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Frequency measuring transducers based on the piezoresonance oscillator systems with external MEMS control

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Abstract: The paper represents the mathematical model of piezoresonance oscillator system (POS), which consists of high- quality element- quartz resonator (QR), the element of connection and low- quality loading. Based on analyses of main characteristics of POS in the system of MatLab, the conditions of minimization of negative impact of low- quality loading onto personal characteristics of QR are defined. The new class of frequency- compensated piezoresonance oscillation systems (FCPOS) based on the systems of automated frequency control (AFC) is proposed. On the example of measuring transducer of humidity of the discrete substances, the peculiarities of building and optimization of characteristics of primary measuring transducers (PMT) “physical parameter- frequency” based on FCPOS are studied. The possibility of increasing the linearity of converting of PMT of present type by means of applying matrix MEMS- transducers, which allows realizing the multi- level mode of control over the elements of connections of FCPOS, is shown.

Keywords: Quartz Resonator, Q-Factor, Low-Quality Loading, Primary Measuring Transducer, MEMS-Capacity

1. Introduction

Measuring transducers of non- electric magnitudes with the frequency output based on controlled piezoresonance oscillation systems (POS) are widely used in measurement equipment thanks to their high accuracy and universality. The examples of POS of this type are primary measurement transducers (PMT) with the frequency output, which are used for determination of viscosity of the different environments [1-4] and humidity of substances [5-8], micro- weighting [9-11], measuring the efforts, pressure and relocation [12-18]. The characteristic peculiarity of these PMT is essential losses of equivalent POS quality, which leads to considerable decrease of measurement accuracy. This requires the use of special constructive solutions and functional methods of minimization (compensation) of negative influence of outer elements of the system onto high- quality quartz resonator (QR), which is the basic element of POS.

One of the methods of maintaining high equivalent quality of controlled piezoresonance oscillation systems, which work in the low- quality mode, is providing optimal (minimal) electric connection between high- quality (QR) and low- quality POS elements. Usually for this, the electronic- controlled connection capacity (variable-capacitance diode, varicap), is used, which permits to set the optimal mode of PMT work. However, the negatives of such type of control are: the increase of the level of phase noise of device, the worsening of harmonic structure of the signal on account of non- linearity of controlling element, as well as considerable problems with micro- electronic realization of varicaps on the crystals of high level of integration. The majority of these disadvantages can be avoided while using controlled MEMS capacitors in the PMT of present type, which do not bring in additional phase noise and permit to provide practically any law of POS control [19-20].

2. Mathematical Model of Piezoresonance Circuit with Low-Quality Loading

Let us represent the equivalent scheme of POS in the form of connected sequentially QR, low- quality loading R_xC_x and circuit connection $R_{cc}C_{cc}$ (fig. 1). Complex equivalent resistance of given POS is defined as the sum

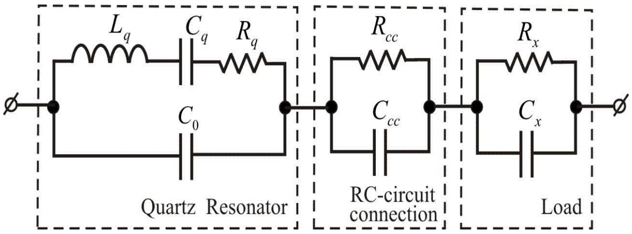

Figure 1. *Equivalent scheme of POS with low- quality loading capacity.*

$$z_e(jw) = z_{QR}(jw) + z_{cc}(jw) + z_{Load}(jw), \tag{1}$$

where $z_{QR}(jw) = \dfrac{(1-\delta^2) + jw\eta_q}{C_0(-w^2\eta_q - jw((m+1)-\delta^2))}$ – complex equivalent resistance of QR;

$z_{cc}(jw) = R_{cc}(1 + jwT_{cc})^{-1}$, $z_{Load}(jw) = R_x(1 + jwT_x)^{-1}$ – complex equivalent resistance of connection circuit and low- quality loading accordingly;

$\eta_q = R_q C_q$, $T_{cc} = R_{cc}\tilde{N}_{cc}$, $T_x = R_x \tilde{N}_x$ – time constants; $\delta = w \cdot W_q^{-1}$ – frequency disorder w POS according to own resonance frequency of quartz resonator; $W_q = 2\pi f_q = (L_q C_q)^{-0.5}$; $m = C_q \cdot (\tilde{N}_0)^{-1}$ – capacitive ratio.

