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DEVELOPMENT OF THE ACCELERATION MEASURING METHOD

The existing acceleration measuring methods are analyzed in the article. An overview of modern research on this topic is also provided. A new method of measuring acceleration in the form of an electrical circuit using a stable frequency generator is developed. Among the already known methods, the following three groups are highlighted in the analysis: methods based on compensatory accelerometers with discrete output; methods based on accelerometers with the analog-to-digital converter; measurement techniques, which use mounted elements. The main difference between the proposed method and the existing ones is the use of circuits of two resonant circles with built-in capacitance sensors, developed according to microelectromechanical system technologies. The principle of operation of the acceleration measuring device is described in the article, and its structural diagrams are provided. The peculiarities of the functioning of its components are analyzed. The main advantages of using the proposed method are highlighted. It is described the technical difference of this method from those already implemented ones, which also lies in the presence of an additional transformer. Based on the proposed method of measuring acceleration in the form of an electrical circuit, the operating frequency characteristics of the device are investigated. The stages of conversion of accelerometer signals are described in the article as well as the forms of input and output signals. The use of two resonant circles within built capacity sensors and the stable frequencies generator in the scheme of acceleration measuring device allows for measurement of the frequency characteristics changes in resonant circuits with minimum capacity changes in sensors. The resulting frequency value is linear in the range of the accelerometer frequency due to the frequency characteristics of the first and second resonance circles, which are reversed and symmetrical about the horizontal axis. A feature of the developed new measurement method is the possibility of using this scheme at very low input voltages. Due to the proposed method, it is possible to increase the accuracy of acceleration measurement and expand the working capabilities of the device. In its turn, it allows applying this device in vibration and position variation conditions.

Keywords: method; resonant circuit; built-in capacitors; microelectromechanical systems; measurement; acceleration; accelerometer; electrical circuit.

Introduction / Вступ

Nowadays, several new scientific and technological areas, which allow the creation of fundamentally new and improvement of existing technological systems, are developing. Microelectromechanical systems [1], [2] are widely used in various fields of science and technology, namely: medicine [3], military techniques [4], outer space [5], domestic technologies [6], acoustic systems [7] and others, they are one of the representatives. The microelectromechanical systems (MEMS) technologies usage enables significant improvement of the developed technical product output settings since MEMS devices have high reliability, low cost and weight, bulk production technology etc. MEMS are used for backend technical devices manufacturing as well as for systems components development: sensors, actuators, microdevices etc. Accelerometers [8], which are referred to as acceleration sensors, have the most significant percentage of such microdevices.

The acceleration sensors are used for getting accurate acceleration values in real time [9], [10], [11], [12]. Such sensors have different shapes and sizes and are based on different acceleration measuring methods [13], [14], [15]. These devices also have different requirements: measuring accuracy, speed, sustainability, high sensitivity, possibility to be developed using group technologies. The vibrating beam MEMS accelerometers can be employed for measurements requiring high levels of stability and resolution with wider implications for precision measurement employing other resonant-output MEMS devices such as gyroscopes and magnetometers [13]. Apart from the mentioned requirements, there are different methods groups for processing signals from sensors and, actually, acceleration measuring.

Accordingly, the development of new methods and improvement of the existing ones with higher acceleration measurement accuracy is the *actual* task nowadays.

The object of research is the measurement process in the acceleration sensors.

The subject of research is a method of constructing a device for measuring acceleration.

The purpose *of the* research is to develop a new method of measuring acceleration in the form of an electric circuit with built-in capacitive sensors, developed using the technologies of a microelectromechanical system, as well as using a stable frequency generator.

To achieve this *purpose*, the following *main research objectives* are identified:

- analysis of existing methods of measuring accelerations and highlighting the main advantages and disadvantages;
- description of the technical side of the developed method;
- research of the main characteristics of the device (in particular, signal processing);
- analysis of device capabilities.

Analysis of recent research and publications. During analysis of the existing methods the three following acceleration measuring methods groups can be distinguished: 1) methods based on compensatory accelerometers with discrete output [16], [17]; 2) methods based on accelerometers with the analog-to-digital converter [18], [19], [20]; 3) measurement techniques which use mounted elements [21].

