Highly sensitive devices for primary signal processing of the micromechanical capacitive transducers

B. Konoplev[a], E. Ryndin*[a], I. Lysenko[a], M. Denisenko[a], A. Isaeva[a]
[a]Southern Federal University, Institute of Nanotechnology, Electronics and Electronic Equipment Engineering, 44 Nekrasovsky St., Taganrog, Russia 347928

ABSTRACT

A method of signal processing devices design for micromechanical accelerometers with capacitive transducers is proposed. This method provides the complex solution of the sensibility increasing and noise immunity problems by finding of the difference frequency of signals, which are formed by two identical generators with micromechanical capacitive transducers in frequency control circuits. In this study the analog and digital versions of the highly sensitive signal processing devices circuits with frequency output were developed. The breadboards of these devices are fabricated and studied and the project of their integral realization is designed.

Keywords: micromechanical accelerometers, capacitive transducers, signal processing devices

1. INTRODUCTION

Micromechanical gyroscopes and accelerometers are widely used in modern devices for different purposes: specialized devices of aerospace technic, transport and defense systems, mobile phones and new generation video game consoles [1]. Device for primary signal processing is the one of the main function block of these sensory microsystems. These devices vastly determine characteristics of gyroscopes and accelerometers [2].

Small sizes and low capacities of the transducers of modern micromechanical gyroscopes and accelerometers stipulate necessity of use high sensitive, linear and high accuracy signal processing devices [2]. Signal processing devices based on highly sensitive charge amplifiers the most fully meets these requirements. However, the high sensitivity to the signal assumes a high sensitivity to the noise level at the amplifier input, which limits the functional characteristics, particularly the sensitivity threshold of signal processing devices [3].

Design of devices for signal processing of gyroscopes and accelerometers with micromechanical capacitive transducers that allow solving above problems is the purpose of this work.

2 DESIGN OF THE HIGH SENSITIVE DEVICES WITH NOISE IMMUNITY FOR SIGNAL PROCESSING OF MICROMECHANICAL CAPACITIVE TRANSDUCERS

In purpose of provide high sensitivity and noise immunity the design principles of devices for primary signal processing of the micromechanical capacitive transducers are proposed.

Device for primary signal processing is realized without high sensitive charge amplifier and has a frequency output. This device performs direct conversion “capacitance-to-frequency” by including micromechanical transducer capacitances in frequency control circuits of signal generators. Noise fluctuations of current and charge are not increase due to absence of charge amplifier and bring in some deformation only in form of output signal. These fluctuations do not affect the pulse repetition frequency of this signal, which is informative parameter in this case. As a result, high noise immunity is provided.

*rynenator@gmail.com; phone +7 8634 361-374; fax +7 8634 361-374; inep.sfedu.ru

International Conference on Micro- and Nano-Electronics 2016, edited by Vladimir F. Lukichev, Konstantin V. Rudenko
Proc. of SPIE Vol. 10224, 102241E · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2266562

Difference principle of output signal forming is used in the device for signal processing for purpose of providing high sensitivity of “capacitance-to-frequency” conversion. The device includes two identical generators, which frequency control circuits include micromechanical transducer capacitances. Capacitances are vary in antiphase under the influence of angular velocity (for gyroscope) or linear acceleration (for accelerometer). Generators are tuned in the way that generated signals has a slightly different frequency in the initial condition, when it is no angular velocity or linear acceleration. Device for signal processing forms output signals, which pulse repetition frequency equal to difference of the generators frequencies.

We denote signal frequency of the first generator as f and signal frequency of the second generator as $K_f f$, where $K_f > 1$.

Then output difference frequency f_{OUT} is determined as

$$f_{OUT} = (K_f - 1)f. \tag{1}$$

Suppose that micromechanical transducer capacitances C are changed by the influence of angular velocity or linear acceleration by some value ΔC. This will cause to decreasing of frequency of the first generator and increasing of frequency of the second generator by some value Δf. Corresponding change of the output difference frequency can be expressed as follows:

$$\Delta f_{OUT} = (K_f f + \Delta f) - (f - \Delta f) = (K_f - 1)f + 2\Delta f. \tag{2}$$

The relative change of the output difference frequency is given by:

$$\frac{\Delta f_{OUT}}{f_{OUT}} = \frac{(K_f - 1)f + 2\Delta f}{(K_f - 1)f} = 1 + \frac{2}{K_f - 1} \cdot \frac{\Delta f}{f}. \tag{3}$$