After set of transformations the equivalent resistance of POS (1) comes to the form [21-24]

$$z_e = \frac{A + jB}{C + jD}, \tag{2}$$

where $A = (R_x + R_{cc}) \cdot (M - \delta^2) +$

$$+ C_0^{-1}\left(T - \delta^2 (T_{cc} + T_x)\right) - w^2 C_e^{-1} \eta_q T_x T_{cc};$$

$$B = w \cdot \left(T_{cc} T_x \left(C_e^{-1}(1-\delta^2) + \eta_q\left((T_{cc}\tilde{N}_1)^{-1} + (T_x \tilde{N}_2)^{-1}\right) + mC_3^{-1}\right) + C_q^{-1} W_q^{-2}\right);$$

$$C = M - \delta^2 + w^2 \cdot \left(T_{cc} T_x (\delta^2 - M) - \eta_q (T_{cc} + T_x)\right);$$

$$D = w \cdot \left((T_x + T_{cc}) \cdot (M - \delta^2) + \eta_q\right) - w^3 \eta_q T_{cc} T_x.$$

Here the following designations are accepted:

$$T = \eta_q + T_{cc} + T_x;\ M = m + 1;\ C_e^{-1} = C_{cc}^{-1} + C_x^{-1} + C_0^{-1},$$
$$C_1^{-1} = C_x^{-1} + C_0^{-1},\ C_2^{-1} = C_{cc}^{-1} + C_0^{-1},\ C_3^{-1} = C_{cc}^{-1} + C_x^{-1}.$$

Equating imaginary part (1) to zero $(BC - AD = 0)$, we get equation according to the frequency w, which allows to define resonance frequency POS $\tilde{W}_q = 2\pi \tilde{f}_q = w^r$:

$$a_6 \cdot w^6 + a_4 \cdot w^4 + a_2 \cdot w^2 + a_0 = 0, \tag{3}$$

where $a_0 = M^2 C_0^{-1} (T_{cc} T_x W_q)^{-2} - \left(T_{cc}^{-2}(C_0^{-1} + MC_x^{-1}) + T_x^{-2}(C_0^{-1} + MC_{cc}^{-1}) + (C_0 T_{cc} T_x)^{-1}\right);$

$$a_2 = -\tilde{N}_0^{-1} T_{cc}^{-2} T_x^{-2} W_q^{-4} + 2\left(W_q^{-2}\left(T_{cc}^{-2}\left(MC_x^{-1} + (1+m/2)C_0^{-1}\right) + T_x^{-2}\left(MC_{cc}^{-1} + (1+m/2)C_0^{-1}\right) + 0.5(\tilde{N}_0 T_{cc} T_x)^{-1}\right) - 0.5\left(\eta_q^2\left(C_1^{-1}T_{cc}^{-2} + C_2^{-1}T_x^{-2}\right) - \left(M^2 C_3^{-1} + MC_0^{-1}\right)\right)\right);$$

$$a_4 = -\left(W_q^{-4}\left(C_1^{-1}T_{cc}^{-2} + C_2^{-1}T_x^{-2}\right) - 2W_q^{-2}\left(MC_3^{-1} + (1+m/2)C_0^{-1}\right) + \eta_q^2 C_e^{-1}\right);$$

$a_6 = -C_e^{-1} W_q^{-4}$; w^r – is frequency of successive resonance.

Expressions (2), (3) also allow defining the basic characteristics of POS: equivalent series resistance

$$\tilde{R}_q = ESR = \Phi(w)\big|_{w = w^r}, \tag{4}$$

where $\Phi(w) = \dfrac{A(w) \cdot C(w) + B(w) \cdot D(w)}{(C(w))^2 + (D(w))^2}$; equivalent quality factor

$$\tilde{Q} = \frac{w}{2} \cdot \left|\frac{d\varphi(w)}{dw}\right|_{w = w^r}, \tag{5}$$

where $\left|\dfrac{d\varphi(w)}{dw}\right| = \left|\dfrac{A(w) \cdot B'_w - B(w) \cdot A'_w}{(A(w))^2 + (B(w))^2} - \dfrac{C(w) \cdot D'_w - D(w) \cdot C'_w}{(C(w))^2 + (D(w))^2}\right|$ – steepness of phase- frequency characteristic of POS for the frequency w;

$A'_w = \dfrac{dA(w)}{dw}$, $B'_w = \dfrac{dB(w)}{dw}$, $C'_w = \dfrac{dC(w)}{dw}$, $D'_w = \dfrac{dD(w)}{dw}$ – are derivatives on frequency.

3. Defining the Parameters of Piezoresonance Circuit with Low- Quality Loading

Analysis of piezoresonance oscillation system in accordance with (2) - (5) is done in the environment of MatLab. Thus, the behavior of POS is described by the system of the following characteristics.

