OPTOELECTRONIC QUARTZ SENSOR OF FORCE AND PRESSURE

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Abstract. Sensors with a frequency output signal are marked as particularly high accuracy, it is easy to switch, and signals may be transmitted over long distances. The main element of such sensors is an electromechanical oscillator connected to the feedback of the autogenerator. String metal oscillators do not provide the required measurement accuracy due to unsatisfactory elasticity, hysteresis, relaxation, and drift of characterisrics. The creation of oscillators made of quartz and silicon due to the perfection of these materials, is difficult. Tere exist the technological problems and problems of conjugation of temperature coefficients of materials expansion. It is proposed a quartz sensor without an oscillator, made from the quartz and equipped by optoelectronic means.

Key words: Optoelectronic quartz sensor, Error, Temperature effect, Frequency signal.

1. Introduction

The operation of sensors with frequency output is based on the principle of changing the frequency depending on the measured value. These sensors are easily switched to one input, which allows them to be easily used in measuring telemetry systems. The error of frequency measurement by sensitive elements is 10^{-6}-10^{-7} %, which opens up opportunities in the creation of measuring transducers. A sensitive element of such transducers is a resonant oscillator. The measured value acts on it, changing the resonant frequency. The best method for determining consists in the implementation of autogenerator (AG), the feedback element of which is a measuring electromechanical resonance unit. The amplification scheme determines the amplitude of oscillations at the output of the AG. The feedback element determines the frequency of the output signal. The higher is the quality factor of the oscillator, the smaller the deviation of the output frequency of the AG from the resonant value [1], and the more stable this frequency would be.

In the circuit containing a wire coil of conductor, the surface of which conducts current well and is covered with insulation, the quality factor reaches 200-300. The quality factor of such oscillating systems located in the air reaches two thousand, and in vacuum increases to tens of thousands [2]. Measuring electromechanical resonance unit contains three main elements: an oscillator, a device for excitation and support of oscillations, a device for reading oscillations.

Despite significant advances in the development of MEMS systems, they have such shortcomings as significant temperature errors due to the use of hetero-geneous materials and the difficulty of matching their temperature coefficient of linear expansion (TCLE), problems that arise when combined with electronic measuring circuits, sensitivity to vibration and shock.

2. Disadvantages

Measuring electromechanical resonance systems, where the frequency setting element is an oscillator with metal strings attached to a metal elastic element, cannot provide the required measurement accuracy. This is due to unsatisfactory elastic properties of metals, their hysteresis, relaxation, creep, temporal instability. The presence of complex excitation and oscillation reading systems, the large number of elements of which they consist, complicate the design and increase the size of sensors. This leads to the need to create sensors with the advantages of the frequency output signal, but on the basis of other more advanced materials.

Physical and mechanical properties of quartz, which has one of the smallest TCLE and is characterized by the absence of hysteresis in the elastic elements allow creating a sensor of high exactness. The advantages of piezoquartz are best manifested when the sensor is made of a single monolith, but then there is a need for manufactured elements of complex shape with a large recess in the thickness of quartz [3].

3. The Goal of the Work

The aim of current work is to study the possibility of designing monolithic quartz sensors for measuring force and pressure while maintaining the advantages of the frequency information signal and minimizing the temperature error.

4. Design of the Quartz Sensor

Elaboration in the sensor’s structure is planned to be achieved by removing electromechanical resonance systems while maintaining the advantages of such an informative signal as frequency. This makes it possible to get rid of both the excitation and oscillation reading devices and the complex circuit of the autogenerator with a phase shifter. Temperature errors are minimized by using quartz elastic elements that can be cast from quartz glass. The structure of the sensitive element (SE) of force or pressure (without electromechanical resonance system) is shown in Fig. 1.

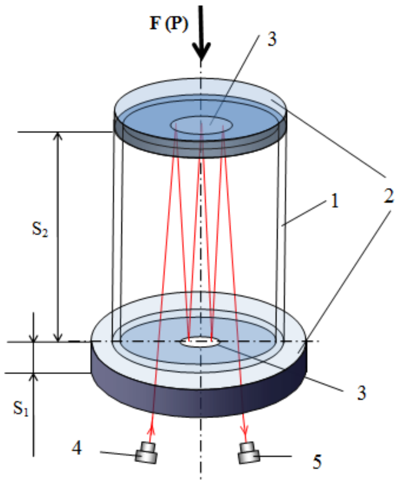

Fig. 1. *The quartz sensor: 1 – quartz cylinder, 2 – quartz caps, sprayed on the inside of the covers; 3 – mirror covers, 4 – light source (a semiconductor laser); 5 – photodetector (pin diode)*