Given that $\frac{\Delta f}{f} \approx \frac{\Delta C}{C}$ and the coefficient K_f, that determine the differences of the generators signals frequencies in the initial condition, is close to 1 $(K_f - 1 << 1)$ from the expression (3) we obtain

$$\frac{\Delta f_{OUT}}{f_{OUT}} \approx \frac{2}{K_f - 1} \cdot \frac{\Delta C}{C}. \tag{4}$$

So, in accordance with the expression (4), conversion coefficient of the relative change of the micromechanical transducer capacitance to the relative change of the output difference frequency can be expressed as follows:

$$K_C \approx \frac{2}{K_f - 1}. \tag{5}$$

The dependence $K_C(K_f)$ obtained based on expression (5) is shown on Figure 1.

The Figure 1 shows that due to the difference principle of output signal forming the conversion coefficient of the device for signal processing can reach values of more than 10^5. That provides high sensibility and high noise immunity.

An additional advantage of the design principles of devices for signal processing of the micromechanical capacitive transducers is increased resistance to destabilizing environmental factors such as temperature and humidity. The frequencies of the signal generators change almost equally by the influence of the destabilizing environmental factors and the corresponding changes of the difference frequency of the output signals will be negligible.

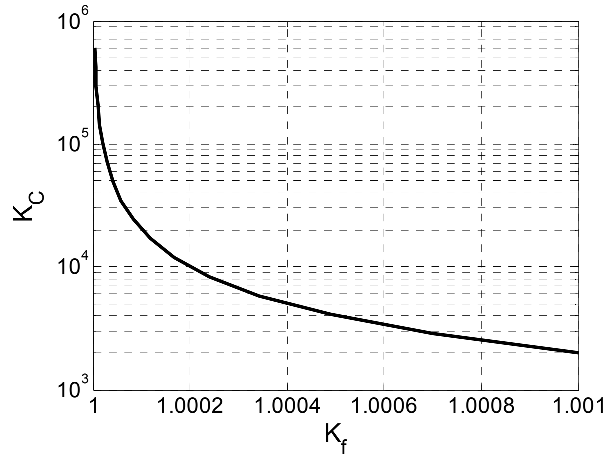


Figure 1. The dependence of the conversion coefficient of the relative change of the micromechanical transducer capacitance to the relative change of the output difference frequency of the device for signal processing on the generators signals frequencies ratio in the initial condition

We consider change of the output frequency of the device for signal processing under the influence of temperature. We denote temperature coefficient of the first generator signal frequency as K_T, and temperature coefficient of the difference frequency of the device output as K_{TOUT}.

Taking into account (1), change of the difference frequency of the output signal $\Delta f_{OUT}(\Delta T)$, that occurs by temperature change ΔT, can be expressed as follows:

$$\Delta f_{OUT}(\Delta T) = (K_f - 1)\Delta f(\Delta T) = (K_f - 1)K_T \Delta T, \tag{6}$$

where $\Delta f(\Delta T)$ is the change of the first generator signal frequency caused by temperature change ΔT.

Temperature coefficient of the difference frequency of the device output signal K_{TOUT} can be expressed as follows:

$$K_{TOUT} = (K_f - 1)K_T. \tag{7}$$

Taking into account that $K_f - 1 << 1$, temperature coefficient K_{TOUT} can take the values to several orders of magnitude smaller, than the coefficient K_T.

3 FUNCTIONAL SCHEMES OF THE DEVICES FOR PRIMARY SIGNAL PROCESSING OF MICROMECHANICAL CAPACITIVE TRANSDUCERS

To evaluate the effectiveness of the design principles of the signal processing device of the micromechanical capacitive transducers we developed two variants of functional schemes. This schemes shows on Figures 2, 3.

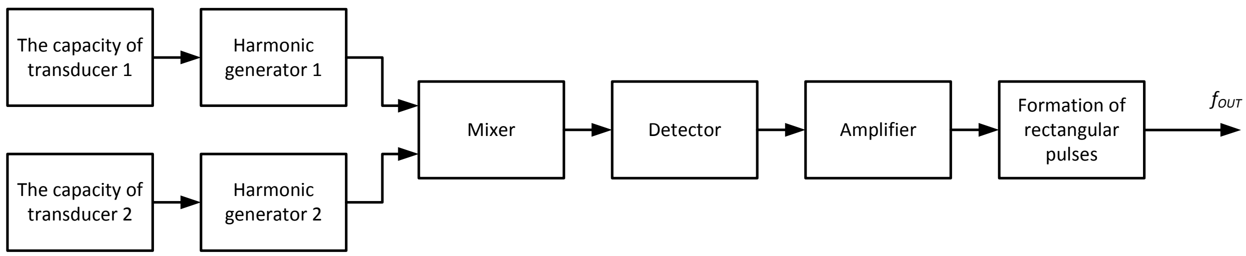


Figure 2. Functional scheme of the first variant of the device for signal processing of the micromechanical capacitive transducers