1. Resonance – changing frequency of series resonance $\Delta\tilde{F}_r(R_x, C_x)$ (fig. 2);

2. Antiresonance – changing frequency of parallel resonance $\Delta\tilde{F}_a(R_x, C_x)$ (fig. 3);

3. ESR – dependences of equivalent serial resistance

$\widetilde{R}_q(R_x, C_x)$ (fig. 4);

4. Q-factor – Q- factor- changing normalized quality factor $\widetilde{Q}(R_x, C_x) = \dfrac{Q_{Load}(R_x, C_x)}{Q_{No\ Load}}$ (fig. 5, 6).

Calculations are done for typical parameters of quartz resonator: dynamic inductivity – L_q = 7.96 mH, capacity $\tilde{N}_q$ =0.0318 pF; resistance R_q =10 Ohm; parallel capacity C_0 =5 pF; own resonance frequency – f_q =10 MHz and quality factor – $Q_{No\ Load} = 50 \cdot 10^3$.

Figure 2 shows the dependence of changing the frequency of series resonance $\Delta\widetilde{F}_r(R_x, C_x)$ on the parameters of low- quality loading R_x, C_x, which defines the characteristics of POS control. The analysis demonstrates that the correlation $\Delta\widetilde{F}_r(R_x, C_x)$ has considerably non- linear character (fig. 2), and with some meanings of R_x, C_x ($R_x \in$ [100, 1000] Ohm, $C_x \in$ [10, 30] pF) there is extreme field, which can lead to uncertainty in comparison of parameters $\widetilde{f}_q(R_x, C_x) \rightarrow (R_x, C_x)$. This should be taken into account while using the POS of present type in primary measuring converters with frequency information output. Such uncertainty can be eliminated by certain choice of parameters of POS on the stage of PMT projecting.

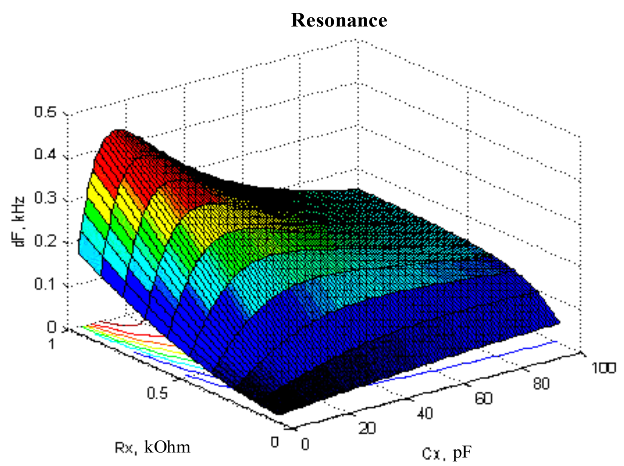

Figure 2. *Changing frequency of series resonance of POS.*

At the same time, the frequency of parallel resonance $\widetilde{f}_a$ remains practically constant (fig. 3). Given result is explained by the fact, that additional circuits (connections, loads) in accordance with equivalent, in fact, are the elements of control over the frequency of successive resonance QR $\widetilde{f}_q$ and do not affect the frequency of parallel resonance $\widetilde{f}_a$. It is convenient to use this dependence for continuous monitoring of reliability of carried- out calculations.

One of the important parameters of POS is the equivalent serial resistance of ESR (fig. 4). Presence of successively connected elements to QR increases considerably the equivalent resistance $\widetilde{R}_q(R_x, C_x)$ of POS compared with personal resistance QR (R_q =10 Ohm) by several orders. Sharp increase of ESR while using the POS in self-oscillation PMT can lead to negative consequences, which can take the form of considerable decrease of the amplitude and even the separation of self- oscillations under certain meanings of parameters of low- quality loading $R_x C_x$. For providing the stable self- oscillation mode under increased meanings of ESR it is necessary to use the modes of PMT with high coefficient of oscillations regeneration, e.g. the modes of filter type self- oscillator.

