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NOISE THERMOMETER FOR NON-CONDUCTING MATERIALS

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Abstract—Temperature is one of the most critical process parameters in many industrial processes, as it determines the kinetics of chemical reactions, phase transitions in materials, the energy efficiency of equipment, and the operational safety of both individual robotic systems and large-scale computer-integrated manufacturing facilities as a whole. Despite the wide range of existing thermometry instruments, temperature measurement in real industrial conditions is often complicated by the destructive effects of aggressive environments, high levels of electromagnetic interference, dynamic delays, and the need for monitoring in hard-to-reach or moving components of process systems. Errors in temperature measurement lead to a reduction in the quality of finished products, excessive energy consumption, and, in some cases, to emergency situations. This paper proposes a noise thermometer for non-conductive materials. The developed device improves the accuracy of temperature measurement by eliminating the influence of uninformative noise and through advanced computational processing of the useful signal.

Keywords—Thermal noise, thermometer, temperature, measurement, non-conducting materials.

I. INTRODUCTION

At the current stage of industrial development, digital transformation and the transition to the ‘Industry 4.0’ concept place stringent demands on the efficiency of production system management. Among all technological parameters, temperature control is one of the most critical, as it determines the kinetics of chemical reactions, phase transitions of substances, the energy efficiency of equipment, and the operational safety of both individual robotic systems and large-scale computer-integrated manufacturing facilities as a whole [1] – [4].

Despite the wide range of existing temperature measurement devices, temperature measurement in real industrial conditions is often complicated by the destructive effects of corrosive environments, high levels of electromagnetic interference, dynamic delays, and the need for monitoring in hard-to-reach or moving components of robotic systems. Errors in temperature measurement [5] – [7] lead to a reduction in the quality of finished products, excessive energy consumption and, in some cases, to emergency situations. Therefore, the improvement of methods and means of temperature monitoring remains a pressing scientific and practical task.

II. PROBLEM STATEMENT

Measuring the temperature of non-conductive materials (dielectrics and high-resistance semiconductors) is one of the most challenging tasks in thermometry, particularly under extreme

conditions (high temperatures, intense radiation, corrosive environments, etc.) [8], [9].

Non-contact optical pyrometry is often attempted for non-conductive materials. However, this approach has significant limitations. Many dielectrics are semi-transparent to infrared radiation (for example, quartz glass and certain types of ceramics). The pyrometer ‘sees’ through the material and reads the temperature of the background rather than that of the object itself [10]. The emissivity of non-conductors varies significantly depending on the surface condition (roughness, oxidation), resulting in an error of tens of degrees [10].

Most non-conductive materials made from polymers, silicates, wood and other plant and animal-based raw materials (leather, wool, cotton, flax, etc.) possess dielectric properties. In such materials, even in the absence of free electrons and ions, which determine the material’s electrical conductivity, thermal noise arises due to the presence within the material of thermally excited polarised molecules that form elementary fluctuating dipoles [11]. The level of thermal noise current and voltage is determined by the thermodynamic temperature of the material and the magnitude of dielectric losses. Therefore, the temperature is estimated based on the values of the noise current or voltage provided by capacitive or inductive sensors.

It is therefore advisable to develop improved noise thermometers for non-conductive materials, which will enhance the reliability and accuracy of temperature measurements.

III. THERMOMETER STRUCTURE

The proposed noise thermometer has the structure shown in Fig. 1.

