Measurement Techniques, Vol. 56, No. 12, March, 2014

METHODS OF CORRECTING THE ADDITIONAL TEMPERATURE ERROR OF RESONATOR SENSORS

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UDC 681.586.2

The operating principle, advantages and disadvantages of resonator sensors are considered. A method of correcting the additional errors of such sensors is proposed. An experimental investigation of the method on string resonator sensors of linear displacements is described.

Keywords: *sensor, resonator, error correction.*

At the present stage of development of measurement techniques, the accuracy of the measurements of the frequency of electric signals is one of the highest, and hence the metrological characteristics of frequency sensors (the output quantity being the frequency) differ from the characteristics of sensors with an amplitude-modulated output signal. Moreover, when using a frequency-modulated signal, the requirements imposed on the connecting lines as regards the stability of the resistances and parasitic EMFs are considerably simplified, since the noise immunity of such a signal is considerably higher than that of an amplitude-modulated signal [1].

The most widely used frequency sensors are resonator sensors, the basic component of which is an oscillatory system (a resonator) with a natural frequency, which is tunable to the action of the measured quantity, which serves as the output signal. However, resonator sensors have a number of limitations. First of all, there is its high sensitivity to the action of external factors, such as the temperature, pressure, vibrations, etc., which leads to the occurrence of additional errors under practical operating conditions. These errors can be eliminated by using a thermostat, reducing the technological tolerances, complicating the construction and by a careful choice of the materials, but these lead to an increase in the cost of the sensors.

In this connection, methods of correcting the additional errors have been developed, the distinguishing feature of which is that they ensure that the actual static conversion function and the nominal conversion function are close to one another when a correcting signal, generated by a computer, is acting. Consequently, to obtain the correction it is necessary to develop an algorithm for estimating this error and to generate the corresponding correcting signal.

The basic principle of the proposed method of correcting the additional temperature error consists of changing the construction of the differential sensor in such a way that one of the sensitive components of the sensor serves to determine the measured quantity, while the second is used to generate a correcting signal. We will consider the use of this method using the example of the correction of the additional temperature error of a string resonator sensor for measuring linear displacements.

All mechanical resonator sensors, including string sensors, have a parabolic conversion function of the form [1]:

$$f = f_0\sqrt{1 + kx}, \tag{1}$$

where x is the measured quantity, f_0 is the initial oscillation frequency of the resonator, and k is a coefficient, characterizing the sensor sensitivity.

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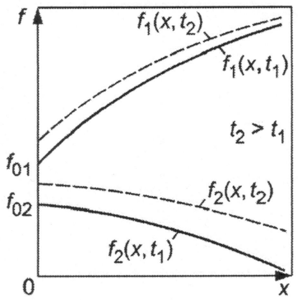

Fig. 1. Shift of the conversion function of a differential resonator sensor due to a change in temperature.

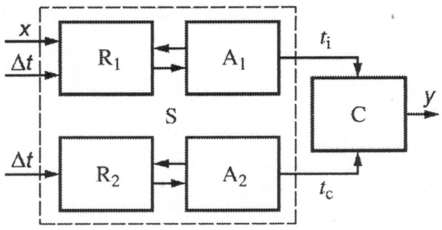

Fig. 2. Block diagram of the method of correcting the additional temperature error of resonator sensors: S is the sensor; R_1 and R_2 are resonators; A_1 and A_2 are electronic amplifiers, which form, together with the resonators, self-excited generators; C is a computer; x is the measured quantity; f_i and f_c are the informative (frequency) and correcting signals, respectively; Δt is the temperature change; and y is the output signal.

Differential sensors are usually distinguished by low sensitivity to a temperature change, since, when they are used to measure the difference between informative signals, obtained from two sensitive components, the additional errors are subtracted from one other. However, this effect does not occur when using frequency resonator sensors due to the different temperature sensitivities of the resonators. The resonators are usually tuned to different initial frequencies f_{01} and f_{02} in order to prevent mutual synchronization of the self-excited generators [1]. The effect of the temperature leads to a change in the initial oscillation frequency of the resonator and the sensitivity, since the coefficient k depends on f_0. Hence, the conversion function of the resonators is shifted nonuniformly and the difference (the ratio) of the frequencies depends on the temperature t (Fig. 1).

Since, to process the experimental data using computers, the linearity of the conversion function is not essential [2], it is possible to transform the differential converter to operate in a mode with automatic correction of the additional temperature error. In this case one of the resonators serves to determine the input signal, while the second is used as an instrument for measuring the temperature and generates a correcting signal. A block diagram of the proposed method of correcting the additional temperature error of resonator sensors is shown in Fig. 2.