The decrease of equivalent quality $Q_{Load}(R_x, C_x)$ is directly connected with the increase of ESR. The quality

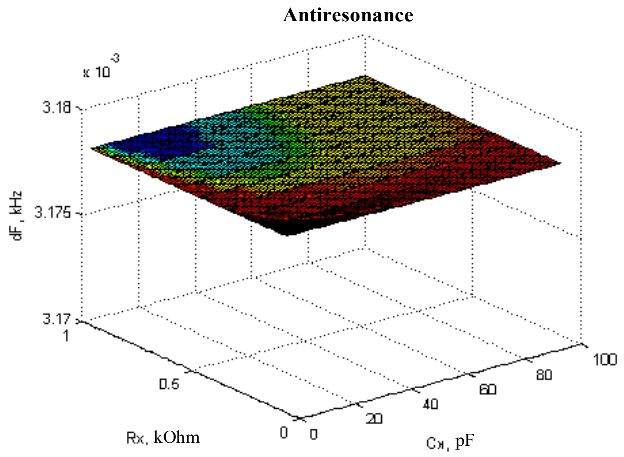

Figure 3. *Changing frequency of parallel resonance of POS.*

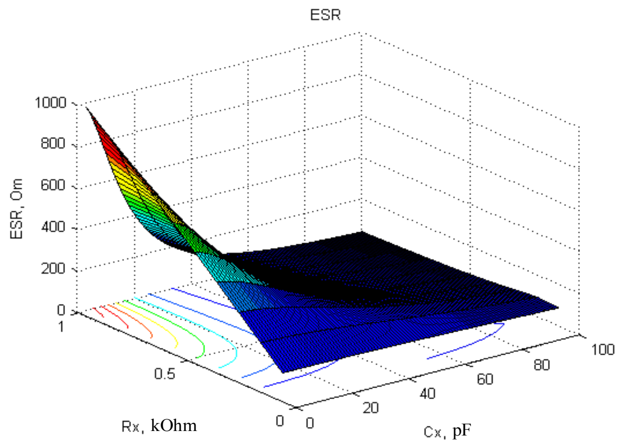

Figure 4. *Dependence of equivalent serial resistance of POS.*

loss is presented by the relations of quality factors $\widetilde{Q}(R_x, C_x) = \dfrac{Q_{Load}(R_x, C_x)}{Q_{No\ Load}}$ on fig. 5 and fig. 6. It is seen, that under certain conditions the losses of quality can reach from 80 to 90 percent and more (fig. 5).

At the same time, even under such unfavourable conditions, using high- quality element – quartz resonator for losses compensation, it is possible to provide excess quality $\widetilde{Q}$ on the level of several thousands. This allows reaching considerably better accuracy characteristics of active oscillators and PMT on basis of POS compared to others, e.g. active oscillator PMT of LC- type.

While decreasing the electric connection between the QR and low- quality capacity it is possible to decrease considerably the loss of quality for small meanings of $R_x \in$ [100, 1000] Ohm. So, for C_{cc} = 2.5 pF the advantage will equal from two to five times more (fig. 6). However, because of the decrease of influence of the parameters R_x, C_x onto personal characteristics of QR, the curve of through characteristic of transformation $\Delta\widetilde{F}_r(R_x, C_x)$ falls, which stipulates the necessity of solving the problem of parametric optimization while projecting the PMT with frequency output based on POS of present type.

With the increase of condenser capacity C_{cc}, the effect of low- quality capacity onto quartz resonator increases

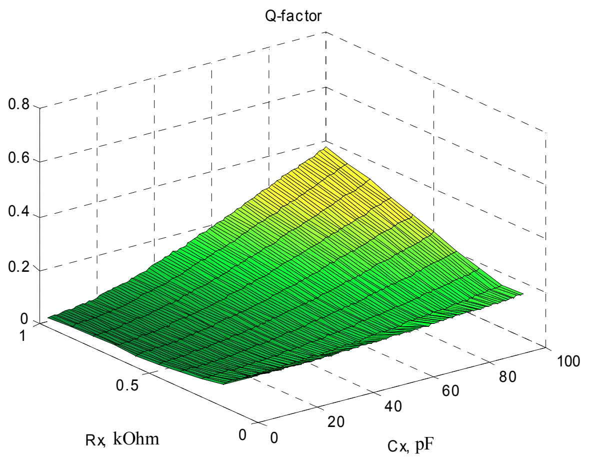

Figure 5. *Dependence of standardized quality of POS under* $C_{cc} \geq 30$ pF .

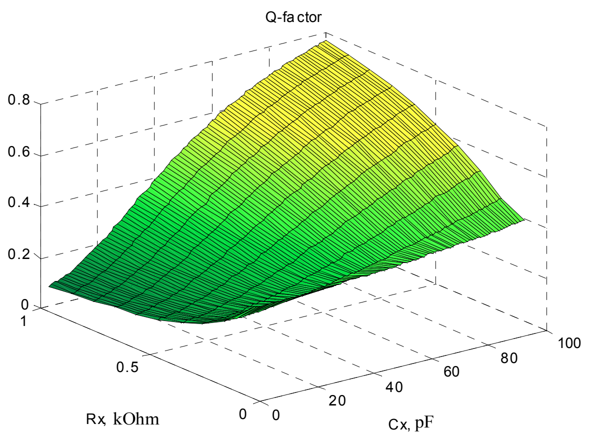

Figure 6. *Dependence of standardized quality of POS under* $C_{cc} = 2.5$ pF .

gradually and the use of connection circuits for C_{cc} > 30 pF loses any sense (fig. 5) [24].

