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ENERGY METHOD FOR MEASURING NONELECTRICAL QUANTITIES USING QUARTZ RESONATORS

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A new method for measuring nonelectrical quantities is described. The method is based on recording the degree of mechanical energy scattering in a piezoelectric pick-up or of the electrical energy in an oscillatory system with a dielectric pick-up. The method makes it possible to register small changes in the parameters of dielectrics.

The familiar frequency method for measuring nonelectrical quantities using quartz resonators (QR) [1] is based on recording the oscillation frequency of a piezoelectric plate, which changes under the effect of a nonelectrical quantity.

It is possible to record changes in the frequency of oscillations of a vacuum quartz resonator when a capacitive sensor is connected in series with it [2]. However, for sensor capacitances higher than 50 pF, the frequency signal is too weak and comparable with the instability of the crystal oscillator.

The need for frequency control requires that two crystal oscillators be used in the device, thus making industrial implementation of the method complicated.

The use of the frequency method is limited by its unsuitability for recording energy dissipation of elastic oscillations of a piezoelectric element and for controlling the energy dissipation of electrical oscillations in dielectrics. Besides, many nonelectrical quantities can be controlled by the change in the loss tangent in dielectrics.

The possibility of measuring mechanical and electrical losses by QR is a substantial advantage of the energy method, which ensures the creation of highly sensitive instruments within a wide range of frequencies.

The energy method for controlling nonelectrical quantities by QR is based on recording the equivalent active resistance of the oscillatory system of a specialized QR controlled by the internal friction of a sensitive coating applied to the piezoelectric element of the QR, which is realized in quartz dissipative converters of mechanical energy (QDC-M) [3].

Control of the equivalent active resistance of an oscillatory system involving a vacuum QR and a dielectric pick-up also refers to the energy method realized in quartz dielcometers (moisture meters) (QD) [4].

We consider the basic principles of the method. The piezoelectric effect in quartz is insufficient; therefore, it can be ignored, thus enabling us to write the equation of motion for shear oscillations of a piezoelement in the form [5]

$$\rho \frac{\partial^2 \varepsilon}{\partial t^2} = (C_{55}^{\sigma} + jH_{55}) \frac{\partial^2 \varepsilon}{\partial y^2} . \tag{1}$$

From Eq. (1) we obtain an expression for the mechanical Q quality of a piezoelement:

$$Q = C_{55}^{\sigma}/H_{55} . \tag{2}$$

An expression is known for the Q of an oscillatory system with one degree of freedom:

$$Q = \frac{\omega m}{2N_0} . \tag{3}$$

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Comparing (2) and (3) and allowing for the fact that $m = \rho l_m l_0 \Delta$, $C_{55} = v^2 \rho$, and $\omega = 2\pi v/4fl_0$, we obtain mechanical resistance of the QR

$$N_0 = \pi l_m \Delta H_{55}/4fl_0 . \tag{4}$$

To find R_0 we multiply (4) by β, which relates the mechanical and electrical parameters of the QR [6]:

$$R_0 = \pi l_m \Delta H_{55} \beta/4fl_0 . \tag{5}$$

Similarly, an expression for the component of the equivalent resistance of the QR that is determined by energy dissipation of elastic oscillations of a piezoelement in metallized electrodes is obtained:

$$R_m = \pi \delta l_m \Delta H_{55}^{m} \beta/2fl_0 . \tag{6}$$

Permissible acoustic losses for the resistance component are obtained in oscillations of a piezoelement in air [7]

$$R_r = 2\rho_a v_a \Delta l_{ave} \beta/(1 + v_a^2/2\pi f^2 \Delta l_{ave}) , \tag{7}$$

where $l_{ave} = l_m l_0/(l_0 + l_m)$. The equivalent active resistance of the specialized QR for a QDC-M is constant within the temperature range of from -50 to $+80$°C [8].

