Numerical method for processing frequency measuring signals from microelectronic sensors based on transistor structures with negative differential resistance

Osadchuk, Alexander, Semenov, Andriy, Zviahin, Oleksander, Savytskyi, Anton, Komada, Paweł, et al.

Alexander V. Osadchuk, Andriy A. Semenov, Oleksander S. Zviahin, Anton Y. Savytskyi, Paweł Komada, Karlygash Nurseitova, "Numerical method for processing frequency measuring signals from microelectronic sensors based on transistor structures with negative differential resistance," Proc. SPIE 11176, Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2019, 111765Y (6 November 2019); doi: 10.1117/12.2536942

Event: Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2019, 2019, Wilga, Poland

Numerical method for processing frequency measuring signals from microelectronic sensors based on transistor structures with negative differential resistance

Alexander V. Osadchuk*[a], Andriy A. Semenov[a], Oleksander S. Zviahin[a],
Anton Y. Savytskyi[a], Paweł Komada[b], Karlygash Nurseitova[c]
[a]Vinnytsia National Technical University; [b]Lublin University of Technology;
[c]East Kazakhstan State Technical University named after D. Serikbayev

ABSTRACT

The application of the proposed mathematical tools, that can be used for signal processing self-generating transducers of physical quantities, are considered. Its operating mechanism is based on frequency modulation, when the frequency deviation depends on the intensity of exposure measurement parameter. It is shown that the action for leveling additive errors in the channel the signal generator is highly stable enough to use approximating second order polynomial.

Keywords: self-oscillator transducer; additive error; noise; definite integral; measurement accuracy; sensor; negative differential resistance

1. INTRODUCTION

The quality of oil and fuel and lubricants is largely determined by the accuracy of their moisture content. Water present in hydraulic and lubricating liquids, causes significant damage to technological units requiring lubrication of parts. Without proper devices and controls, it is difficult to see their current destruction. The water available in oil contributes to corrosion, during transportation it can distort the displays of flowmeters, as well as leads to premature wear of equipment and the emergence of emergency situations. Therefore, it is very important to develop systems for measuring and controlling this parameter of liquid hydrocarbons[1,2,3].

Currently, there are used measuring systems the quantity and quality parameters of crude oil (MSPCO), intended for automated accounting at delivery of commodity oil from the supplier to the consumer, for qualitative definition indicators of oil refinings, as well as at carrying out of accounting and settlement operations at transportation oil and petroleum products[4]. MSPCO performs automatic calculation of the mass of petroleum products and sampling to determine such parameters as temperature, pressure, viscosity, humidity; and transfer of measurement results to a computerized control panel[5,6,7].

2. THEORETICAL AND EXPERIMENTAL RESEARCH

It can be seen a block diagram of MSPCO (Fig. 1). It includes: measurement and control unit, block of filters (BF) and block of the stationary pipe-piston installation (BPI)[8,9].

In turn, the measuring and control unit includes a measuring unit for quality indicators that provides measurement of density, viscosity, flow rate, humidity, pressure and temperature of oil (Fig. 2).

As a humidity analyzer in the unit of measurement of quality indicators, a system for measuring and controlling the humidity of oil and petroleum products, the structural scheme of which is given in Fig. 3. The system works in follow way: the humidity change of the liquid to be studied leads to the change in the humidity-sensitive capacitance of the condenser cylindrical structure (CCS)[10] and, accordingly, to the change of oscillations frequency at the output of FM oscillator (FMO)[11], then the signal is digitized and means of displaying information (LCD-display, PC screen) displays the value of the oil product humidity.