4. Synthesis of Frequency-Compensated Piezoresonance Oscillatory System

Generic structure of frequency- compensated piezoresonance oscillation system (FCPOS) (fig. 7) consists of active oscillator (elements 1-4) and the system of automated frequency control (AFC) (elements 5-7, 3).

Active part of active oscillator (1) is intended to provide undamped oscillations in the system. Passive, frequency-set part of active oscillator, represents POS (fig. 1), the basic element of which is QR, as the element of high-frequency loading circuits (2). It is connected with other (low- quality) circuits (4) with the help of connection element (3). System AFC includes high- stability quartz discriminator (5) [24] with the elements of reverse connection (6,7). With the help of AFC the optimal connection between high-quality and low-quality circuits of passive part of active oscillator is set, which is aimed at the compensation of influence of the last ones onto its characteristics,

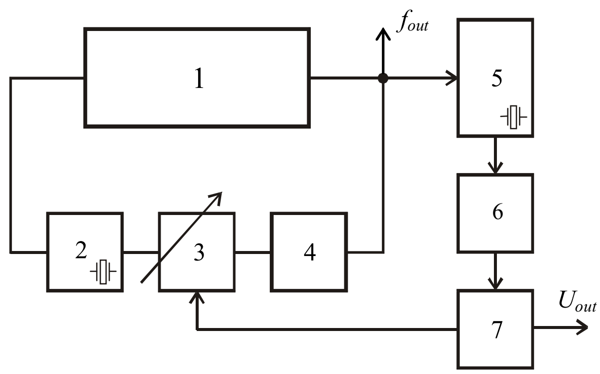

Figure 7. *Structure of frequency- compensated piezoresonance oscillation system: 1- Active part of active oscillator; 2,4- High- quality and Low-quality circuits of passive part of active oscillator; 3- Circuits connection; 5- Frequency discriminator; 6- Filter of low frequencies; 7- Amplifier.*

in the first place, onto the frequency of generation signal (f_{out}). Using FCPOS as initial measuring transducers, the signal of compensation U_{out} is informational. This signal is definitely connected with changes of resonance frequencies of the circuits of passive part of oscillator under the activity of one of measuring magnitudes.

Let us have a look at the procedure of choosing optimal parameters of oscillatory system (FCPOS) on the example of its use as initial measuring transducers of humidity of discrete substances. At given case the low- quality circuits $R_x C_x$ reflects equivalent parameters of dielcometric coaxial cell with internal d_{int} and external D_{ext} diameters, height H_{ext} and electrode height h_{int} (fig. 8), which is filled with humidity H_w mixture [25].

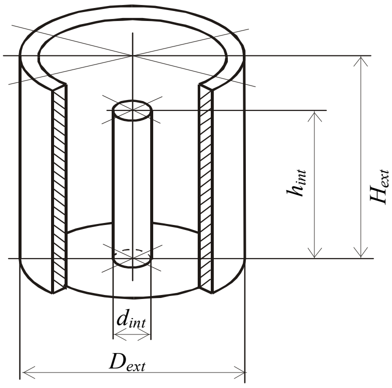

Figure 8. *Construction of coaxial cell.*

In general arrangement of parametrical synthesis of FCPOS desired solution will find depending on criterion:

$$\vartheta_n^{opt} = \min_{\mathbf{x}\in D_x} \vartheta_n(\mathbf{x}, C_{cc}(U, H_w)), \qquad (6)$$

$$D_x = \{\mathbf{x} \in \Re : \; x_{i_{\min}} \le x_i \le x_{i_{\max}}, \; i = 1,2\},$$

where $\vartheta_n(\mathbf{x}) = \max_{\mathbf{x}\in D_x} |\, U_n(\mathbf{x}) - U_l(\mathbf{x}) \,|$ – is nonlinearity of the open characteristic of humidity- voltage, $U_n(\mathbf{x})$ i $U_l(\mathbf{x})$ – are non- linear (real) and linear (nominal) characteristics of conversion;

$\mathbf{x} = (R_x, C_x)^T$ – vector of parameters of low- quality circuits, $\mathbf{x}_{\min} = (R_{x_{\min}}, C_{x_{\min}})^T$, $\mathbf{x}_{\max} = (R_{x_{\max}}, C_{x_{\max}})^T$ – are the vectors, which define the margins of changes of parameters of coaxial cell when measuring humidity;

$\mathbf{V} = (b_0, b_1, b_2, ..., b_n)$ – vector of coefficients of approximation of volt- farad characteristic of connection element.