In the first group of methods, the accelerometer sensor contains the sensitive element with strength and displacement sensors, the reversed connection amplifier and the integration current in the frequency converter [16], [17]. Moreover, the reversed connection amplifier inlet is joined with the displacement sensor. In addition, this block is equipped with inductance and the capacitor, which are connected in series between each other, and in parallel with the integration converter inlet. Between the inductance capacitor and one of the input amplifier's terminals connection points, there is a switched resistor. The disadvantage of this method is the limited scope of use in the Microsystems field, which is due to a pendulum-type sensor, which requires significant sizes of the pendulum, and the pendulum deviation countdown mechanism. The other reason is the impossibility to measure small accelerations.

Methods, based on accelerometers with the analog-to-digital converter (ADC) [18], [20], improve linear accelerations measurement, using compensatory accelerometers with analog-to-digital converters with incoming integration capacitor [19] by enhancing its output discreteness via additional incoming converter's comparators while improving sustainability with the help of RC-filter, which is located between accelerometer's analog part output and converter's analog-to-digital input. The impulse of referenced dischargeable current is given to the capacitor's input when the voltage value became equal to the ratio of referenced current and referenced time product to the electrical capacities of the analog-to-digital converter's input integration capacitor, and the capacitor's RC-filter sum. While the additional information impulses are formed, the input capacitor has a part of mentioned voltage proportional to the additional comparator serial number to the total comparators' number ratio.

The disadvantage of this method is the high measurement error level due to the device's insensibility to small accelerations, and the force impact on the moving device's mechanical elements. The other drawbacks are concentrated in gauge and are caused by the irregularity of additional comparators triggering level settings. The presence of such items as capacitors for signals transmission in RC filters, integration and separating circles prevent micro sizes of such devices.

Measurement techniques, which use mounted elements, are based on the device consisting of two electrodes-capacities, located on both sides along one measuring body axis. Each electrode is connected through a resistor with a power source, and through the according transistor with the ground. The electrodes are also switched to two inputs of a differential amplifier, which output through the sampling. And the storage device is combined with the output of the measuring device [21]. The conductive impulse voltage is provided to the transistors' basis. In the case of transistors openness, the voltage on the electrodes is equal to zero, or closeness – the voltage on electrodes grows according to the exponential low.

The main disadvantage of the moving bodies measurement method is significant measurement error, caused by the device's insensibility to small accelerations, which affects measurement accuracy. Additionally, the above-mentioned device's body is conventionally grounded, and therefore there is possible potential displacement. The other minus is body movement, stipulated by friction, e.g., with the air. As an outcome, the parasitic electrical charge can occur, decreasing measurement accuracy and operational capabilities.

Materials and methods of research. In comparison to existing approaches, the technical essence of the developed method is the presence of a transformer additional. Primary transformer winding is connected to a generator outlet-stable frequency generator, and secondary winding outlets are linked with two consistently joint acceleration capacity sensors. Besides, the peculiarity of the method's practical realization is that every capacity sensor is parallel connected to the appropriate section of transformer secondary winding and the first inlets of the oncoming connected peak detectors, secondary inlets through a joint point between acceleration capacity sensors are coupled to the middle point of secondary transformer winding.

Research results and their discussion / Результати дослідження та їх обговорення

There is a well-known device for body acceleration measuring, which contains two capacitive electrodes. Each of them is connected to the power supply via the appropriate resistor and with the ground through the corresponding transistor. Besides, the electrodes are tied with two inlets of the differential amplifier, where the outlet is connected with the device outlet through sampling and storage construction.

The disadvantage of this device for measuring body movement is the scheme's complexity and limited operational capacity due to the need for measured body grounding.

Development of the acceleration measurement method. The acceleration measuring device [21], which contains a generator, two capacitive acceleration sensors and two peak detectors, with the outlets that are the device outlets, are the closest in technical case to the proposed one.

Capacity values, formed on the electrodes are very small, the range: $10^{-15} \div 10^{-18}$ F. Accordingly, complicated transformation schemes should be used for their measurement. For instance, to ensure the optimal signal conversion options, the impulses generator should create signals with the following period $1 \div 10^{-3}$ sec.

The method is based upon the challenge to improve acceleration measurement devices. It should be reached by the scheme constructing with two capacitive sensors usage. They are consistently connected with two resonance circles, which are joined with the counter-connected peak detectors, and stable frequency generator. It will measure frequency characteristics changes in resonant circuits with minimum capacity changes in capacity sensors. Additionally, it will increase acceleration measurement accuracy, and expand the device's operational capabilities.

