A FREQUENCY DETERMINATION METHOD FOR AUTOMOTIVE NANOSENSORS

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Abstract. *The growing popularity of nanosensors in various automotive applications requires new methods for counting the frequency of electrical signals, into which the measured non-electrical parameters are converted. This need is because automobile nanosensors are to register very small changes in the measured parameters that, besides, can change very fast. The paper proposes for use in automotive nanosensors a frequency calculation method based on the principle of rational approximation, which meets the above requirements.*
Key words: *automotive nanosensors, frequency measurement, rational approximation.*

Introduction

A modern automobile is a complex mechatronic system that includes mechanical and electronic components connected with a single sensor network [1, 2]. A significant part of the promising and existing automotive sensors based on nanotechnology [3–5]. Nanosensors allow for the reduction of the size of the sensor at a lower cost.

On the other hand, nanosensors have some significant differences from traditional ones. First, the sensitivity threshold of nanosensors can be minuscule. Second, the values of the physical parameters measured by the sensors can change very fast. These factors cause some significant difficulties after converting the measured parameter to the frequency of the electrical signal, since the classical methods of frequency measuring [6] do not allow the frequency to be registered fast and accurately at the same time. Nevertheless, frequency-domain sensors are some of the most promising tools in metrology due to their high resolution and sensitivity, wide dynamic range and good stability [7]. Moreover, many physical parameters can be easily converted into the frequency of an electrical signal. Thus, frequency measurement methods are needed that meet all the requirements for use in automotive nanosensors.

Review of the literature

The first frequency counters used conventional counting when the number of input cycle trigger events occur during a fixed reference gate was counted [8, 9]. Due to the simplicity of implementation, this method is still used. However, it is not suitable for low and medium frequencies.

The wide spreading of microcontrollers contributed to the using of reciprocal frequency counting [8–10]. In this method, the average cycle time MT is first determined, over which N input signal periods are registered. Then the mean frequency value is calculated:

$$f_x = \frac{N}{MT} . \qquad (1)$$

Further evolution of frequency counting is associated with both the improvement of reciprocal counting and the development of new methods: continuous time-stamping method [8]; the dependent count [9]; methods, based on delay-chain technique [11, 12], and multi-average frequency measurement principle [13].

There are some methods, provides for the conversion of an analogue sine signal to a digital signal which is then processed by any digital signal processing technology, for instance, based on Fast Fourier Transform [14, 15].

Purpose and Problem Description

The literature survey shows the presence of numerous frequency counting methods that are used to measure various non-electrical quantities. However, some of these methods are complicated or need expensive instruments, and some of them long time for data processing. This paper proposes to use the method for determining the signal frequency presented by the authors earlier [16–18] in modern automotive nanosensors to ensure the speed and accuracy of measurements.

The rest of the paper is organized as follows. The following section reviews the applications of automotive nanosensors and describes the design and principles of operation of some of

them. Then, the main provisions of the method for determining the frequency are given, some examples are considered, and the accuracy of this method is analyzed. Finally, concluding remarks are given in the last section.

Applications of nanosensors in automotive industry

Recent advances in nanomaterials and nanotechnology have made them promising for automotive applications. Today nanotechnology is used in the production of lightweight and durable cars bodies, their components and assemblies, more resistant paints, antifriction layers, and antiwear additives, etc. [3, 4, 19–21]. The use of nanotechnology opens up tremendous opportunities in various automotive monitoring and control systems. It is well known that a modern automobile has a huge number of sensors [1, 22-26]. Their growing responsibilities are taken care of improving the performance, safety, and comfort aspects. All the variety of these sensors can be divided into the following groups (Fig. 1):
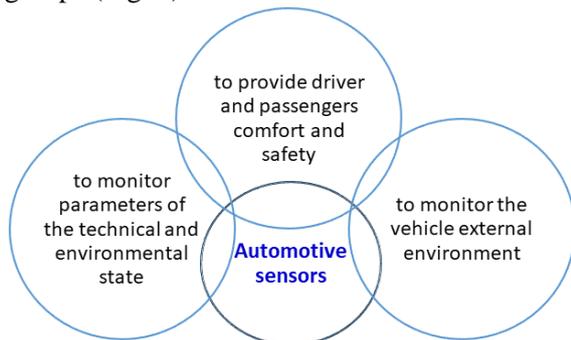
Fig. 1. Automotive sensors classification

i) to monitor various parameters of the technical and environmental state of the vehicle;

ii) for systems that provide driver/passengers comfort and safety;

iii) sensors for monitoring the vehicle external environment.

