko A I, Koblov A V, Napol'sky A N, Petrov B A and Radomsky S A 2014 RF Patent No 2518470 (10 June 2014)
[4] Harry L. Van Trees, Kristine L. Bell and Zhi Tian 2013 *Detection Estimation and Modulation Theory* (USA: Wiley)

Journal of Physics: Conference Series **1488** (2020) 012004 doi:10.1088/1742-6596/1488/1/012004

[5] Lyons R G *Understanding Digital Signal Processing* (USA: Prentice Hall)
[6] Percival D B 1993 An introduction to spectral analysis and wavelets *Proc. Workshop Advanced Math. Tools Metrology* (Torino, Italy, October 1993) EDP Ciarnini (Singapore: WS) pp 175–186
[7] Dichev D, Koev H, Bakalova T and Louda P 2015 *Meas. Sci. Rev.* **15 (1)** 19–26
[8] Cardoso G and Saniie J 2005 *IEEE Trans Ultrason Ferroelectr Freq Control* **52 (2)** 313–325
[9] Hirsekorn M, Delsanto P P, Batra N K and Matic P 2004 *Ultrasonics* **42 (1-9)** 231–235
[10] Moreira A J C, Valadas R T and Duarte A M D O 1996 *IEEE Proc. J. Optoelectronics* **143 (6)** 339–346
[11] Pavlikov V V 2012 *IEEE Antenn. Propag*. **54 (5)** 152–159
[12] Tao R, Li Y L and Wang Y 2010 IEEE *Trans. Signal Process.* **58 (5)** 2568–80
[13] Shen T, Li H, Zhang Q and Li M 2014 *Meas. Sci. Rev.* **17 (1)** 48–52
[14] Silveira L F Q, Silveira L G Q Junior, Assis F M and Pinto E L, 2009 *IEEE Trans. Wireless Commun.* **8 (2)** 563–567
[15] Lu Y, Demirli R, Cardoso G and Saniie J 2006 *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **53 (11)** 2121–31
[16] Zhang H, Fan H H and Lindsey A 2001 A wavelet packet based model for time-varying wireless communication channels. *Third IEEE Signal Processing Workshop on Signal Processing Advances in Wireless Communications*, (Taiwan, 20–23 March 2001) (Piscataway, NJ: IEEE) pp 50–53
[17] Nedoma J, Fajkus M, Martinek R, Kepak S, Cubik J, Zabka S, and Vasinek V 2017 *Proc. Int. Conf. on Telecommunications and Signal Processing* (Piscataway, NJ: IEEE) pp 420–424
[18] LydonK, Su B Y, Rosales L, Enayati M, Ho K C, Rantz M, and Skubic M, *Proc. Int. Conf. of the IEEE Eng. Med. Biol. Soc.* (Piscataway, NJ: IEEE Service Center) pp 7175–79