Fig. 2 demonstrates one of the possible variants of the scheme for such a SE. A pulse shaper is installed between the photodetector and the laser, which generates short-term pulses excited by light pulses received by the pin diode. The duration of the light pulses is determined by the pulse duration of the shaper to the output of which the semiconductor laser is connected. At the time of the pulse, an injection current flows through the semiconductor laser to produce coherent radiation. The light pulse from the laser through the transparent quartz cover enters the cylinder, is reflected from the mirrors, enters the photodetector changing its output current. The latter opens the transistor, causing the excitation of the next pulse. Under the action of force (pressure) on the sensor cover, the quartz cylinder is compressed, reducing the distance between the mirrors. The time of pulses between the mirrors decreases, and the frequency of generation increases. Thus, a functional relationship is formed between the action of force (pressure) on the SE and the output frequency of the pulse shaper.

A differential amplifier is installed at the input of the shaper. Two NX6351GP pin diodes are connected to its inputs. When reverse voltage is applied, a current not exceeding 7 mA flows through the mentioned diodes. The differential amplifier eliminates the temperature impact and current arising from unwanted penetration of external light. These pin diodes operate in the bandwidth of up to 5 GHz. So, the signal delay can be not lesser 0.2 ns. Let the operating time of Schottky transistors T1 and T2 are equal to 1 ns. In the shaper of short-term pulses, one of the logic elements of the chip SN74AUC2G00 [4] with the signal delay time (of the logic element D1.1) equal to 1 ns is applied.

Between the collector of transistor T1 and the semiconductor laser the 2[nd] similar logic element D1.2 is installed; it delays the signal by 1 ns. Thus, the shaper generates short-term pulses lasting 1 ns with a delay of 1 ns. According to technical data of laser diode, the delay between the input current pulse and the light output pulse is 50 ps. Semiconductor laser radiation is pulse modulated by the injection current. Therefore, the total delay of light pulses by the electronic circuit is assessed as t_{fi} = 0.2 ns + 1 ns + 1 ns + 0.05 ns = 2.25 ns.

A circuit for starting and controlling the laser excitation pulses is connected to the pulse shaper. This circuit generates a pulse to start the shaper and checks the presence of pulses in its subsequent operation. If the pulses are missing for some reason, it starts the shaper again. The functional scheme of the measuring instrument is shown in Fig. 3. It includes a quartz sensitive element SE, the pulse shaper PS, which yields in addition to the shaper of short pulses, a pin diode and a semiconductor laser, the circuit start and control CSC of pulses, frequency measurement circuit FMC, digital adder and indicator.

From the frequency divider based on the chip SN74AUC2G00 signal is fed to the input of the frequency measurement circuit. The digital code of the measurement result *F* (ΔL) and the code of the initial value of the frequency *F* (0) are fed to the digital adder, which distinguishes their difference, visible on the display. CSC performs the initial start-up of the scheme and controls the presence of pulses at its output. If there are no pulses, it restarts the measurement. To measure the pressure, the volume limited by the quartz cylinder and lids, must be sealed. In the absence of air in this volume, the sensor can be used to measure absolute pressure. The choice of maximum pressure is determined by the cylinder wall thickness, so for the appropriate pressures it is necessary to compute their corresponding thickness. In order for quartz to be used within elastic deformations, the relative change in its size should not exceed 0.1 %. Quartz is unstable to tension, but resistant to compression. So, the quartz sensors must work on compression.

Let's estimate the initial and final values of the sensor frequency, the frequency change and the linearity of its transform characteristic. Let the distance between the quartz caps S_2 is 7.5 cm (see Fig. 1), and the thickness of the lower cover S_1 is 1 cm. The maximum displacement at relative elongation ε = 0.001 is 75 μm. Since the laser beam runs 6 times between the mirrors, the maximum reduction of its path ΔL is equal to $\Delta L = 6 \cdot \varepsilon \cdot S_2$, where ΔL is a function of force and