This classification is conditional since, for instance, sensors that monitor the external environment can be attributed to systems for improving driving safety, etc.

Further development of sensors for these applications is associated with the use of nanotechnology. Nanosensors offer at the same time several key attributes such as small size elements, low power consumption, fast response time, high sensitivity and selectivity.

A nanosensor is a measuring device that combines electronic and mechanical components, the size of which does not exceed 100 nm, which is more than a thousand times smaller

than the diameter of a human hair and slightly larger than the size of one atom. By now, a number of nanoelements suitable for use in nanosensors have been developed. These include Carbon Nanotubes (CNT), nanowires based on semiconductor materials, metals, dielectrics, high-temperature oxides, nitrides, etc. [4, 27, 28].

There are different types of nanosensors that measure various physical parameters. For example, pressure sensors are widely used in vehicles for engine control systems to improve the vehicle fuel efficiency (e.g., monitoring manifold absolute pressure, fuel injection), to measure fuel tank, common rail and oil reservoir pressure. Moreover, pressure sensors are necessary for the brake system, adaptive suspension, air conditioning, tire pressure monitoring, airbag control. These sensors work on various principles like electro-optics, electromagnetic and piezoelectricity.

In particular, Maddipatla D. et al. [29] developed, fabricated and investigated an efficient, flexible and cost-efficient CNT-based capacitive pressure sensor. Plesco et all presented a highly sensitive piezoelectric pressure sensor based on microstructured graphene aerogel functionalized by CdS nanocrystalline thin film [30]. A piezoresistive pressure sensor (Fig. 2) with a 200 μm diaphragm with silicon nanowires (SiNWs) as the sensing element was also developed by Lou et al [31]. The sensor is able to sustain the pressure above 330 psi.
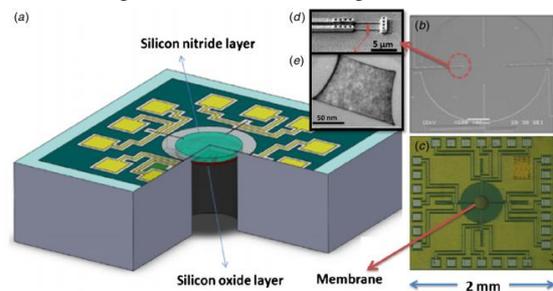
Fig. 2. (a) Schematic drawing of a pressure sensor, (b) a SEM picture of the central part of the pressure sensor, (c) an optical picture of the pressure sensor, (d) a SEM picture of a 5 m SiNW after metal deposition, and (e) a TEM picture of the SiNW [31]

Zhang (Fig. 3) also presented the sensor with silicon nanowire piezoresistors. The authors achieved a high sensitivity of 495 mV/V·MPa in the range of 0–100 kPa with the maximum of 0.13 kPa [32].

Several variants of piezoresistive pressure nanosensors were described in other reports, for instance [33–37]. Moreover, pressure

nanosensors that work on other physical principles are also developed [38].
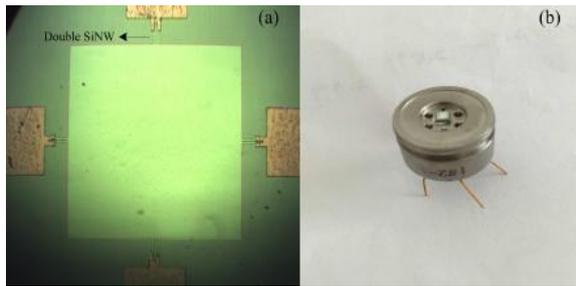
Fig. 3. (a) A photograph of the fabricated SOI pressure sensor die using double SiNW before the release; and (b) a photograph of packaged pressure sensor [32]

Other, devices, nanogenerators, have a promising potential for tire pressure monitoring, as well as for the traction coefficient determining [26, 39, 40]. The nanogenerator is a miniature device consisting of zinc oxide nanofibers, which have a well-known piezoelectric effect under the influence of low mechanical energies. These devices have a high signal-to-noise ratio, low cost, flexibility, durability, the ability to work in harsh environments, and more importantly, a nanogenerator is a source of energy.