* osadchuk.av69@gmail.com

Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2019,
edited by Ryszard S. Romaniuk, Maciej Linczuk, Proc. of SPIE Vol. 11176, 111765Y
 · doi: 10.1117/12.2536942

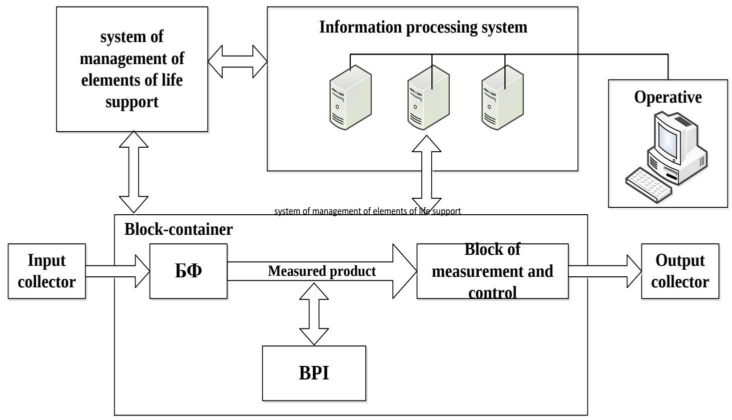

Figure 1. Block diagram of MSPCO.

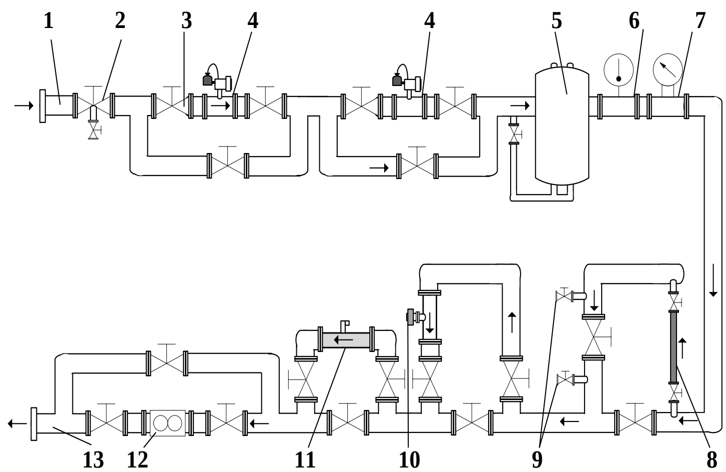

Figure 2. Block of measurement of quality indicators: 1 – oil from sampling device; 2 – manual sampler; 3 – stop valves; 4 – sampler automatic; 5 – cylinder thermostat for the hydrometer; 6 – temperature sensor; 7 – pressure gauge; 8 – density sensor; 9 – place of connection of the pycnometer; 10 – Viscosimeter; 11 – a moisture meter; 12 – flow meter; 13 – oil output.

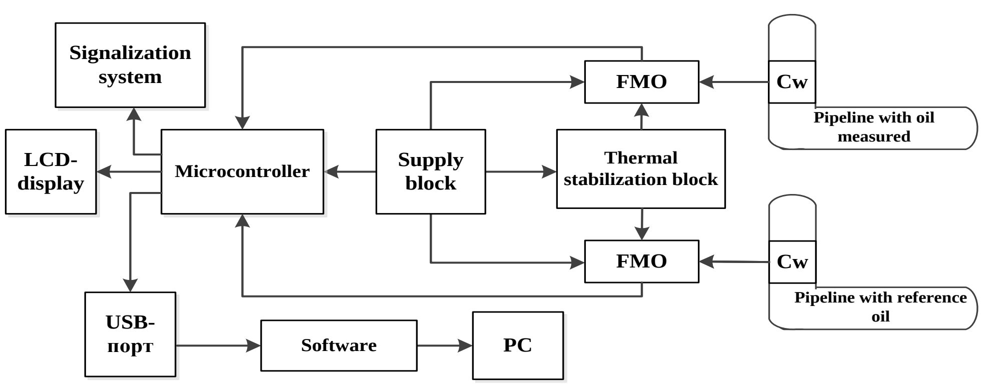

Figure 3. Structural scheme of the system for measuring and controlling the humidity of oil and petroleum products.

Discribed system allows not only to measure and store the humidity values for a certain time, but also to control the permissible humidity value given by the executable program. When the permissible humidity value is exceeded, the signaling device is triggered and a message is displayed that the petroleum product does not correspond to the tolerance value (on the screen the user sees the inscription "norm" or "abnormality").