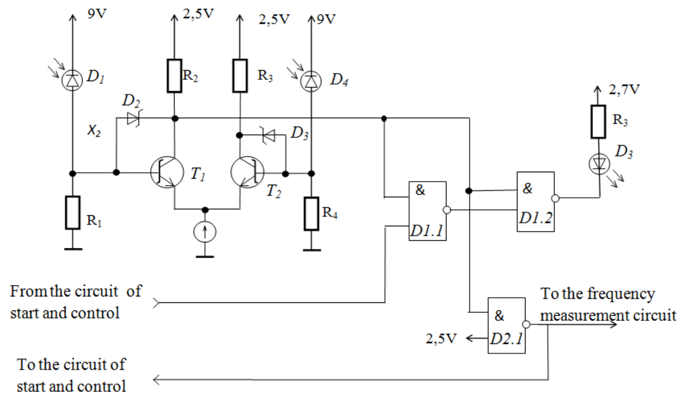

Fig. 2. Scheme of the pulse shaper

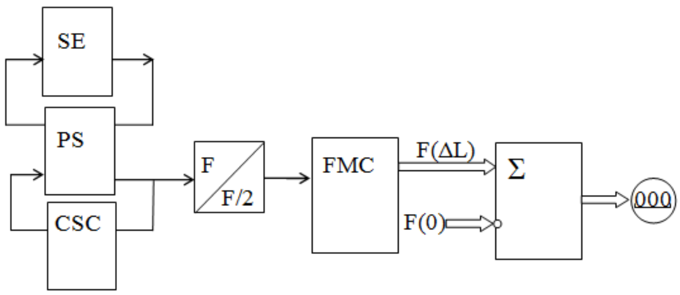

Fig. 3. Functional scheme of the designed sensor

varies from 0 to 450 µm. The path L_1 passing the beam in the quartz substrate is double, so $L_1 = 2 \cdot S_1$, L_1 = 2 cm. Between the sensor covers the beam passes six times L_2 = 0.45 m. The beam passes six times between the sensor covers, so L_2 is 0.45 m. During measurements the path $L_2(\Delta L)$ of the beam is shortened by ΔL to $L_2(\Delta L) = 6 \cdot S_2 - \Delta L$. The refractive index of light in quartz n is defined as: $n = \frac{C}{V}$, where C is the speed of light in vacuum; V is the speed of light in quartz. The refractive index for quartz is n = 1.4165. Determine the time t_1, during which the beam passes twice through the sensor cover, as $t_1 = L_1 n/c$. Determine the time $t_2(\Delta L,)$, during which the light pulse passes through the sensor (from the laser to the photodetector) during the measurements: $t_2(\Delta L) = L_2(\Delta L)/c$. The laser and photodetector may be at some distance from the bottom cover of the sensor. Let each of them be at a distance of 1 cm. The time of passing this distance consists of t_3 equal to $6.666667.10^{-11}$s. The period of time T, during which the pulse bypasses the sensor, excites the pulse shaper and is again generated by the laser is: $T(\Delta L) = t_1 + t_2(\Delta L) + t_3 + t_{fi}$, where t_{fi} is the delay time of the pulses by the shaper. Determine the initial and final values of the frequency during the measurements by: $F(\Delta L) = T^{-1}(\Delta L)$. Also determine how much $F(\Delta L)$ deviates from the straight line expressed by the equation $Y(\Delta L) = F(0) + K \cdot (\Delta L)$, where K is the angular factor. The obtained results are presented in Fig.4 -5. Figure 4 shows the graphs of the functions $F(\Delta L)$ and $Y(\Delta L)$, and Fig. 5 demonstrates their difference $\Delta F(\Delta L) = F(\Delta L) - Y(\Delta L)$.

As can be seen in Fig. 5 the maximum deviation from the linear characteristics of the sensor does not exceed 5 Hz, which at the above initial and final values of frequencies and their difference equal to 49,04898 kHz, is quite small – 0.01 %. That is an error of non-linearity.

To estimate the temperature errors of the sensor in the range from -40 to +60 ^{o}C, we take the average TCLE of quartz equal to K_Q == $0.5 \cdot 10^{-6}$ and normal temperature conditions at 20 ^{o}C. Determine how the path $L_2(Q)$ changes when the temperature alters in the specified temperature range: $L_2(Q) = L_2(1 + K_t \cdot (Q - 20^o C))$, where Q is the temperature in Celsius degrees. The travel time of this distance $t_2(Q)$ is equal to: $t_2(Q) = L_2(Q)/c$. The change in frequency caused by the temperature impact is defined as: $F(Q) = (t_i + t_2(Q) + t_3 + t_{ji})^{-1}$ (Fig. 6). Absolute and relative errors are determined relative to $F(20)$, i.e. the frequency of the sensor under normal conditions (Fig. 7a; 7b). Here $F(20)$ is the frequency of the sensor under normal conditions: $F(20)$= $1,278413 \cdot 10^8$.

5. Conclusion

Traditional measuring resonance MEMS with metal strings cannot provide the required measurement accuracy due to unsatisfactory elastic properties of sensitive materials, their hysteresis, relaxation, drift, etc.