One of the important applications of nanosensors for the automotive industry is sensors for monitoring exhaust gases [41]. The main component of the sensor is a sensitive layer placed on a solid substrate, which, in contact with the molecules of targeted gas, changes its electronic property due to the adsorption effect [28]. The components of the active layer are metal oxides and sulfides, electrically conductive polymers, and nanostructures. For example, nanocrystals of organometallic compounds of platinum exhibit high sensory activity on SO_2. Gas sensors based on carbon nanotubes are also efficient [42-44]. The problem of selectivity of components of complex gas mixtures can be successfully solved by using graphene.

Exhaust gas sensors also include sensors that measure the concentration of carbon monoxide in a vehicle cabin [45].

Apart from pressure and gas sensors, the other significant types of automotive sensors are speed and acceleration sensors, position sensors, temperature sensors, and mass/air flow sensors.

The most important automotive systems are safety systems, which reduce the burden of death and injury to drivers and passengers in road traffic accidents. With this end in view, manufacturers develop both passive (e.g., air-bags) and active safety systems, such as dynamics control systems and rollover protection systems. One of the most important factors in the improvement of such safety systems is the further development of acceleration and angular rate sensors [46–48].

These sensors contain an array of nanowires with suspended silicon mass. Mechanical loading changes the electronic properties of nanowires. Various materials are used as a material for nanowires, for example, barium titanate $(BaTiO_3)$ [49]; however, carbon modifications, in particular, graphene, are most popular [50]. Accelerometers consisting of movable and stationary electrodes made of silicon materials (Fig. 4) are also widespread [51, 52].
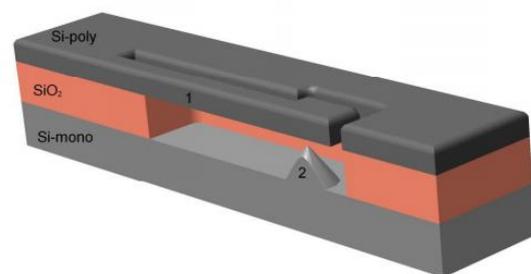
Fig. 4. Schematic representation of sensing accelerometer element based on silicon nanostructures: 1 – movable electrode; 2 – stationary electrode [51]

Most of the sensors mentioned above change some electrical parameters during the measurement. This parameter is then expedient to convert to the change frequency of the electric signal for further registration of measured data. However, as noted above, it is necessary to implement the technology of frequency signal processing, which can increase its reliability in the case of dynamic measurements using nanosensors. Nevertheless, as we can see from the above, with all the versatility of papers, devoted to automotive nanosensors, there is not a sufficient number of research devoted to improving the accuracy and reliability of frequency measurement in nanosensors. In the next section, we present the results of research [16–18], which will fill the gap in the indicated area, and their application will allow us to measure the frequency fast and accurate.

Fundamentals of principle of rational approximation

The principle of rational approximation proposed by the authors [16–18] is based on a well-

known method in which the required frequency is determined by comparison with a given standard frequency. However, the main difference is that not the usual counting of pulses in the time sample is performed, but a particular algorithm is utilised. According to this algorithm, the crossings of both frequencies is detected. For this, two regular independent narrow pulse trains with widths τ are formed (see Fig. 5). One of the train S_x corresponds to the unknown (desired) frequency f_x and the second one S_0 to the given standard frequency f_0. These trains are compared for pulses coincidence and when the pulses coincide, a coincidence pulse train $S_x\&S_0$ is generated.