When using as connection element C_{cc} of varicap, its volt- farad characteristic with accurate enough degree is described by exponential function

$$C_{cc}(U) = b_0 + b_1 \exp(-b_2 U). \qquad (7)$$

When finding the solution (6) the real limit on minimal steepness of transformation is

$$S_H = \frac{\Delta U}{\Delta H} \ge S_{\min} \qquad (8)$$

in the interval of voltage $U \in [U_{\min}, U_{\max}]$.

Let us take the procedure of optimization of parameters of FCPOS on the example of humidity of dry substances (forming mixture). With the help of thermogravimetric method, there were received the experimental parameters of coaxial cell [25]:

$\mathbf{R_x} = [2509.2; 124.85; 36.71; 14.52; 7.51; 3.43; 1.36]$ [кOhm];

$\mathbf{C_x} = [13.5; 14.82; 16.87; 19.06; 21.8; 24.81; 26.55]$ [pF],

which correspond the humidity $\mathbf{H_w} = [0; 1; 2; 3; 4; 5; 6]$ [%].

On the first stage, in accordance with (3) the fields of isofrequent lines $\Delta\tilde{F}_r(C_{cc}, H_w) = const$ (fig. 9) are built. The following curves allow defining necessary law of changes C_{cc} and the possibility of its physical realization (the choice of varicap type and their quantity, applying parallel and successive connections with constant capacities).

On the second stage, on the basis (7) the open characteristic of conversion $U(H_w)$ (fig. 10) is built and its linearization (fig. 11) is done depending on (6). At the same time, on received dependences $C_{cc}(H_w)$, $C_{cc} \in [C_{cc\min}, C_{cc\max}]$ the vector of approximating coefficients $\mathbf{V}$ (the type of varicap is chosen) is found, and the non-linearity of characteristic $\vartheta_n(\mathbf{x})$ is minimized by means of bilateral search of optimal meanings of central frequency of discriminator $f_q + \Delta F_D$ and initial shift on a varicap U_{bias} on condition $(U_{bias} + U) \le U_{lim}$, where U_{lim} is maximum permissible reverse voltage on varicap.

The process of finding optimal meanings of parameters FCPOS is represented in fig.11. As the elements of connection the varicaps KB121 (Russia) are used, for which the approximating coefficients are defined: $b_0 = 3.94$ pF, $b_1 = 52.89$ pF, $b_2 = 0.21\ 1/\text{V}$; mean squared deviation $\sigma = 0.079$ pF.

It is seen, that with reduction of the value ΔF_D the steepness of characteristic of transducers increases (fig.10), which is specified by the character of izofrequent lines (fig. 9). For such type of volt- farad characteristic C_{cc} (7) there exists an extreme point, which corresponds the demands (6) with a glance of limitations (8). At that non-linearity ϑ_n^{opt} equals 2.28% (fig. 11) under the conversion steepness $S_H > 0{,}5\ \text{V}/\%$. If to use two connected parallel varicaps in the cell of connection, you can achieve maximal non- linearity less that 1.5%, which is enough for measuring transducers of the following type [24].

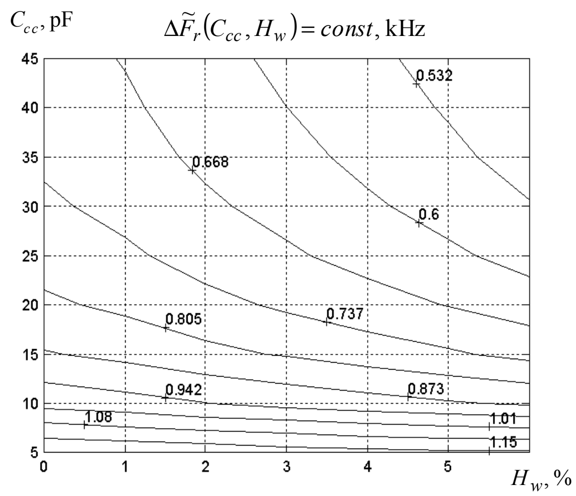

Figure 9*. The Field of izofrequent lines* $\Delta\tilde{F}_r(C_{cc}, H_w) = const$.