The schematic diagram of the developed system is shown in Fig. 4 consists of a 8-bit microprocessor with a USB interface PIC18F4550, a PC, a FMO, an LCD display WH1602C-YGH-CTK, and also contains a thermostabilization system. The system of thermostabilization consists of the first thermochemical detector, which is installed with FMO and controls the value of the temperature within the limits of 53°C ± 0,5°C. If the temperature becomes less than 52.5°C, then the heating element is switched on and the FMO is heated to 53,5°C. The second and third thermocouples are installed on a humidity sensitive CCS to take into account the influence of temperature, in particular to select a certain conversion function, from the list of those prescribed in the program at different temperatures[12]. The used DS18B20 thermocouples are connected in parallel.

The information on the FMO, the sensory elements (CCSs) are installed in the pipeline in such a way that one is in the measuring line, and the other in the reference, through the input nodes enters the microcontroller where the frequency measurement takes place and their difference is calculated. The result of the difference in the frequency of data signals based on the conversion function, recorded in the microcontroller, shows the percentage of water in the oil. Indication of the results of the measurement of humidity is possible in two versions: the first with an LCD display, the second on the screen of the PC monitor.

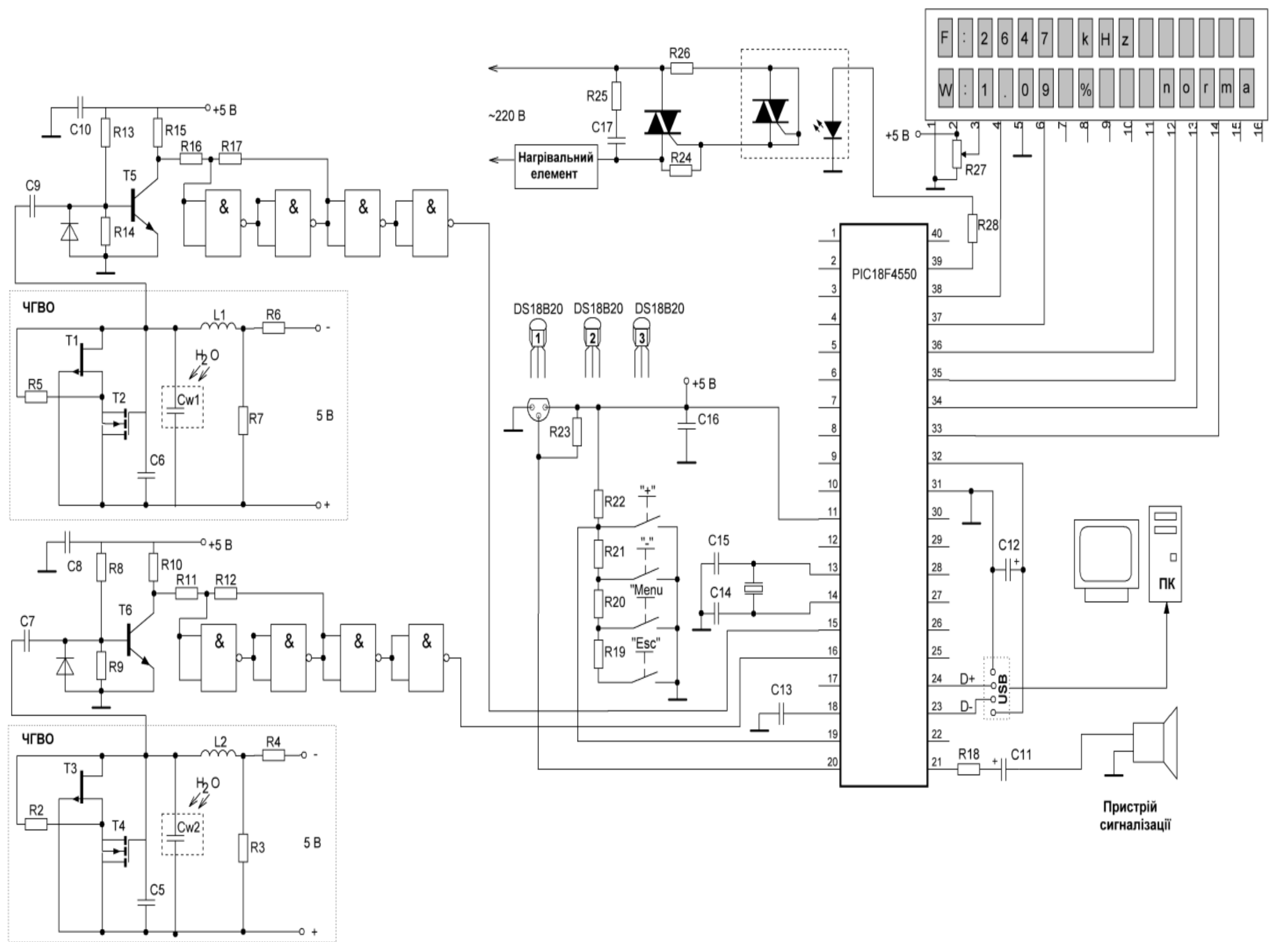

Figure 4. Principal scheme of the system for measuring and controlling the humidity of oil and petroleum products