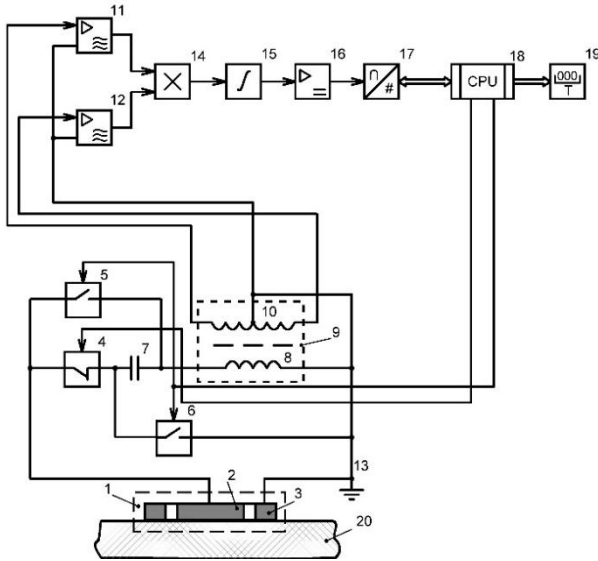


Fig. 1. Noise thermometer structure

The overlay capacitive sensor 1, comprising a potential disc electrode 2 and a ring-shaped grounded electrode 3, is connected to the measuring circuit via controlled switches 4, 5 and 6. The normally closed switch 4 is connected between the potential disc electrode 2 and the capacitor 7 of the resonant circuit. A normally open switch 5 is connected between the potential disc electrode 2 and the point where capacitor 7 connects to one end of the primary winding 8 of the high-frequency transformer 9. A third normally open switch 6 is connected in parallel with the resonant circuit between capacitor 7 and the grounded end of the primary winding 8 of the high-frequency transformer 9. The secondary winding 10 is earthed at its midpoint; its high-potential ends are connected to the inputs of the broadband amplifiers 11 and 12, the low-potential inputs of which are connected to a common earthed bus 13. The outputs of the broadband amplifiers 11 and 12 are connected to the inputs of the multiplier 14, whose output is connected to the integrator 15, to the output of which an analogue-to-digital converter 17 is connected via the amplifier 16, the digital input of which is connected to the input of the microcontroller 18. A digital display 19 is connected to the output of the microcontroller, and controlled switches 4, 5 and 6 are connected to its logic outputs.

Position 20 denotes the tested non-conductive material.

IV. PRINCIPLE OF OPERATION

The noise-based temperature sensor for non-conductive materials works as follows.

The capacitive sensor 1 with its electrodes 2 and 3 is placed on the tested material 20. In a non-conductive material, even in the absence of free electrons, broadband thermal noise arises due to fluctuations in the electric dipole moments of the polarised molecules of the substance. In the position of the controlled switches 4, 5 and 6 shown in Fig. 2, the electrodes 2 and 3 of the capacitive sensor are connected to a series resonant circuit comprising a capacitor 7 with capacitance C and the inductance L of the primary winding 8 of the high-frequency transformer 9.

At the resonance frequency

$$f_0 = \frac{1}{2\pi\sqrt{LC}}, \quad (1)$$

at elements 7 and 8 of the resonant circuit, noise voltage resonance occurs, and the noise current in short-circuit mode is determined solely by the internal resistance of the noise source. According to Nyquist's formula, the root-mean-square noise resonance current

$$I_p = \sqrt{\frac{4kT_x\Delta f}{ReZ}}, \quad (2)$$

where k is the Boltzmann constant; T_x is the temperature of the material being tested; Δf is the frequency range of thermal noise separated by a resonant circuit; ReZ is the active component of the total impedance of a capacitive sensor.

In the parallel configuration of the electrode system of capacitive sensor 1, the active component:

$$ReZ = \frac{\text{tg } \delta}{2\pi f_0 C (1 + \text{tg}^2 \delta)}, \quad (3)$$

where $\text{tg } \delta$ is the tangent of the dielectric loss angle of the studied material.

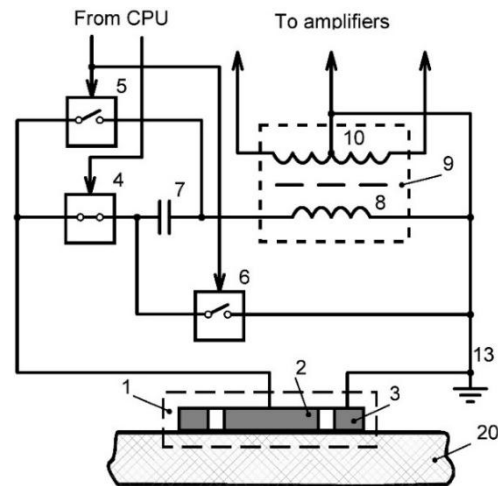


Fig. 2. Resonant circuit configured to serial scheme

The frequency range of thermal noise separated by the circuit:

$$\Delta f = \frac{f_0}{Q}, \quad (4)$$

where Q is the quality of the oscillating circuit.