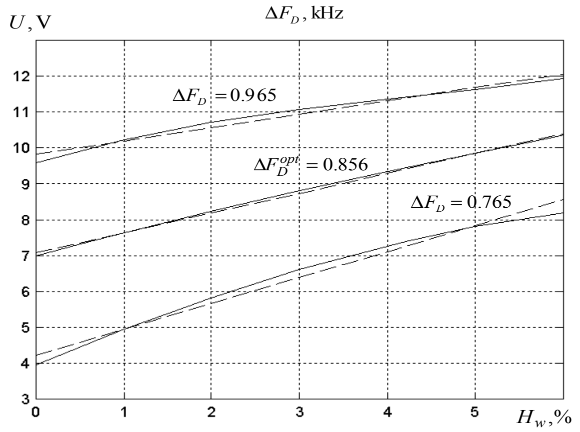

Figure 10. *The open characteristics of humidity- voltage depending on central frequency* ΔF_D.

Applying the circuits connection between QR and low-quality R_xC_x circuits of load influences positively the equivalent quality POS $Q_{Load}(R_x, C_x)$ (fig. 12). It is seen that this mechanism acts effectively on the areas with big losses in quality, where the influence R_xC_x of the circuits

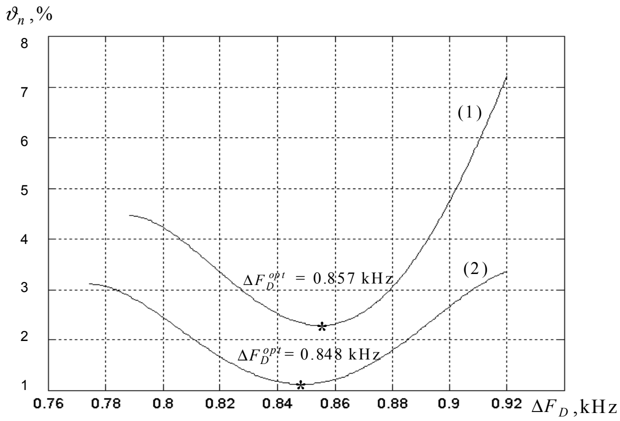

Figure 11. *Dependence of non- linearity* ϑ_n *on the frequency of discriminator* ΔF_D *when using one (1) and two (2) varicaps in the circuits of connection FCPOS.*

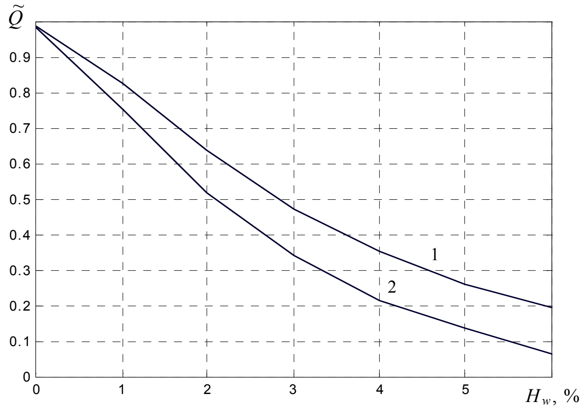

Figure 12. *Changes of quality of POS for* $C_{cc} = C_{cc}^{opt}$ *(1) and in absence of* C_{cc} *(2).*

is the biggest. At that, the advantage on equivalent quality on too "problem" areas (under the humidity more than three percent) accounts from 1.5 to 4 times, which with typical meanings of parameters of QR gives the rise of equivalent quality of POS from 5000 to 10000 units. This promotes the considerable rise of accuracy and resolving ability of active oscillatory measuring transducers on basis of FCPOS.

5. Using MEMS-Capacity, Controlled by Voltage, as the Elements of Connections

In consideration of the fact that using FCPOS as initial measuring transducers the "physical parameter- frequency", their parameters depend considerably on the accuracy of reproduction "volt- farad" characteristics of elements of connection of QR and low- frequency voltage, the paper proposes the improved structure of frequency- compensated POS, whereas the circuit of connection the capacity is applied, it is controlled by the voltage on basis of MEMS (MicroElectroMechanical systems) (fig. 13) [26-27].