In the system for oil and petroleum products humidity measuring and controlling, FMO is used on the basis of the structure of two field-effect transistors[4] with CCS based on cylindrical electrodes.

The advantage of the described system is the application of the frequency modulation of the information signal, which allows significantly increase the noise immunity of the data transmission channel[13-16].

The FMO transformation function is described by the expression:

$$F = \frac{\sqrt{2}\sqrt{LC_{s2}C_i\left(W,T\right)\cdot\left(\left(R_{ds2}{}^2C_{ds2}-L\right)\cdot C_{s2}C_i\left(W,T\right)+R_{ds2}{}^2A_1+\sqrt{A_2}\right)}}{4\pi LC_i\left(W,T\right)C_{s2}R_{ds2}C_{ds2}}, \tag{1}$$

where $A_1 = C_{ds2}{}^2\left(C_{s2}+C_i\left(W,T\right)\right)$;

$$A_2 = R_{ds2}{}^4C_{ds2}{}^2C_{s2}{}^2C_i^2\left(W,T\right)+2R_{ds2}{}^4C_{ds2}{}^3C_{s2}C_i\left(W,T\right)\left(C_{s2}+C_i\left(W,T\right)\right)-$$
$$-2LR_{ds2}{}^2C_{ds2}C_{s2}{}^2C_i^2\left(W,T\right)+R_{ds2}{}^4C_{ds2}{}^4\left(C_{s2}{}^2+2C_{s2}+C_i^2\left(W,T\right)\right)+$$
$$+2LR_{ds2}{}^2C_{ds2}{}^2C_{s2}C_i\left(W,T\right)\left(C_{s2}+C_i\left(W,T\right)\right)+L^2C_{s2}{}^2C_i^2\left(W,T\right),$$

R_{ds2} – MOSFET’s drain-sourse resistance; L – inductor; C_{s2}, C_{ds2} – MOSFET’s drain-gate and drain-sourse capacitances; $C_i\left(W,T\right)$ – capacitance of humidity-sensitive CCS.

Fig. 5 and Fig. 6 show the theoretical and experimental dependences of the transformation functions, namely, the frequency of FMO generation due to humidity of petroleum products[17,18].

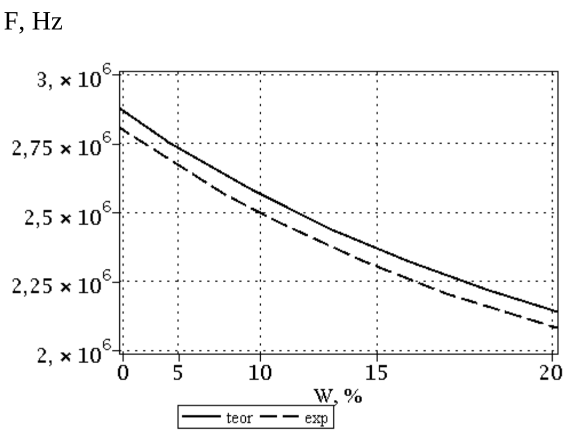

Figure 5. Conversion functions for motor oil 5W40.