The resonant noise current (2) causes a voltage drop across the primary winding 8 of the high-frequency transformer 9:

$$U_1 = 2\pi f_0 L I_p, \quad (5)$$

which is transformed by the secondary winding 10 to a value of

$$U_2 = K_1 U_1, \quad (6)$$

where K_1 is the transformation factor.

The output voltage (6) of the high-frequency transformer 9 is a narrow-band random signal which, together with the inherent noise of amplifiers 11 and 12, is amplified, squared by multiplication in the multiplier 14, and averaged in the integrator 15. When multiplying noise signals, it should be noted that the averaged product of two uncorrelated random signals from independent sources, given the wide frequency bandwidth of amplifiers 11 and 12, is close to zero; that is, it does not produce a DC voltage component. At the same time, the amplification of two narrow-band signals from a single transformer winding with a grounded centre tap, followed by multiplication and averaging, yields a DC voltage component due to their mutual correlation. As a result, the influence of the intrinsic noise of the broadband amplifiers 11 and 12 is suppressed, and the amplified informative thermal noise, generated by the resonant circuit, is converted into a DC voltage:

$$U_3 = \frac{1}{4} K_2 K_3 S K_4 \bar{U}_2^2, \quad (7)$$

where K_2 and K_3 are gain factors of broadband amplifiers 11 and 12; S is the steepness of the multiplication transformation of multiplier 14; K_4 is the transfer coefficient of an integrator 15.

The DC voltage (7) is amplified by amplifier 16 and converted into a digital code by analogue-to-digital converter 17. The digital code is fed to microcontroller 18, where its value is stored:

$$N_1 = \frac{1}{4} \frac{K_2 K_3 S K_4 K_5 \bar{U}_2^2}{q}, \quad (8)$$

where K_5 is the gain of amplifier 16; q is the least significant bit of the analogue-to-digital converter 17.

Next, on a command from microcontroller 18, switch 4 opens, whilst switches 5 and 6 close. As a result, the resonant circuit comprising capacitor 7 and the primary winding 8 of high-frequency transformer 9 is converted into a parallel circuit, as shown in Fig. 3.

The circuit resistance rises sharply to a value of

$$R_k = \frac{L}{Cr}, \quad (9)$$

where r is the low resistance of the primary winding 8, which causes the noise current (2) to be interrupted.

Since the resistance of the parallel circuit is $R_k \gg \text{Re}(Z)$, an open-circuit condition arises, in which the root-mean-square noise voltage across the circuit becomes equal to

$$U_p = \sqrt{4kT_x \Delta f \text{Re}(Z)}. \quad (10)$$

The noise voltage (10) is transformed into the secondary winding 10 of the high-frequency transformer 9 to a value of

$$U_4 = K_1 U_p. \quad (11)$$

The noise voltage (11) is amplified by two broadband amplifiers 11 and 12 and squared by a multiplier 14. After the product of the noise signals is averaged by an integrator 15 – which extracts the DC component of the voltage – and following further processing steps similar to the previous ones, a second digital code value is generated

$$N_2 = \frac{1}{4} \frac{K_2 K_3 S K_4 K_5 \bar{U}_4^2}{q}, \quad (12)$$

which is stored in microcontroller 18.

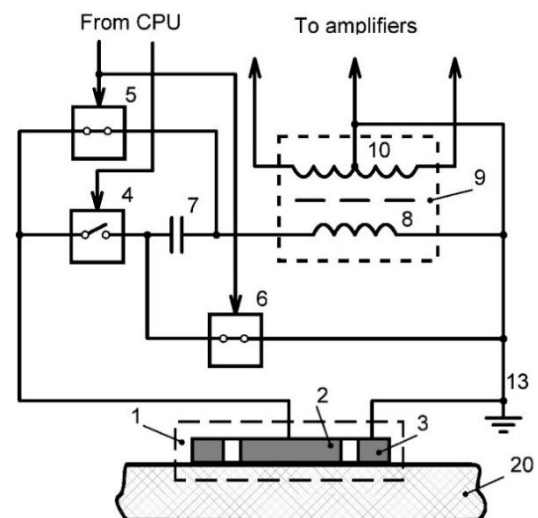


Fig. 3. Resonant circuit reconfiguration to parallel scheme

The microcontroller's processor then performs computational processing of codes (8) and (12) according to the specified programme

$$N_3 = \sqrt{N_1 N_2}. \quad (13)$$

Substituting the values of codes (8) and (12) into (13) and taking into account relation (5), we obtain the resulting code

$$N_3 = \frac{1}{2} \frac{K_1 K_2 K_3 S K_4 K_5 \pi f_0 L I_p U_p}{q}. \quad (14)$$