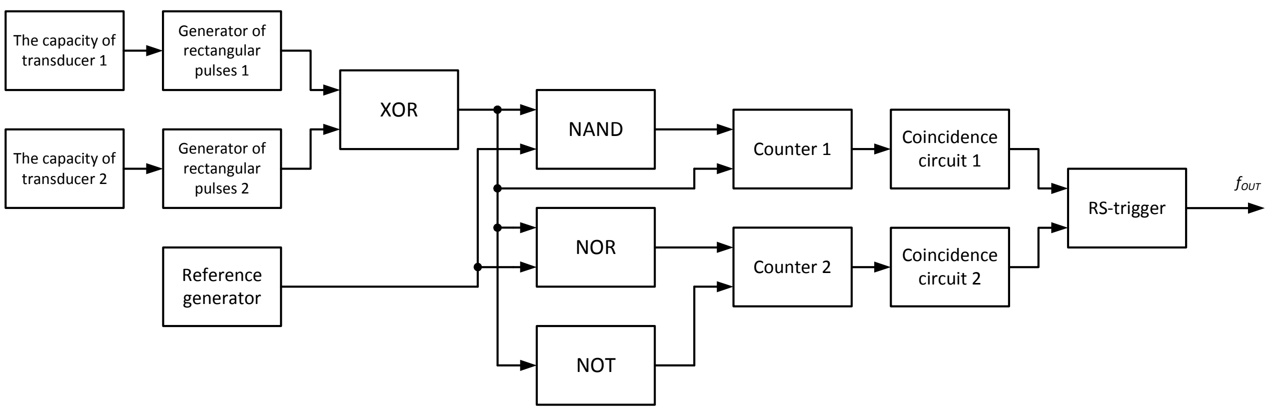


Figure 3. Functional scheme of the second variant of the device for signal processing of the micromechanical capacitive transducers

First variant is the analog variant of the scheme. In this scheme generators of harmonic signals, which frequency control circuits include micromechanical transducer capacitances, are used. These transducer capacitances change under the influence of angular velocity or linear acceleration. Generators signals are sent to the input ports of the mixer, which forms beat signal with an envelope frequency equals to difference of the generators signals frequencies. Than detector selects the envelope of the beat signal and it is sent to the input port of the amplifier, which amplifies the amplitude of the detected signal. From the output port of the amplifier signal is sent to input port of the rectangular pulses former of the difference frequency.

Second variant is the digital variant of the scheme. In this scheme generators of rectangular pulses, which frequency control circuits include micromechanical transducer capacitances, are used. Generators rectangular pulses are sent to the input ports of the XOR mixer that forms a sequence of rectangular pulses. Duration and duty cycle of these pulses periodically change with frequency equal to difference of the generators signals frequencies. Signal from the output port of the XOR element is sent to input of difference frequency rectangular pulses former. This former consists of a reference oscillator, logical elements such as NAND, NOR, NOT, two pulse counter, coincidence circuits and RS-trigger.

Signal from the output port of the XOR mixer with periodically changing duration and duty cycle is sent to input ports of the logical elements NAND and NOR. High frequency signal of reference oscillator is sent to another input ports of these elements. Frequency f_{REF} of this signal can be determined as follows:

$$f_{REF} \approx 2^R f, \tag{8}$$

where R is the bit depth of the pulse counter; f is the frequency of the first generator in the initial condition.

Pulse packets of the reference generator are formed on the output ports of the logical elements NAND and NOR. These pulse packets fill the output pulses of XOR element (on the NAND output) and the intervals between these pulses (on the NOR output).

Then pulse packets arrive at the counting inputs of the counters. In this case the counters are reset by antiphase pulses with the input and output of the NOT element.