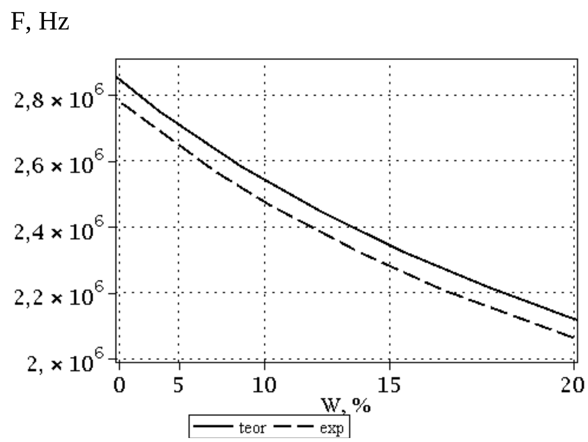

Figure 6. Conversion functions motor oil M8V.

As can be seen from Fig. 5 and Fig. 6 FMO transformations are nonlinear, but they can be easily approximated. The sensitivity of FMO in the range of changes in the humidity of petroleum products from 0% to 20% is from 25.7 kHz/% to 43 kHz /%. The difference between the theoretical and experimental results for FMO is not exceed 3%.

In the case of measuring the humidity content of petroleum products, this accuracy is not always sufficient. In order to improve metrological characteristics by reducing the additive error, the averaging method is used[17]. In the case where the information signal is represented as a discrete sample, the need for the application of numerical methods arises. In this article, the authors present a method of applying numerical methods for signal averaging.

Let the measurement result be a quasi-stationary value provided that the measuring parameter of the object is constant $a_f(t)$ is a quasistationary value a_f, and the sum of all cascades the frequency display error is "white noise", which is described by the function $\varepsilon(t)$. Then at each moment of time a signal that is a signal of frequency and noise, which is a function of frequency instability can be described $y(t) = a_f + \varepsilon(t)$. Apply the accumulation effect through the use of integral signal processing, which will be observed for some time of research T_D. Thus at the output of the integrator a signal is formed[19,20]:

$$Y(t) = \int_0^{T_D} y(t)dt = \int_0^{T_D} [a_f + \varepsilon(t)]dt = a_f T_C + \int_0^{T_D} \varepsilon(t)dt\,. \tag{2}$$

In this case, the signal / noise ratio will determine the error from the effect of the additive interference after the frequency/amplitude conversion to the interval of the frequency detector-indicator device:

$$n = \frac{P_{a_f}}{P_n} = \frac{\left(a_f \cdot T_D\right)^2}{\mathrm{D}\left[\int\limits_0^{\mathrm{T_D}} \xi(\mathrm{t})\mathrm{dt}\right]}, \tag{3}$$

where P_{a_f} i P_n – signal strength and interference respectively.

Provided that the measuring system corresponds to Kotelnikov's theorem, we can give the following properties of this system:

- the calculation method is valid for systems in which the information signal is quasi-constant, or periodic (including pulse);
- the information signal, as well as the signal interference can be represented as a sum of samples with the corresponding sampling rate;
- the variance of the sum of random variables (offset distances) will also be a random variable.

Based on the above statements, the following expressions can be written:

$$\int\limits_0^{T_D} \varepsilon(t)dt \cong \sum_{i-1}^{k} \varepsilon(t_i)\tau_0 , \tag{4}$$

where $k = T_D / \tau_0$; τ_0 – period of noise autocorrelation function.