The problem is solved by using the additional transformer in the acceleration measurement device, with the generator, two capacitive acceleration sensors and two peak detectors. Their outlets are the device outlets. The transformer's primary winding is connected to the generator outlet, used as a stable frequency generator. The secondary winding outlets are linked with two consistently joined acceleration capacitive sensors and with the first counter-connected peak detectors, whose second outlets are connected with the middle point of the transformer secondary winding via the joint point of two consistently connected acceleration capacity sensors.

The use of two resonant circles within built capacity sensors and the stable frequencies generator in the acceleration measuring device diagram enables measuring frequency characteristics changes in resonant circuits with minimum capacity changes in capacitive sensors. That increases acceleration measurement accuracy extends the device usability, and allows applying it in vibration and position variation conditions.

Figure 1 demonstrates the structure of the acceleration-measuring device. Figure 2 presents the acceleration measuring device circuit diagram. Figure 3 depicts frequency characteristics.

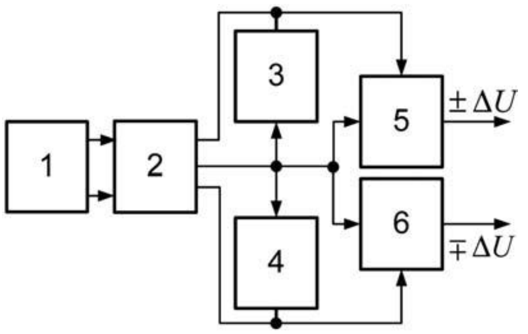

Fig. 1. Acceleration measuring device diagram / Схема пристрою вимірювання пришвидшення

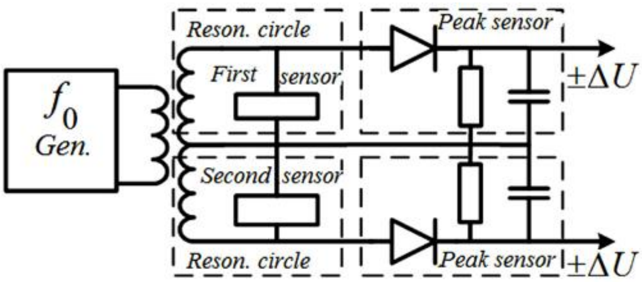

Fig. 2. The device's electric circuit diagram / Електрична схема пристрою

The acceleration measuring device (fig. 1) has a stable frequency generator (1) with outlets, connected to the transformer (2) primary winding, and the secondary winding outfits, tied with two consistently joined acceleration capacity sensors (3, 4). Therefore, each of the capacitive sensors is connected in parallel to the corresponding section of the transformer (2) secondary winding. Moreover, the first inlets of the counter are linked to peak detectors (5, 6) with the second outlets, connected with the middle point of the transformer (2). The secondary winding via the joint point of two consistently is linked to acceleration capacity sensors (3, 4).

The acceleration measuring device has the following workflow: two capacity sensors, located on the investigated object, are used to measure the acceleration. The signal from the stable frequencies generator (1) is given to the transformer (2) primary winding. And subsequently to the first resonant circuit, formed by the transformer (2) secondary winding and the acceleration capacitive sensor (3), and to the second resonant circuit, formed by the transformer (2) secondary winding, and the second acceleration capacitive sensor (4). In the case of acceleration – the first acceleration sensor (3) capacity increases, and the capacity of the second one (4) – decreases. When the acceleration direction changes, the first acceleration sensor (3) capacity decreases, and the second one – increases. In case of additional acceleration, both circuits change their settings due to the capacity value variation (fig. 3,*a*). When there is positive acceleration, capacity increases on both acceleration sensors (3, 4) (f_1–Δf, f_2–Δf), where f_1 is the first circuit's oscillations frequency; f_2 is the second circuit's own oscillations frequency; Δf is the frequency change magnitude value.

As a result, the frequency value is shifted to the right (fig. 3,*b*). When the acceleration vector changes, capacity decreases on both sensors (3, 4) (f_1–Δf, f_2–Δf).