The first coincidence pulse of the train $S_x\&S_0$ is a trigger to start counting pulses P and Q of the trains S_x and S_0 respectively. The second coincidence pulse of the train $S_x\&S_0$ is the stop pulse (Fig. 5). This second coincidence pulse stops the P and Q counting and their values are used for the unknown frequency f_x calculation. The corresponding block diagram of the circuit, providing the frequency f_x measurement, is shown in Fig. 8. The "Coincidence detector" block compares the trains of pulses S_x and S_0 for coincidence. Precisely at the moment of pulses coincidence, the first pulse of the train $S_x\&S_0$ is

formed which starts counting the pulses of the trains S_x and S_0 with the "P Counter" and "Q Counter". The next coincidence stops the pulses counting. The microcontroller unit MCU controls this process and calculates the frequency f_x by multiplying the given standard frequency f_0 by the ratio of the sum of pulses P and Q:

$$f_x = f_0 \frac{\sum\limits_{m} P_n}{\sum\limits_{m} Q_n}, \qquad (2)$$

where n is the number of pulses coincidence; P_n and Q_n are the number of counted pulses from the trains S_x and S_0 that occur between adjacent coincidences n and $n + 1$.

Besides, MCU stores in its memory the numbers P and Q of impulses from the trains S_x and S_0 counted by the "P Counter" and "Q Counter".

Consider the essence of the principle of rational approximation in more detail, again focusing on Fig. 5. We have two pulse trains S_x and S_0 of frequencies f_x and f_0. The periods corresponding to the frequencies are $T_x = 1/f_x$ and $T_0 = 1/f_0$. The widths τ of the pulses are equal. For this, the signal with an unknown frequency needs adjusting with maintaining the original frequency.
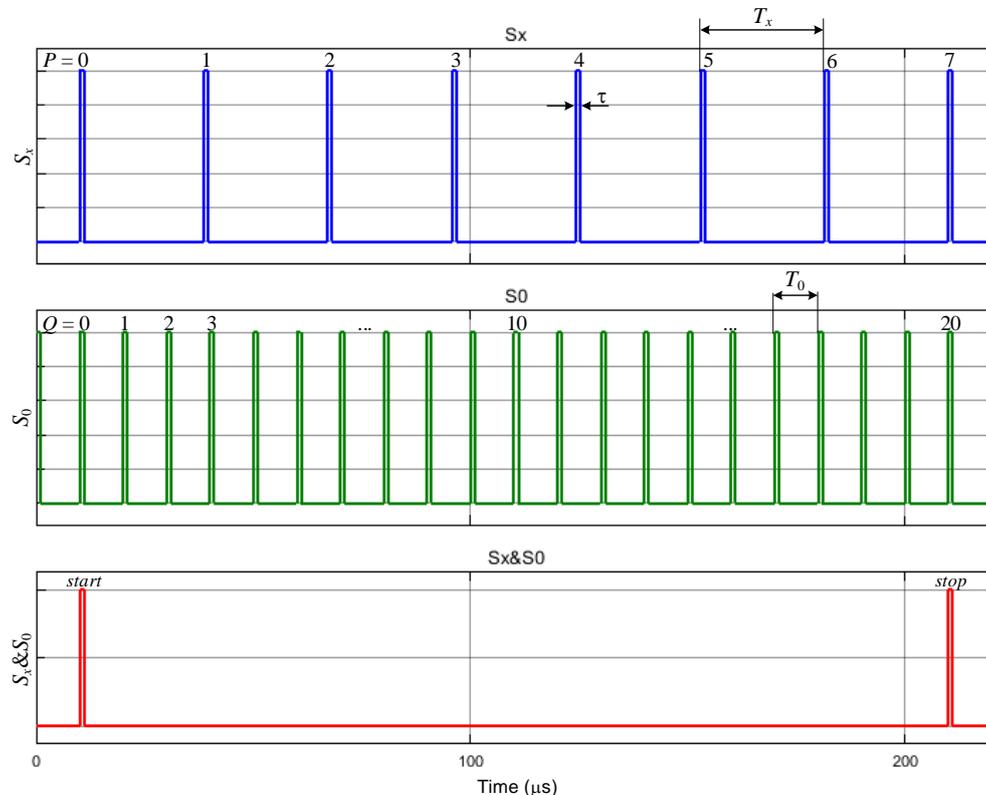
Fig. 5. Process of direct frequency comparison: geometric theory of coincidence transformation
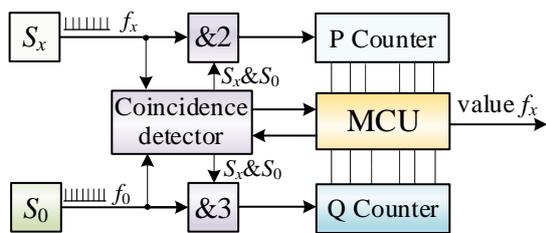
Fig. 6. Block diagram of frequency meter circuit