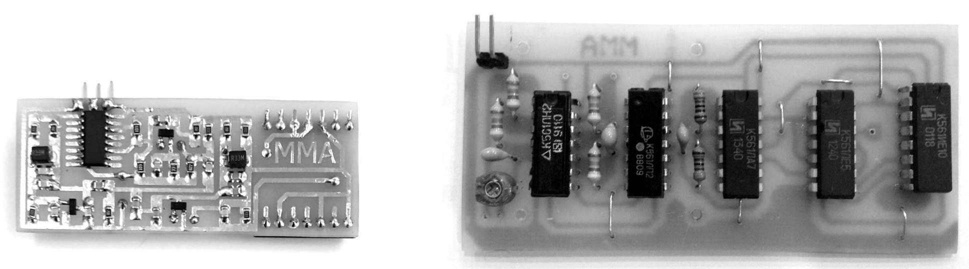
The outputs of counters sent to the inputs of coincidence circuits. These circuits select signaling packets with a maximum number of reference generator pulses and send it on the inputs of the first and second counters.

The outputs of the coincidence circuits control RS-trigger which output port forms rectangular pulses of the difference frequency.

First variant of the analog scheme of the device for signal processing can be realized using the smallest number of elements. In the same time, the second digital variant is more convenient for the integrated implementation, because it can be realized using standard technologies of fabrication of digital integrated circuits.

4. RESEARCH OF SIGNAL PROCESSING DEVICES BREADBOARDS

Breadboards of the device for signal processing of the micromechanical capacitive transducers based on the functional schemes were realized. These breadboards shown on Figure 4.



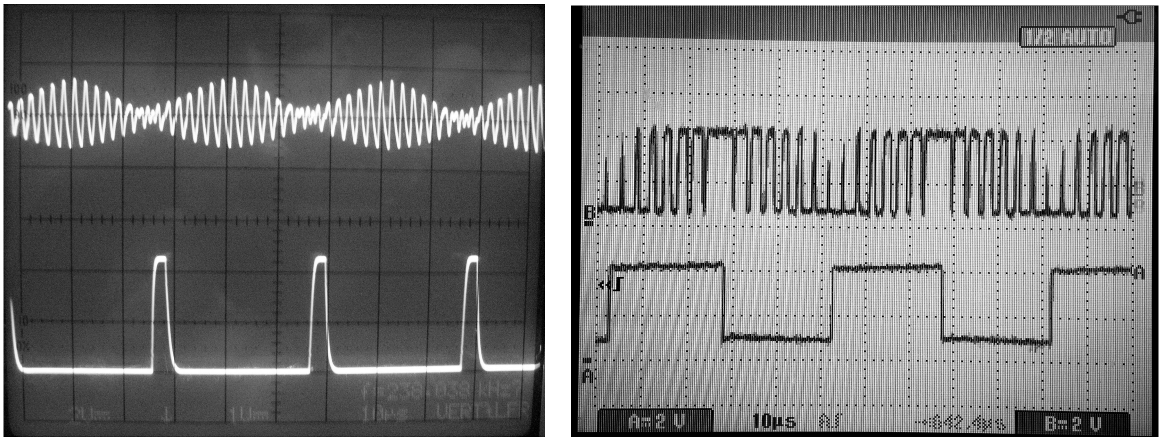
a b

Figure 4. The breadboards of the analog (a) and digital (b) variants of the device for signal processing of the micromechanical capacitive transducers

Oscillograms that were obtained studying breadboards of the device for signal processing are shown on Figure 5. The upper oscillograms show output signals from the mixers of analog (Figure 5,a) and digital (Figure 5,b) variants of the device for signal processing layouts. The lower ones show output difference frequency signals of the breadboards.

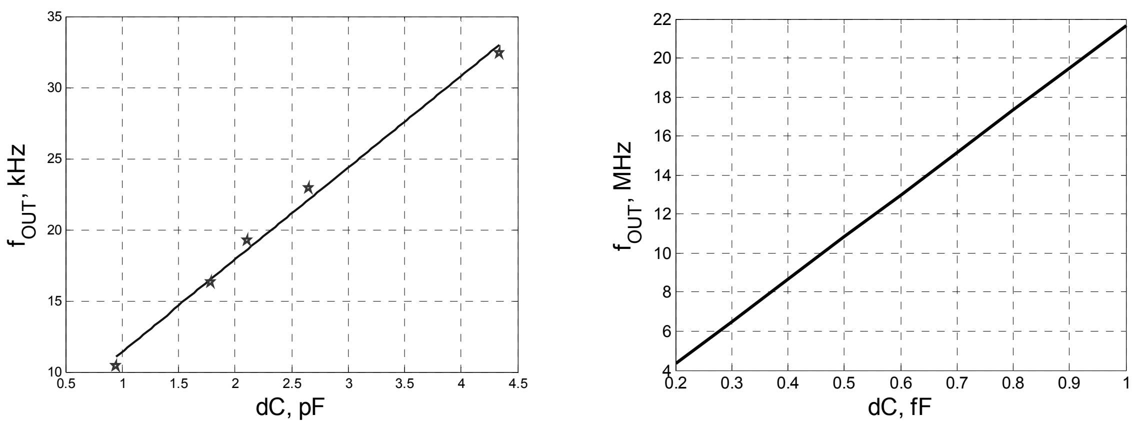
It can be seen that signal of the analog mixer (Figure 5,a) has the form of the beats with envelope frequency equals to output difference frequency of the device. Signal from the digital mixer (Figure 5,b) has the form of the rectangular pulses sequence, which duration and duty cycle periodically change with frequency equal to output difference frequency that is shown on lower waveform.