Thereby, the frequency value is moved to the left (fig. 3,*c*). It should be taken into account that in both cases one should use such acceleration sensor capacities in the first and second resonant circuits. In the case of the acceleration vector both increase, and on the opposite vector – decrease.

If the acceleration is absent, the device's resulting frequency will be as shown in fig. 3,*d*. The characteristic has zero value at the point $f = f_0$. Resonant frequencies f_1 and f_2 are equally distanced from the frequency f_1, and, when circuits' parameters are equal, the resulting frequency is symmetric in relation to the point $f = f_1$, and $U_{out} = 0$. If there is the acceleration vector, which causes capacities reduction on both sensors (3, 4), frequency characteristics of the resonant circuits are displaced in relation to their initial position on Δf value, as it is shown in fig. 3,*b*. The resulting device frequency value is evenly shifted on Δf value to the right. Since the frequency sensor device outlet obtains the stable frequency generator signal, there will be –ΔU voltage, formed on the device outlet, fig. 3,*b*. If an acceleration vector is present, the frequency characteristics of the resonant circuits are displaced in relation to their initial position on the Δf value (fig. 3,*c*), which causes capacities' increase on both sensors (3, 4). The resulting device frequency value is evenly shifted on Δf value to the right. Since the frequency sensor device outlet gets the stable frequency generator signal, there will be +ΔU voltage formed on the device outlet (fig. 3,*c*).

The accelerometer signals converting scheme. The direct current amplifier (DCA) with MDM channel [22], [23] was used for the signals processing scheme in the developed accelerometers.

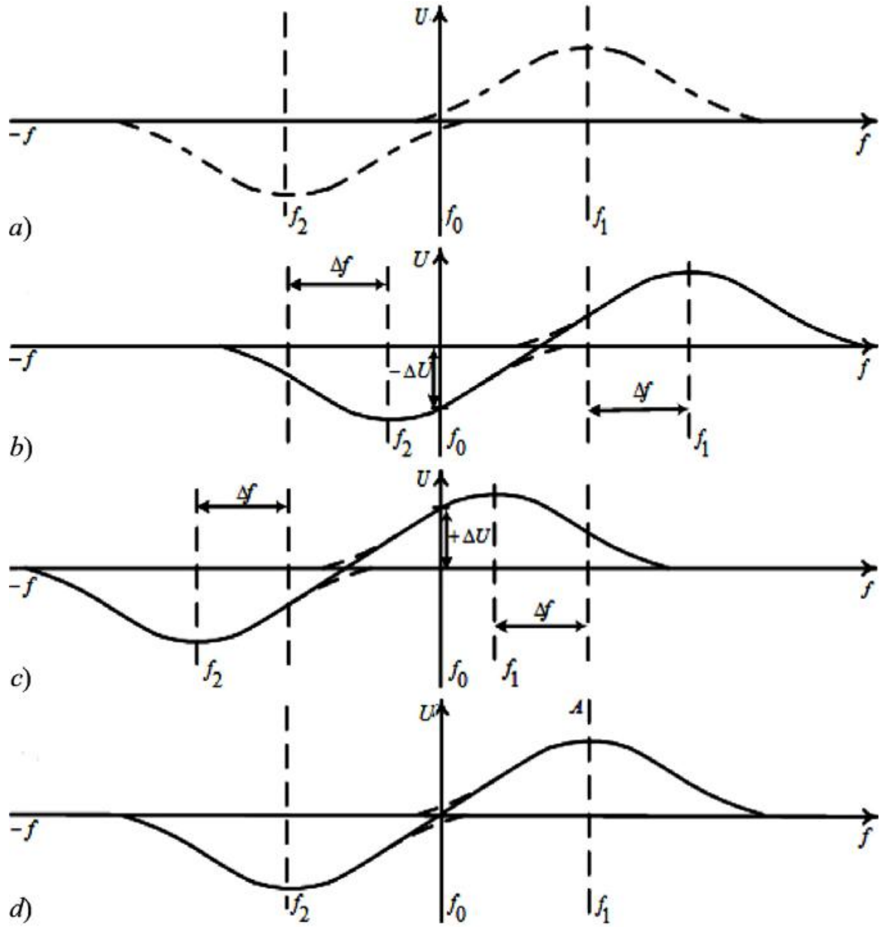

Fig. 3. The device performance frequency characteristics based on the suggested acceleration measuring method / Частотні характеристики роботи пристрою на підставі запропонованого методу вимірювання пришвидшення

This channel is used for amplifying the input voltage, which is less than a hundred microvolts. The amplifier block diagram is presented in fig. 4. The main principle is described by slowly changing signal voltage, which is transformed into the alternating current voltage with amplitude varying proportionally to the input signal changes. The AC amplifiers amplify the converted signal. The amplifier outlet has a rectifier, which straightens the signal that is amplified according to the input signal polarity. The input signal to the alternating current voltage conversion is made by the frequency transducer-modulator usage.