Denote ΔT as greatest common factor (gcf) of both periods T_x and T_0. ΔT is the minimally discernible time interval and indirectly the quantum, which, as shown below, is determined by the stability of the standard frequency. It should be noted, that ΔT and the pulses widths τ are independent parameters. With the help of gcf ΔT we can write $a = T_x/\Delta T$, $b = T_0/\Delta T$. Hence, a common multiple is $c = T_x/\Delta T \times T_0/\Delta T$. If we denote $T_{x0} = T_x T_0/\Delta T$, then $c = T_{x0}/\Delta T$.

Fig. 5 shows that some pulses from the trains S_x and S_0 coincide exactly along the time axis. In general, adjacent coincidences n and $n+1$ can be either complete or partial. The first pair of these impulses ($P_0 = 0$, $Q_0 = 0$) is a command to start frequency measurement by the frequency meter shown in Fig. 6. The Simulink diagram in Fig. 7 demonstrates one of the possible ways to determine this coincidence and generate the start pulse. An AND gate block fixes the coincidence and generates the start pulse of the train $S_x\&S_0$ (Fig. 8). The start pulse sets/resets the outputs Q and !Q of a JK flip-flop. The appearance of a logic "1" from the flip-flop Q output at the inputs of &2 and &3 begins counting the number of pulses P and Q.
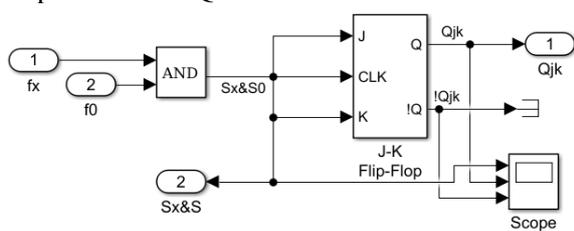
Fig. 7. Simulink diagram of the Coincidence detector

The next coincidence ($P_x = 7$, $Q_0 = 20$ in Fig. 5) generates the stop pulse which resets/sets the outputs at Q and !Q of the JK flip-flop (Fig. 8). The counting of pulses P_n and Q_n is completed and the unknown frequency f_x is calculated using the formula (2):

$$f_x = 100\frac{7}{20} = 35 \text{ kHz.}$$
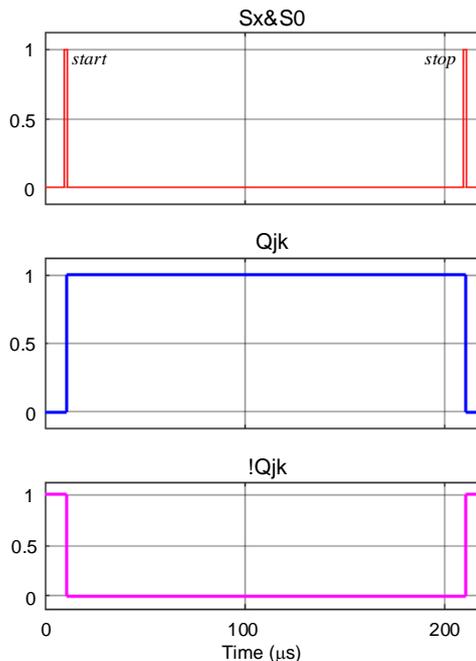
Fig. 8. Input and output signals of the JK flip-flop

Fig. 9 shows a Simulink diagram to simulate the described above example of determining the unknown frequency. The counting of pulses is performed by the "Counter P" and "Counter Q" blocks; as an example, Fig. 10 displays the contents of the "Counter P" block.