In Fig. 3, we show experimental results of the use of the proposed method for correcting the additional temperature error of the zero of a string linear displacement sensor. For these investigations, we used a differential sensor and a sensor, practically identical in construction, in which the measured quantity acts on only one string. The differential sensor was tested in two modes of operation – a frequency ratio mode and a frequency difference mode, while the differential sensor was tested in modes in which the additional temperature error was corrected and without correction (see Fig. 3).

The results of the experiment showed that the additional temperature error of the zero in the correction mode is reduced by a factor of 10–20 compared with the classical differential modes of operation in which either the frequency dif-

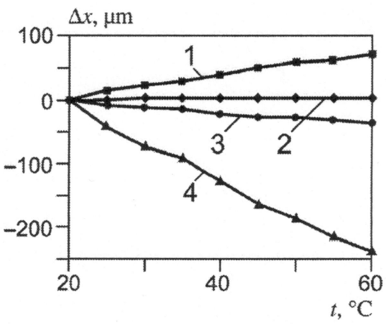

Fig. 3. The additional temperature error of the zero of string sensors in the following modes of operation: *1*, *2*) for the case when there is no correction and with additional correction, respectively; *3*, *4*) for the frequency difference and frequency ratio methods, respectively.

ference or the frequency ratio is measured, and is 10–15 times less than when using a single resonator in the mode of operation without correction.

To calculate the correcting signal, we used the properties of conversion function (1) of resonator sensors. The higher the value of f_0, the less the frequency increment for the same elastic deformation [1], and, consequently, we can conclude that the temperature sensitivity of the resonator is reduced as the oscillation frequency increases.

For a string resonator, we can write [1]:

$$f_0 = a\sqrt{F_0}; \quad f = f_0\sqrt{1 + \Delta F / F_0},$$

where a is a coefficient, characterizing the resonator sensitivity, and F_0 and ΔF are the initial stretching force of the string and its change, respectively.

Then

$$\Delta f = f - f_0 = f_0\left(\sqrt{1 + \Delta F / F_0} - 1\right) = f_0\left(\sqrt{1 + \frac{a^2 E l_0 \alpha' \Delta t}{f_0^2}} - 1\right), \tag{2}$$

where l_0 is the initial length of the string, α' is the difference between the coefficients of linear expansion of the body of the sensor and of the string, E is the modulus of elasticity of the string material, and Δt is the change in temperature.

To simplify (2), we expand it in a power series and confine ourselves to the first two terms. We obtain

$$\Delta f \approx a^2 E l_0 \alpha' \Delta t / f_0. \tag{3}$$

Hence, if we denote the changes in the frequency of the measuring resonator by Δf_1, and the change in the frequency of the correcting resonator by Δf_2, we can write from (3)

$$\Delta f_1 / \Delta f_2 = \left[a_1^2 E_1 l_{01} \alpha_1' \Delta t / f_{01}\right] \Big/ \left[a_2^2 E_2 l_{02} \alpha_2' \Delta t / f_{02}\right] = b f_{02} / f_{01}, \tag{4}$$

where b is a coefficient, which depends on the properties of the resonators.

It follows from (4) that the value of the correcting signal, equal to the change in the frequency Δf_1, can be found as

$$f_c = \Delta f_{01} = b \Delta f_{02} (f_{02} / f_{01}). \tag{5}$$

Expression (5) is the basic expression for correcting the additional temperature error of the sensor. If the frequency of the first (informative) resonator is given by the formula

$$f_1 = (f_{01} + \Delta f_{01})\sqrt{1 + kx},$$

while the frequency of the second (correcting) resonator is given by the formula

$$f_2 = f_{02} + \Delta f_{02},$$

then, when condition (4) is satisfied, we obtain the relation for determining the linear displacement:

$$x = \frac{1}{k}\left[f_1^2\left(f_{01} + (f_2 - f_{02})b\frac{f_{02}}{f_{01}}\right)^{-2} - 1\right]. \tag{6}$$

Thus, the algorithm for processing the signals in order to correct the additional temperature error of the zero is as follows: measurement of the oscillation frequencies of the resonators f_1 and f_2, and the determination of the measured quantity from (6). The algorithm is suitable for correcting the temperature error when making the measurements. In this case, f_1 is changed by the action of the measured quantity x, and the correcting signal will also be changed in accordance with (5), so (6) can be represented in the form

$$x = \frac{1}{k}\left[f_1^2\left(f_{01} + (f_2 - f_{02})b\frac{f_{02}}{f_1}\right)^{-2} - 1\right].$$

The advantages of this method of correction are: the additional temperature error of the sensor is reduced considerably, and there is no need to connect an additional measuring instrument in order to determine the temperature and to calculate the thermal inertia of the converter, since the resonators, as a rule, are under identical conditions. Moreover, when using this method it is possible to correct other additional errors, caused by the effect, for example, of atmospheric pressure and the supply voltage. However, other methods [3] must be used to reduce any additional errors due to mechanical actions.

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