It should be taken into account that the signal, which arrived from the capacitive sensor, is already modulated by the frequency vibration. The modulator block can be eliminated from the block diagram, and replaced with the differential amplifier. In this case, the scheme will be as shown in fig. 5.

The AC signal is converted into the output signal by the frequency sensor rectifier-demodulator at the amplifier outlet. The demodulator obtains the rectangular voltage, called reference or carrier frequency voltage. The Low-frequency filter (LFF) at the demodulator outlet selects the useful signal range and does not pass the side transformation products, which lie above the highest output signal frequency. To ensure the conversion settings stability DCA has the reversed connection. At the LFF the output signal is integrated and supplied to the read-only memory storage device inlet, which is the analog signal fixation block (ASFB) (fig. 6).

Discussion of research results. The output signal U_{out} is a measured capacity dependency function on the applied acceleration: the vibration amplitude is converted into a direct current voltage (fig. 7). At the AC the amplifier U_{subs_2} signal has the same shape as the input signal. At the integrator output the U_{out} signal takes a pulverized shape, and is fixed in the read-only memory storage device U_f with the following capture delay T_f.

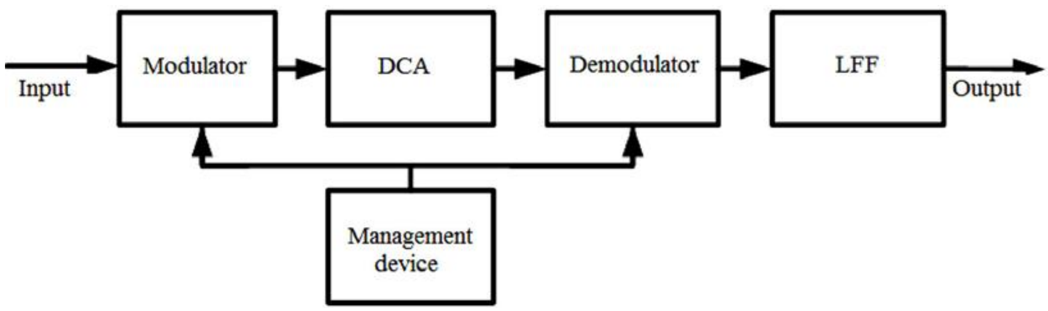

Fig. 4. The DCA with MDM block diagram / Блок-схема DCA з MDM

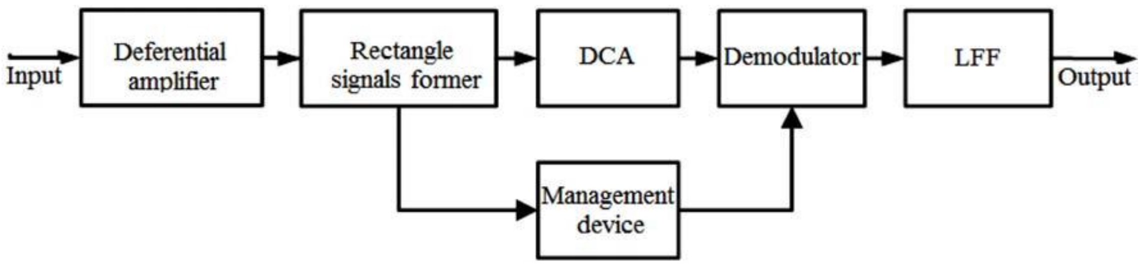

Fig. 5. The DCA with differential amplifier block diagram / Блок-схема DCA з диференціальним підсилювачем