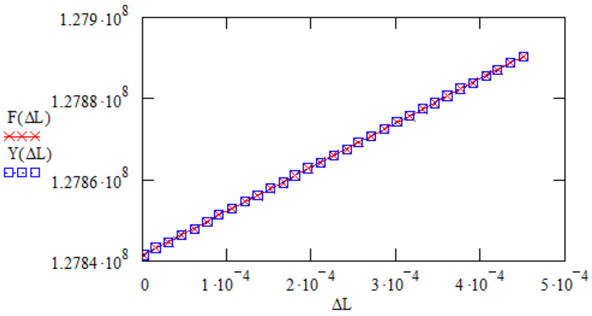

Fig. 4. Graphs of functions F (ΔL) and Y (ΔL)
F (0) = 127.841272 MHz; F (450.10^{-6}) = 127.890321 MHz;
F (450.10^{-6}) – F (0) = 49.04898 kHz.

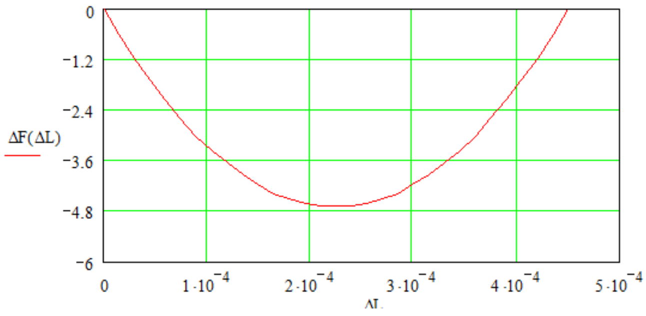

Fig. 5. The difference of initial and final frequencies ΔF(ΔL) = F(ΔL) – Y(ΔL)

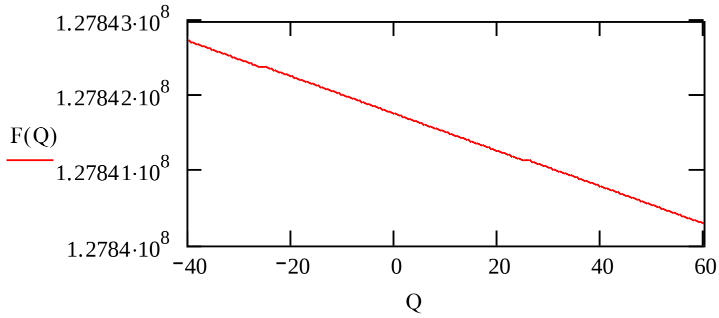

Fig. 6.. Dependence of sensor frequency on temperature

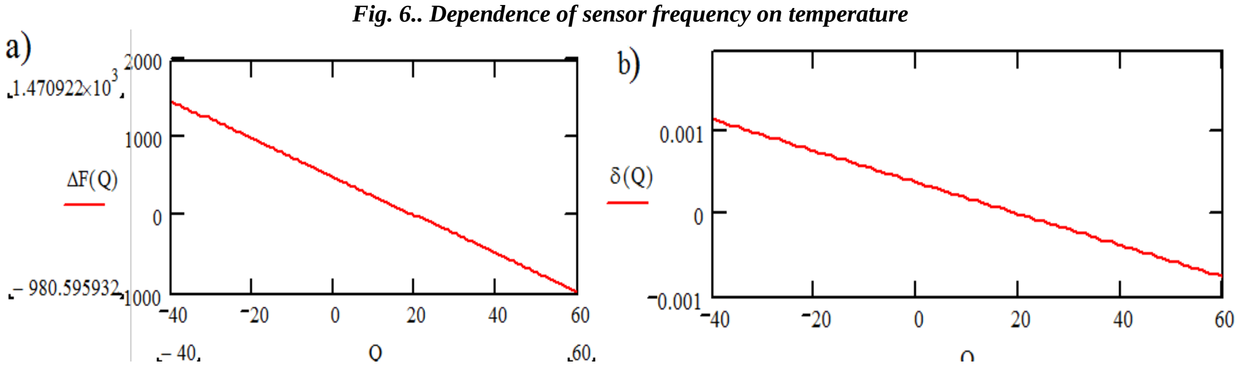

Fig. 7. Absolute (a) and relative (b) errors of quartz sensor

Small TCLE of quartz and the absence of hysteresis make it possible to create a high accuracy frequency resonance sensor under the development of an optoelectronic transducer. It is avoided the need for an electromechanical oscillator with a frequency output signal. The relative measurement error is close to 0.001 % at unlinearity of performance below 0.01 % within permitted temperature range -40 – +60 °C.

6. Acknowledgment

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7. Conflict of Interests

There is no conflict of interest while writing, preparing, and publishing the article, as well as mutual claims by the co-authors.

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