The dispersion of the noise at the output of the integrator is determined by the expression:

$$D\left[\int\limits_0^{T_D} \varepsilon(t)dt\right] \cong D\left[\sum_{i=1}^{k} \varepsilon(t_i)\tau_0\right] \approx \tau_0^2 \cdot D\left[\sum_{i=1}^{k} \varepsilon(t_i)\right] = \varepsilon_0 \cdot n \cdot D(\varepsilon) = T_D \cdot \tau_0 \cdot D(\varepsilon). \tag{5}$$

Reducing interference is determined by the signal / noise ratio at the input and output of the integrator:

$$\frac{P_{a_f.вих}}{P_{n.вих}} \cong \frac{(a_f \cdot T_D)^2}{T_D \cdot \tau_0 \cdot D(\varepsilon)} = \frac{T_D \cdot a_f^{\,2}}{\tau_0 \cdot D(\varepsilon)} = \frac{T_D}{\tau_0} \cdot \frac{P_{a_f.вх}}{P_{n.вх}} . \tag{6}$$

As can be seen from the last expression, the signal / noise gain increases with increasing integration time (observation) and the frequency of the auto-correlation function of the interference.

In this case, for the Kotelnikov theorem to run the system, there is a problem of ensuring the speed of the integrator with the simultaneous provision of the necessary accuracy of the measurement. In[18], the possibility of applying the curvilinear approximation of the table-defined function by the arc segment was shown (Fig. 7), which is essentially a curvilinear refinement of the known trapezoidal method. The essence of the method is to assume that the graph of the approximated function on each reference in the curvilinear and refinement of the trapezoid method is due to the finding of an area limited by the straightforward approximation of the trapezium and the segment of the arc by the radius proposed in[19,20]. In this case, unlike the Simpson formula, it is eliminated the need to replace the segment of the desired straight line with two parabolas with intersection points in the middle of this segment, since this point can be found with some probability[21-23].

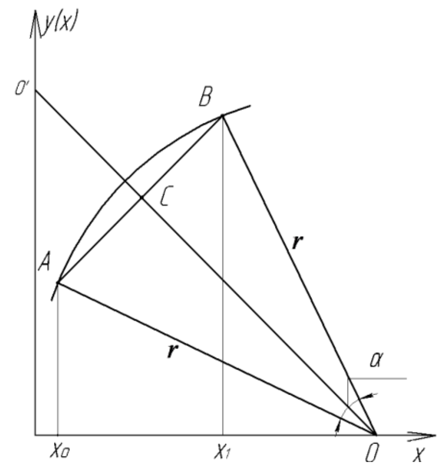

Figure 7. Graphic interpretation of the integration method.

The mathematical apparatus of the proposed integration techniques is given below[5,24]:

$$r_n = \sqrt{\left(\frac{(t_n^2 - t_{n-1}^2) + \left(y^2(t_n) - y^2(t_{n-1})\right) - 2ht_{n-1}}{2h}\right)^2 + y^2(t_{n-1})}\ . \tag{7}$$

$$\sin\alpha_n = \sqrt{1 - \left[1 - \left(\frac{(t_n - t_{n-1})^2 + (a_{f.n} - a_{f.n-1})^2}{2r_n^2}\right)\right]^2}\ ; \tag{8}$$

$$\alpha_n = \left|\arcsin(\sin\alpha_n)\right|; \tag{9}$$

$$S_{segm.n} = \frac{r_n^2}{2}\left(\pi\frac{\alpha_n}{180^0} - \sin\alpha_n\right). \tag{10}$$

Area, contoured by function graphs $t = t_0$, $t = t_n$, $y(t)$ is replaced by an integral sum:

$$\int_{t_0}^{t_n} y(t)dt = \sum_{i=1}^{m} S_{trap.i} + \sum_{i=1}^{m} S_{segm.i}; \tag{11}$$

$$\sum_{i=1}^{m} S_{trap.i} = h\left(\frac{y(t_0) + y(t_n)}{2} + y(t_1) + y(t_2) + ...\right); \tag{12}$$

$$\sum_{i=1}^{m} S_{segm.i} = \sum_{i=1}^{m}\frac{r_i^2}{2}(\pi\frac{\alpha_i}{180^0} - \sin\alpha_i)\ . \tag{13}$$

The accuracy of numerical integration depends on the degree of integrable polynomial. So, with substitution of original function y(t) with a line segment (the method of tangents, the trapezoid method), the integration error is determined by the residual term[21-23]:

$R(t) = \frac{(t_n - t_{n-1})^3}{12} y''(\varsigma)$, where $\varsigma \in [x_{n-1}; x_n]$ midpoint of the cut-off.