Figure 6 shows the dependence of the difference frequency of the processing device output signal obtained in the study of the breadboard (Figure 6,a), and on the basis of circuit simulation results (Figure 6,b) with the parameters of the device elements, corresponding to the integral performance with design rules 500 nm.



a b

Figure 5. Oscillograms of the analog (a) and digital (b) breadboards of the device for signal processing of the micromechanical capacitive transducers: output signals from the mixers (upper oscillograms) and output difference frequency signals (lower oscillograms)



a b

Figure 6. Dependences of the difference frequency of the output signal processing device on the micromechanical transducers capacities changes obtained in the study of the breadboard (a) and based on circuit simulation (b), with the parameters of the device elements, corresponding to the integral performance with 500 nm design rules

According to Figure 6,a the sensitivity of the transfer characteristic obtained in the study of the processing device breadboard, was 6,3 kHz/pF. According to Figure 6,b the sensitivity of the transfer characteristic resulting from the circuit simulation of the project of signal processing device integrated implementation amounted 21,3 MHz/fF. In both cases, it is achieved a high transfer function linearity.

5. CONCLUSION

Signal processing device for micromechanical capacitive transducers of the gyroscopes or accelerometers presented in this study designed without the use of highly sensitive charge amplifiers. These devices have a frequency output and realize the direct conversion of "capacity-to-frequency" through the inclusion of capacities of a micromechanical transducer into frequency control circuit generators. In this case the noise charge and current fluctuations, firstly, not amplified due to the absence of highly sensitive amplifier, and secondly, make some distortion only in the form of output pulses, but practically no effect on their repetition frequency, which is informative parameter. The result is a high resistance of the device to the effects of noise.

Due to the difference principle of the output pulse formation coefficient of the signal conversion in the micromechanical capacitive transducers processing device can reach more than 10^5, providing high transfer function sensitivity (21,3 MHz/fF as a result of the circuit simulation of the device integrated implementation project).

An additional advantage of the proposed construction principles of micromechanical transducer signal processing devices is increased resistance to the effects of destabilizing factors in the external environment, such as temperature and humidity. This is because the frequency of the signal generators under destabilizing factors influence will vary substantially equally and the corresponding changes of the difference output signal frequency would be extremely small. In accordance with the expression (7) temperature coefficient of the difference-frequency device output signal can have values in the 2 – 5 orders of magnitude smaller than the temperature coefficient of the generator frequency with micromechanical transducer capacities in the frequency control circuit.

Developed and manufactured breadboards confirmed the effectiveness of the proposed construction principles and functional schemes for high sensitivity capacitive micromechanical transducer signal processing devices with high resistance to noise and linearity of the transfer characteristic.

The results have been obtained using the equipment of the Shared Equipment Center and the Research and Educational Center “Nanotechnology” of the Institute of Nanotechnologies, Electronics and Electronic Equipment Engineering, Southern Federal University (Taganrog, Russia). This study was supported by the Ministry of Education and Science of the Russian Federation (contract №14.575.21.0045 from June 30, 2014, RFMEFI57514X0045).

REFERENCES

[1] Verner, V. D., Malcev, P. P., Reznev, A. A., Saurov, A. N. and Chapligin, Yu. A., “Modern Tendencies in Development of Micro System Technique,” Nano- and microsystem technology 8, 2-6 (2008).
[2] Raspopov, V. Ya., [Micromechanical devices], Mashinostroeniye, Mockow, 400 (2007).
[3] Lysenko, I. E., Ryndin, E. A. and Dudin, N. K. “Signal Processing Devices of Micromechanical Components Capacitor Converters,” Nano- and microsystem technology 7, 48-51 (2012).