Substituting the value of the resonant noise current from (2) and the value of the resonant noise voltage from (10) into (14), we finally obtain

$$N_3 = \frac{2kK_1 K_2 K_3 S K_4 K_5 \pi f_0 L \Delta f}{q} T_x. \quad (15)$$

It follows from equation (15) that the resulting code N_3 is proportional to the measured temperature T_x and is independent of the dissipative losses ReZ of the studied material.

Since the temperature-to-code conversion function (15) is linear, the resulting steepness of the conversion

$$S_p = 2kK_1 K_2 K_3 S K_4 K_5 \pi f_0 L \Delta f, \quad (16)$$

can be determined using a known calibration temperature T_k :

$$S_p = \frac{qN_4}{T_k}, \quad (17)$$

where N_4 is the code obtained during the calibration of the noise temperature sensor.

During the ongoing measurements, the temperature T_x is determined using the formula

$$T_x = \frac{qN_5}{S_p}, \quad (18)$$

where N_5 is the code obtained during the measurement process.

The measurement result (18) is calculated by the microcontroller's processor 18 and displayed on the digital indicator 19.

V. CONCLUSIONS

Thus, the proposed noise meter circuit enables temperature measurement in non-conductive materials that lack electrical conductivity, regardless of the level of dielectric losses – which determine the value of ReZ – and, consequently, the level of thermal noise. The extraction of noise current and noise

voltage directly at the output of the measuring circuit by a resonant circuit with a variable structure improves the signal-to-noise ratio, and the subsequent correlation processing of the resonant circuit's output voltage by two independent wideband amplifiers helps to suppress the influence of inherent noise on the temperature measurement result.

Avoiding the use of a reference capacitor with a capacitance equal to that of the surface-mounted sensor simplifies the algorithm for processing the results of intermediate measurements. These circuit design innovations ensure a significant improvement in temperature measurement accuracy (the error does not exceed ± 0.1 – 0.2 K).

To eliminate the influence of uninformative low-frequency noise and interference (flicker noise, vibrations, induced noise), as well as high-frequency radio interference and electromagnetic fields, it is advisable to isolate the informative thermal noise using a resonant circuit in the high-frequency range (10–20) MHz with a circuit bandwidth of $\Delta f = (5$ – $10)$ kHz. Taking into account the statistical nature of the noise current and voltage, the measurement time should be set sufficiently long (several seconds or more), which is determined by the integrator's time constant and the switching period of the switches, which is set by the microcontroller.

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М. П. Василенко. Шумовий термометр для непровідних матеріалів

Температура є одним з надзвичайно важливих технологічних параметрів багатьох процесів, оскільки визначає кінетику хімічних реакцій, фазові перетворення речовин, енергетичну ефективність обладнання та безпеку експлуатації як окремих робототехнічних комплексів, так і масштабних комп'ютерно-інтегрованих виробництв загалом. Незважаючи на широку номенклатуру існуючих засобів термометрії, вимірювання температури в реальних промислових умовах часто ускладнюється деструктивним впливом агресивних середовищ, високим рівнем електромагнітних завад, динамічними запізненнями та необхідністю контролю у важкодоступних або рухомих вузлах технологічних систем. Похибки у вимірюванні температури призводять до зниження якості готової продукції, перевитрати енергоресурсів, а в окремих випадках – до аварійних ситуацій. В роботі запропоновано шумовий термометр для непровідних матеріалів. Розроблений прилад дозволяє підвищити точність вимірювання температури шляхом усунення впливу неінформативних шумів та завдяки вдосконаленій обчислювальній обробці корисного сигналу.

Ключові слова: тепловий шум, термометр, температура, вимірювання, діелектричні матеріали.

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