In Fig. 5 the pairs of pulses $P_0 = 0$, $Q_0 = 0$ and $P_n = 7$, $Q_n = 20$ completely coincident. However, between two completely coincident pairs of pulses, some of the pulses may coincide partially. These partially coinciding pulses can also be used to estimate the unknown frequency f_x.
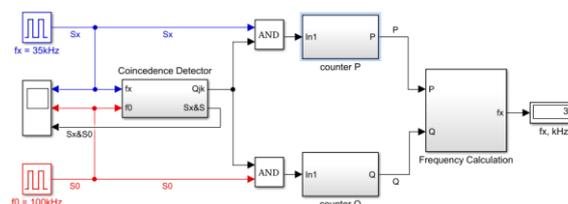
Fig. 9. Simulink diagram of the frequency counter
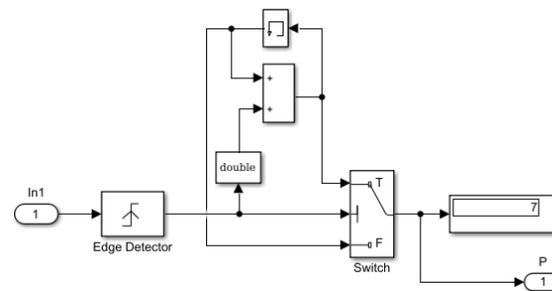
Fig. 10. Content of the block "Counter P" in Fig. 9
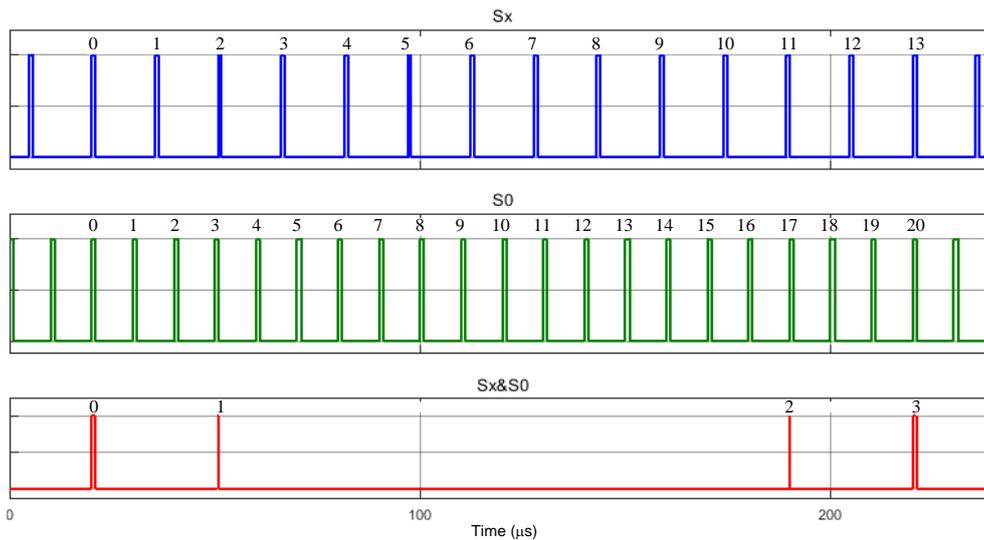
Fig. 11. The pulse trains with partially coinciding pulses

Consider as an example the pairs of partially coinciding pulses in Fig. 11: $P_1 = 2$, $Q_1 = 3$, $P_2 = 11$, $Q_2 = 17$.

Each of the ratios

$$\frac{P_1}{Q_1} = \frac{2}{3}, \ \frac{P_2}{Q_2} = \frac{11}{17} \qquad (3)$$

can be used for estimating the unknown frequency f_x. However, this estimation is not optimal. If we have two relations of the form (3), we can find the mediant [53]:

$$\frac{P_2}{Q_2} < \frac{P_1 + P_2}{Q_1 + Q_2} < \frac{P_1}{Q_1}. \qquad (4)$$

Thus, the rations (3) are approximants to each other and to their mediant:

$$\frac{P_1 + P_2}{Q_1 + Q_2} = \frac{2 + 11}{3 + 17} = \frac{13}{20}. \qquad (5)$$

The mediant (4), (5) is the specific case. For the general case, we can write:

$$\frac{\sum_m P_n}{\sum_m Q_n} \ \left(n = 1, 2..., m = 2, 3, ...n - 1\right), \qquad (6)$$

where n is the number of the ratio, and m is the number of the mediant.