To manufacture a QDC-M, a sensitive coating is applied to the piezoelement. The friction of this coating depends on a nonelectrical quantity, e.g., on air humidity. The component of the equivalent active resistance of the QR caused by energy losses of elastic oscillations of a piezoelement in a dry sorbent R_d is determined by the expression [3]

$$R_d = \frac{\pi^2 (l_m + \Delta + 2\Delta') \Delta' H_{55}^{d} \beta}{2f (l_0 + 2\Delta')} . \tag{8}$$

In wet air, the energy losses of elastic oscillations of a piezoelement are determined by the resistance component R_{moist} [3]

$$R_{moist} = \frac{\pi^2 (l_m + \Delta + 2\Delta') \beta}{l_0 + 2\Delta'} \Delta' \eta . \tag{9}$$

The viscosity, or the coefficient of internal friction, of a moist capron coating changes in a wet medium by 300%, providing high sensitivity of the QDC-M. Equation (9) can be written in the form

$$R_{moist} = K_0 \Delta' \eta . \tag{10}$$

Comparison of the calculations of QR equivalent active resistance by expressions (5)-(9) with the experimental results showed that the divergence does not exceed 10–15%.

As an example we give the values of the components of the equivalent resistance of a QDC-M which is used as an air humidity indicator: $R_0 = 0.3\ \Omega$, $R_m = 68\ \Omega$, $R_r = 168\ \Omega$, $R_d = 1135\ \Omega$, $R_{moist} = 1896\ \Omega$. The total resistance in dry air (relative humidity 20–30%) is 1203.3 Ω, and in wet air (relative humidity 90–95%), it is 3265.3 Ω, i.e., the change in the effective signal due to air humidity amounts to 63% of the nominal pick-up resistance. This large informative signal greatly simplifies the design of air humidity indicators with a quartz primary converter, because high reliability and accuracy of air humidity measurements are provided at a high sensitivity.

A humidity indicator equipped with this pick-up has operated for several years in waveguides of TV stations in Ivanovo and Rodniki (Ivanovo region). In winter, the waveguide temperature can reach minus 35–40°C, while in summer time it can reach +40°C.

Air humidity indicators with quartz pick-ups of the energy method operate reliably at the "Teplichnyi" state farm (Ivanovo) in greenhouses for vegetable cultivation where water falling on the pick-up is not improbable. The readings of the humidity indicator are constantly analyzed by a computer.

Under laboratory conditions it is convenient to use a portable SG-1 hygrometer, which is easily handled (its dimensions are 200 × 85 × 30 mm and its weight is 300 g) and has a digital liquid-crystal display and a single battery "Krona" as a power source.

The SG-1 as well as other quartz humidity indicators were tested in a "Feutron" artificial-climate chamber. Their absolute error does not exceed ±1.5% of air relative humidity, and the additional temperature error per 10°C does not exceed ±0.7% of relative humidity, which is smaller than that of the "Volna" humidity indicator with a piezoelectric pick-up operating by the frequency method.

The QDC-M is used not only to control air humidity; internal friction in thin metal and polymer films [10, 11] and the rheological properties of human blood [12] are also determined by it. Using QDC-M one can measure the viscosity of different substances, including fuels and oils.

The QDC-M has the following parameters: $l_m = 15.6$ mm; $l_0 = 6.2$ mm; $\Delta = 0.2$ mm; the piezoelement cut is $yxl/-52$ degree; the thickness of the nickel electrodes is 0.5–0.7 μm; the resonant frequency of the piezoelement is 300 ± 1 kHz; the equivalent electrical resistance is 236 ± 50 Ω (this quantity changes slightly within the temperature range of from −40 to +50°C); the conversion ratio $K_0 = 5416.74$ kΩ·sec/kg.

A quartz dielcometer (QD) was based on a vacuum quartz resonator controlled by an electric pick-up connected in series or parallel with the QR. The equivalent electric resistance of the circuit, including the vacuum QR and the series-connected capacitive sensor with dielectric losses, is determined by the expression [13]

$$R' = R\left(1 + \frac{C_0}{C_s}\right)^2 + \frac{R_s}{1 + (\omega C_s R_s)^2}. \tag{11}$$

The first term in (11) depends on the sensor capacitance C_s, and the second term depends on both the sensor capacitance and loss resistance R_s. The equivalent resistance of the QR–sensor circuit is measured by an IPK-1 automatic self-balancing bridge manufactured according to [14].