In this case, the total error of measurement equals the sum of errors for each reference[24]:

$$R(t)_\Sigma = \sum_{i=1}^{n}\frac{(t_i - t_{i-1})^3}{12} y''(\varsigma_{i-1})\ . \tag{14}$$

The application of numerical integration with higher order polynomials reduces the error of integration. In this case, the remainder of the integral equality described by expression[25-27]:

$$R(t)=\left(\frac{t_n-t_{n-1}}{2}\right)^5\frac{y^{(IV)}(\varsigma)}{90}. \quad (15)$$

Similarly, for this case, the total error of numerical integration can be determined by remainder member[28]:

$$R(t)_\Sigma=\sum_{i=1}^{n}\left(\frac{t_i-t_{i-1}}{2}\right)^5\frac{y^{(IV)}(\varsigma_{i-1})}{90}. \quad (16)$$

An algorithm has been developed for calculating a definite integral for averaging the results of measuring the humidity of oil and petroleum products. On the basis of this algorithm, the software of the microcontroller system for processing the information signal was developed.

3. CONCLUSIONS

The microprocessor system for monitoring the humidity concentration in petroleum products, which can be used in the system for control systems of crude oil at refineries, is developed. Dependences of the transformation function for different petroleum products are obtained. The sensitivity of the measuring instrument in the range of changes in the humidity of petroleum products from 0% to 20% is from 25.7 kHz /% to 43 kHz /%. Absolute error of measuring the humidity of petroleum products is not more than 5 ppm. This result has been achieved by using the mathematical apparatus of the averaging of the results of the measurement of the humidity of petroleum products on the basis of numerical integration methods. In this work a mathematical apparatus was developed that was used for implementation MSPCO.

REFERENCES

[1] Sergey, Y. Y., "Sensors and Transducers: Frequency Output Versus Voltage Output," Sensors & Transducers Magazine 11, 302-305, (2004).

[2] Sergey, Y. Y., [Digital and Intelligent Sensors and Sensor Systems: Practical Design], Tutorial, Rome, (2012).

[3] Osadchuk, V. S., Osadchuk, A. V. and Yushchenko, Y. A., "Radiomeasuring thermal flowmeter of gas on the basis of transistor structure with negative resistance," Elektronika ir Elektrotechnika 4, 89-93, (2008).

[4] Osadchuk, V. S., Osadchuk, A. V., "Radiomeasuring Microelectronic Transducers of Physical Quantities," Proc. International Siberian Conference on Control and Communications – SIBCON, (2015), doi: 10.1109/SIBCON.2015.7147167.

[5] Osadchuk, V. S. and Osadchuk, A. V., "The microelectronic transducers of pressure with the frequency," Elektronika ir Elektrotechnika 5, 105-108, (2012), doi: 10.5755/j01.eee.121.5.1661.

[6] Pidchenko, S. K., "Dual-frequency temperature-compensated Quartz Crystal Oscillator," Proc. 23rd International Crimean Conference Microwave and Telecommunication Technology, 669-670, (2013).

[7] Taranchuk, A. A., Pidchenko, S. K. and Khoptinskiy, R. P., "Dynamics of temperature-frequency processes in multifrequency crystal oscillators with digital compensations of resonator performance instability," Radioelectronics and Communications Systems 6, 250-257, (2015).

[8] Leonov, A. V., Malykh, A. A., Mordkovich, V. N., and Pavlyuk, V. I., "Sensors with SOI FET Primary Transducers and Frequency Output," Proc. SENSOR 2015 and IRS2 2015, 864-867, (2015).

[9] Azcona Murillo Cristina, Calvo Lopez Belén and Celma Pueyo Santiago, [Voltage-to-Frequency Converters: CMOS Design and Implementation], Springer Science+Business Media, New York, (2013).