Expression (6) provides continuous averaging of the pulses ratio P_n / Q_n during the measurement time.

Denote the ratio of frequencies as $\alpha = f_x / f_0$. Since the median (6) is closer to α than the fractions that form it, we can write:

$$\frac{f_x}{f_0} = \frac{\sum_m P_n}{\sum_m Q_n}. \qquad (7)$$

Using the approximants and their mediant we can calculate the value of unknown frequency and the systematic error of the frequency determination:

$$f_{xm} = f \frac{\sum_m P_n}{\sum_m Q_n}, \qquad (8).$$

where f_{xm} is the approximation of unknown frequency f_x value.

For the above example (Fig 11) equation (8) yields:

$$f_{xm} = 100 \frac{13}{20} = 65 \ \text{kHz},$$

which is exactly equal to the frequency fx from the sequence S_x in Fig. 11.

However, in the general case, calculating the frequency of an unknown sequence using coinciding pulses can be accompanied by an error:

$$\beta_{xm} = \frac{\Delta f_{xm}}{f_x} = \frac{1}{\sum_m P_n \times \sum_m Q_n}, \qquad (9)$$

where β_{xm} is the systematic error of frequency measurement.

In (5) we can chose the mediant that satisfies the following expression:

$$0 \le \left| T_x \sum_m P_n - T_0 \sum_m Q_n \right| < \Delta T. \qquad (10)$$

Conclusions

Processes in automotive systems can change very fast, so the corresponding sensors have to have a high processing speed. The use of nanotechnology in automotive sensors imposes additional requirements, such as high and resolution, wide dynamic range, and noise immunity.

The analysis of nanosensors carried out in this paper showed that most of them convert the measured parameter into a change in the frequency of the output signal.

The considered method for determining the frequency allows meeting mentioned requirements. In the first place, it increases the resolution and reduces the measurement time required for a quantitative assessment of the measured parameters. It should also be noted that the error in determining the frequency is caused only by the instability of the reference frequency, which increases the measurement accuracy.

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Метод визначення частоти для автомобільних нанодатчиків

Анотація. Актуальність. Сучасний автомобіль є складною мехатронною системою, що містить механічні та електронні компоненти, з'єднані єдиною мережею датчиків. Значна частина перспективних і наявних автомобільних датчиків на основі нанотехнологій. Проте нанодатчики мають деякі суттєві відмінності від традиційних, наприклад, менший поріг чутливості та високі динамічні характеристики. Оскільки переважна кількість автомобільних нанодатчиків перетворює зміну вимірюваного параметра на зміну частоти електричного сигналу, то актуальним є завдання використання нових методів визначення цієї частоти, та як класичні методи не дозволяють реєструвати частоту одночасно швидко й точно. Мета. Забезпечення швидкості та точності вимірювань параметрів автомобільними нанодатчиками за рахунок використання нового методу визначення частоти сигналу. Метод. Запропоновано для забезпечення швидкості та точності вимірювань сучасними автомобільними нанодатчиками використовувати метод визначення частоти сигналу, що запропонований авторами в попередніх роботах. Результати. Проведений аналіз нанодатчиків показав, що більшість із них перетворює вимірюваний параметр у зміну частоти вихідного сигналу. Наведено основні положення та приклади використання методу визначення частоти на основі раціональної апроксимації; виконано аналіз точності методу, запропоновано його технічну реалізацію. Висновки. Запропонований метод визначення частоти дозволяє забезпечити виконання вимог до автомобільних датчиків: високу швидкість вимірювання, низький поріг чутливості, а також високу точність за рахунок того, що помилка визначення частоти викликана лише нестабільністю еталонної частоти, та знижуватиметься з удосконаленням відповідних технічних засобів.

Ключові слова: автомобільні нанодатчики, вимірювання частоти, метод раціональної апроксимації.

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