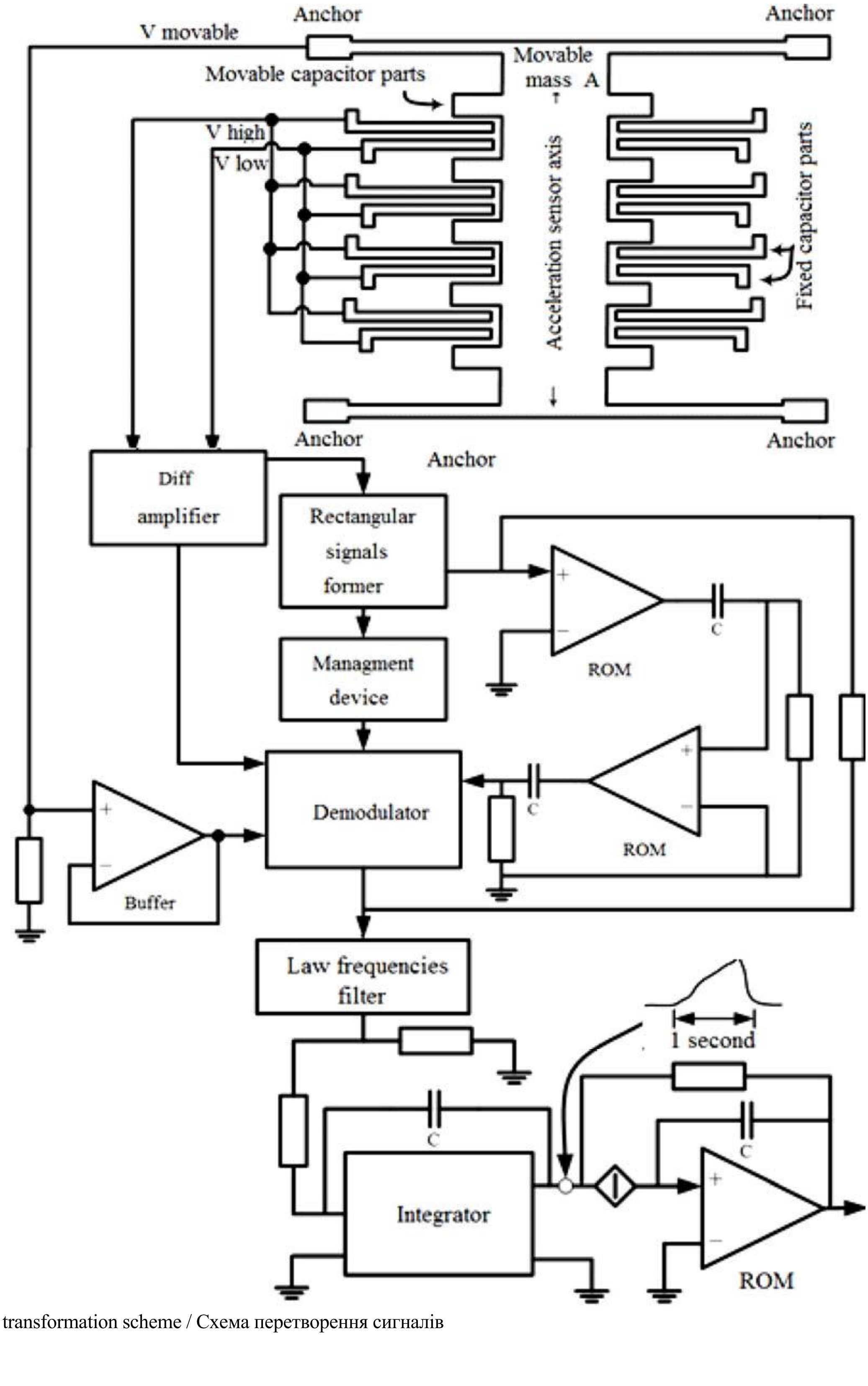

Fig. 6. Signals transformation scheme / Схема перетворення сигналів

Since the first and second resonant circles' frequency characteristics are inverse and symmetrical related to the horizontal axis, the resulting frequency value is linear in the accelerometer frequencies range.