To measure the loss resistance of a sample, the equivalent electric resistance of the sensor is first measured without a sample; then, with a sample. An experiment confirmed by calculations by (11) shows that when a 1-pF capacitor, which simulates the sensor, is connected in series to a QR with a of frequency 300 kHz ($C_0 = 6.5$ pF, $R = 90$ Ω), the equivalent electrical resistance of the circuit is 5062 Ω. When a 1-GΩ resistor, which simulates the losses in a capacitive sensor, is connected in parallel with this capacitor, the resistance of the circuit increases by 262 Ω, which is easily controlled by an IPK-1 device, which reliably identifies a change in the equivalent resistance of the circuit of ±10 Ω.

Quartz dielcometers implementing series control of the QR [15] have been used for many years in VK-2 and VT-20M humidity indicators for textiles, which have been adopted by the State Commission as measuring units (State Register No. 8388-81 and No. 8786-82) in portable IVP-1 devices manufactured by the "Impuls" plant (Ivanovo). The technique for testing humidity indicators is given in [16].

QDs, due to high sensitivity, can control small moisture contents of materials with low losses, such as wool, glass-fiber, and synthetic fibers. Devices have been developed based on a QD with series control that make it possible to distinguish slight loss resistances at frequencies to 30 MHz, which cannot be done by known devices.

Even higher sensitivity can be obtained using parallel control of the QR [17], which is distinguished by the fact that the electric pick-up is connected in parallell with the QR and QR excitation is achieved through a capacitor $C_{\text{in-ser}}$ connected in series with the QR; its change controls the sensitivity of the dielcometer.

To calculate the equivalent resistance of a QR circuit with parallel control, the formula

$$R' = R\left(1 + \frac{C_0 + C_s}{C_{\text{in-ser}}}\right)^2 + \frac{1}{\omega^2 C_{\text{in-ser}}^2 R_s}. \tag{12}$$

is used.

It follows from (12) that an increase in sensor capacitance increases the equivalent resistance of the circuit R', while with series control the equivalent resistance of the circuit decreases with an increase in sensor capacitance. Due to this fact, when controlling small moisture contents in dielectrics one can substantially increase the sensitivity of the device. It is important, for example, in control of small moisture contents in aviation fuel [18].

Non-contact devices for controlling humidity of moving textiles of the IVB-1 type are designed based on a dielcometer with parallel QR control. These devices have shown reliable operation in the manufacture of textiles. A QD can be used to control the quality of polymers and industrial rubber products [19].

NOTATION

ρ, quartz density; ε, displacement; C^{σ}_{55}, H_{55}, elasticity and hysteresis constant of piezoelement; Q, N_0, Q-factor and mechanical resistance of piesoelement; m, mass of piezoelement; l_m, l_0, Δ, length, width, and thickness of piezoelement; v, sound velocity in quartz; R_0, R_m, R_d, R_{moist}, R_r, components of equivalent electric resistance of QR determined by losses of energy and elastic oscillations of piezoelement in quartz, in metallized electrodes, in dry and wet sorbent, and for ultrasound radiation, respectively; β, electromechanical coefficient; H^{d}_{55}, hysteresis constant of dry sorbent; f, ω, frequency of oscillations and angular frequency of oscillations of piezoelement; H^{m}_{55}, hysteresis constant of metal; δ, thickness of electrodes; v_a, sound velocity in air; ρ_a, air density; Δ', thickness of film of sensitive substance; η viscosity of wet capron coating; K_0, conversion ratio of QDC-M; R_1', equivalent electrical resistance of circuit quartz resonator- sensor circuit; R, C_0, equivalent electrical resistance and interelectrode capacitance of QR; C_s, R_s, capacitance and loss resistance of sensor; $C_{in\text{-}ser}$, value of capacitor connected in series with quartz resonator.

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