[10] Osadchuk, A., Koval, K., Semenov, A. and Prutula, M., "Mathematical model of transistor equivalent of electrical controlled capacity," Proc. International Conference TCSET 2008, 35-36, (2008).

[11] Osadchuk, A.V. and Osadchuk, I.A., "Frequency transducer of the pressure on the basis of reactive properties of transistor structure with negative resistance," Proc. International Siberian Conference on Control and Communications – SIBCON, (2015), doi: 10.1109/SIBCON.2015.7147168.

[12] Taranchuk, A. A., Pidchenko, S. K., and Khoptinskiy, R. P., "Determination of bulk density of the source of heat in the analysis of thermodynamic processes in the quartz piezoelectric element," Proc. 24rd International Crimean Conference Microwave and Telecommunication Technology, 716-717, (2014).
[13] Mahajan Ajay, Oesch Christopher, Padmanaban Haricharan, Utterback Lucas, Chitikeshi Sanjeevi and Figueroa Fernando, "Physical and Virtual Intelligent Sensors for Integrated Health Management Systems," International Journal on Smart Sensing and Intelligent Systems 3, 559-575, (2012).
[14] Kwang-Jow Gan, Kuan-Yu Chun, Wen-Kuan Yeh, "Design of Dynamic Frequency Divider using Negative Differential Resistance Circuit," International Journal on Recent and Innovation Trends in Computing and Communication 8, 5224-5228, (2015).
[15] Kychak V. and Kychak V., "Computer-aided design of digital radio devices with frequency representation of information," Proc. 11th International Conference Modern Problems of Radio Engineering, Telecommunications and Computer Science, 405, (2012).
[16] Frankiewicz, M. and Kos, A., "Thermal analysis of CMOS voltage-controlled oscillators," Informatyka, Automatyka Pomiary w Gospodarce i Ochronie Srodowiska – IAPGOS 4b, 3-6, (2012).
[17] Dogadin, N. B., [Fundamentals of radio engineering], Lan, St. Petersburg, (2007).
[18] Maplesoft, [Maple User Manual], Waterloo Maple Inc., (2014).
[19] Berezin, I. S. and Zhydkov, N. P., [Metody vychyslenyi], State publishing house of physical and mathematical literature, Moscow, (1962).
[20] Osadchuk, O. V., Zviahin, O. S. and Savitsky, A. Yu., " Processing of the sensor's measurement signal using parabolic interpolation," Journal of Khmelnitsky National University 2, 153-158, (2015).
[21] Bronstein, I. N., Semendyayev, K. A., [Handbook of mathematics for engineers and students of technical colleges], The main editors of physical and mathematical literature, Moscow, (1986).
[22] Chernyshova, T. I. and Chernyshov, N. G., [Simulation of electronic circuits], TSTU, Tambov, (2010).
[23] Vedmitskyi, Y. G., Kukharchuk, V. V. and Hraniak, V. F., "New non-system physical quantities for vibration monitoring of transient processes at hydropower facilities, integral vibratory accelerations," Przeglad Elektrotechniczny 3, 69-72, (2017).
[24] Kukharchuk, V. V., Kazyv, S. S. and Bykovsky, S. A., "Discrete wavelet transformation in spectral analysis of vibration processes at hydropower units," Przeglad Elektrotechniczny 5, 65-68, (2017).
[25] Kukharchuk, V. V., Hraniak, V. F., Vedmitskyi, Y. G., Bogachuk, V. V., et al., "Noncontact method of temperature measurement based on the phenomenon of the luminophor temperature decreasing," Proc. SPIE 10031, 100312F, (2016).
[26] Kukharchuk, V. V., Bogachuk, V. V., Hraniak, V. F., Wójcik, W., Suleimenov, B. and Karnakova, G., "Method of magneto-elastic control of mechanic rigidity in assemblies of hydropower units," Proc. SPIE 10445, 104456A, (2017).
[27] Azarov, O. D., Dudnyk, O. D., Duk, M. and Porubov, D., "Static and dynamic characteristics of the self-calibrating multibit ADC analog components," Proc. SPIE 8698, 86980N, (2013).