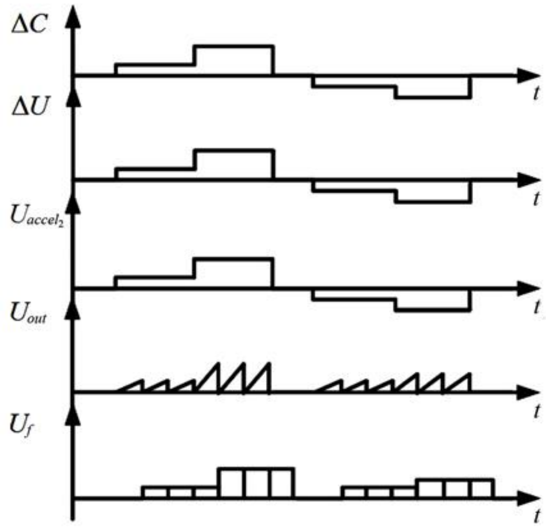

Fig. 7. Form of input and output signals / Форма вхідних і вихідних сигналів

The feature of the developed *new method* of measuring accelerations is the possibility to use this scheme with very low input voltages: below one hundred microvolts. It is performed by the direct current amplifier impact with the differential amplifier, which handles signals from the micro accelerometer.

So, based on the results of the work performed, it is possible to formulate the following scientific novelty and practical significance of the research results.

The scientific novelty of the obtained research results – a new method is developed for measuring acceleration in the form of an electrical circuit using a stable frequency generator.

The practical significance of the research results – the proposed method will allow to increase in the accuracy of acceleration measurement and expand the working capabilities of the device, which enables applying this device in vibration and position variation conditions.

Conclusions / Висновок

The article describes the development of the first acceleration measuring method, which differs from the existing ones. In its diagram, the two resonance circles are used with included capacity microsensors, constructed with the help of MEMS technologies, and also the stable frequency generator is applied. Thereby, that allows measuring frequency characteristics change in resonant circuits with minimum sensor capacity changes. As an outcome, acceleration measurement accuracy increases, the integrated device performance possibilities are extended, and the working process in vibration and position variation conditions is enabled. In addition, the signals converting scheme for the capacitive type accelerometer was developed. The scheme's peculiarity is its possibility to work with very low input voltages: below a hundred microvolts. It is performed by the direct current amplifier impact with the differential amplifier, which handles signals from the micro accelerometer. This feature has great importance in the microelectromechanical systems' design.

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РОЗРОБЛЕННЯ МЕТОДУ ВИМІРЮВАННЯ ПРИШВИДШЕНЬ

Проаналізовано наявні методи вимірювання пришвидшень, наведено сучасні дослідження з даної тематики та розроблено новий метод у вигляді електричної схеми з використанням генератора стабільної частоти. Серед уже відомих методів виділено три такі групи – на підставі компенсаційних акселерометрів з дискретним виходом, на підставі акселерометрів з аналого-цифровим перетворювачем та методи вимірювання з використанням навісних елементів. Основною відмінністю запропонованого методу від наявних є використання в його схемі двох резонансних контурів із вбудованими давачі ємності, розроблених за технологіями мікроелектромеханічної системи. Описано принцип роботи пристрою вимірювання пришвидшення, наведено його структурні схеми та проаналізовано особливості функціонування його складових. Наведено основні переваги застосування запропонованого методу та описано його технічну відмінність від уже впроваджених, що полягає також у використанні додаткового трансформатора. На підставі запропонованого методу вимірювання пришвидшення у вигляді електричної схеми досліджено робочі частотні характеристики пристрою, описано етапи перетворення сигналів акселерометра та наведено форми вхідних і вихідних сигналів. Використання двох резонансних кіл у вбудованих давачах потужності та генератора стабільних частот у схемі приладу вимірювання пришвидшення дає змогу визначати зміни частотних характеристик у резонансних контурах з мінімальними змінами потужності в ємнісних давачах. Остаточне значення частоти є лінійним в діапазоні частот акселерометра, оскільки частотні характеристики першого і другого резонансних кіл є зворотними і симетричними відносно горизонтальної осі. Особливістю розробленого нового методу вимірювання пришвидшень є можливість використання цієї схеми при дуже низьких вхідних напругах. Завдяки запропонованому методу можна досягти підвищення точності вимірювання пришвидшення, розширення робочих можливостей самого пристрою, а це дає змогу застосовувати його в умовах вібрації та зміни положення.

Ключові слова: метод; резонансний контур; вбудовані давачі ємності; мікроелектромеханічні системи; акселерометр; електричне коло.

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