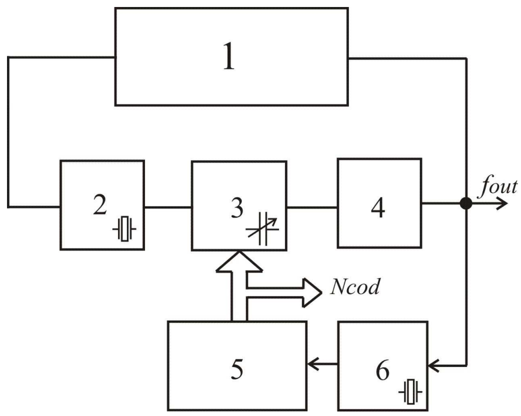

Figure 13. *Structure of FCPOS with digital control MEMS- capacity of connection: 1 - Active part; 2 - Quartz resonator; 3 – MEMS - capacity; 4 - Load with a low Q - factor; 5 - Microcontroller with analog-digital converter; 6 – Quartz frequency discriminator.*

Controlled MEMS- capacity (fig. 14) represents the substrate on which there is applied a fixed electrode and the dielectric structure, made of the array of separate cells (e.g. 5x5).

In each cell, there is a separate active electrode on elastic springs. To each electrode through one out of four elastic springs, the individual electrical output of control is brought, which is connected with individual source of control voltage.

The principle of work of controlled MEMS- capacity is in following. When there is absence of control voltage, which is brought to active and fixed electrodes, the change in value of gap between the last does not happen. When there is difference in potentials between each elementary electrode and mutual parallel fixed electrode, electrostatic force appears. This electrostatic force makes elementary

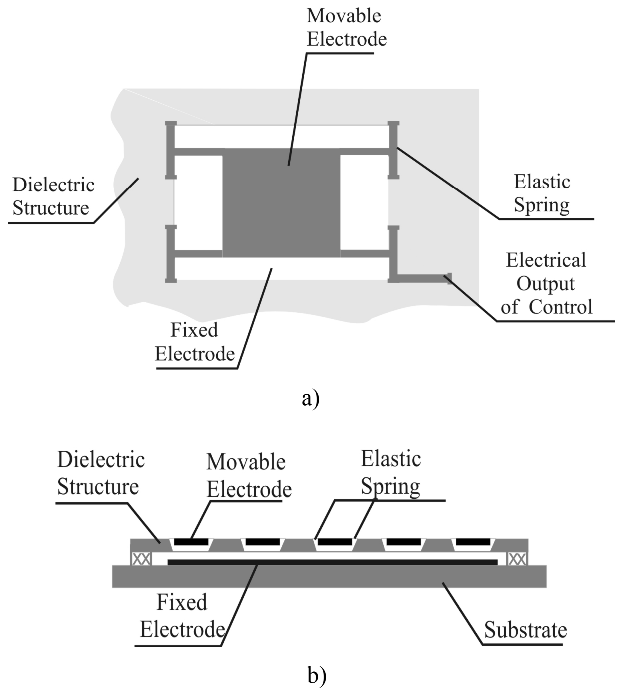

***Figure 14**. Construction MEMS- capacity: Side View (a), Top View (b).*

electrodes to attract in direction of fixed electrode until there is balance between electrostatic force and mechanical forces of elasticity of springs. The state of balance can be described by the following equation [26-28]

$$kx = \frac{1}{2}\cdot\frac{dC_{cc}}{dx}\cdot U^2 = -\frac{1}{2}\cdot\frac{\varepsilon\varepsilon_0 SU^2}{(d+x)^2}, \qquad (9)$$

where k is the coefficient of spring elasticity; U - controlled voltage; S - electrode area; d - is the gap between electrodes at the moment of difference absence; ε - dielectric area permeability; $\varepsilon_0 = 8{,}85\cdot 10^{-12}$ F/m – dielectric constant.

Dependence of the value of elementary electrode shift on control voltage is defined by the correlation

$$x = \frac{1}{3}\left[2d - 1{,}6\frac{d^2k}{A} - 0{,}63\frac{A}{k}\right], \qquad (10)$$

where $A = \Big(4d^3k^3 - 27\varepsilon\varepsilon_0 Sk^2U^2 +$

$$+ 5{,}2\sqrt{-8d^3\varepsilon\varepsilon_0 Sk^5U^2 + 27\varepsilon^2\varepsilon_0^2S^2k^4U^4}\Big)^{1/3}.$$

The condition of balance is fulfilled only when the value of air gap between electrodes equals not less than 1/3 of the value of the gap in initial condition. If the electrostatic force is more than elasticity force, the contact can appear between electrodes (the effect of electrode "adhesion").

In fig. 15 there can be seen the scheme of activation of controlled MEMS- capacitor. Separate control of each active electrode allows realizing multi- level control mode, under which the control voltage $U_{c_1}(t) \neq U_{c_N}(t)$ is changed, and the variable geometry of matrix active electrode is

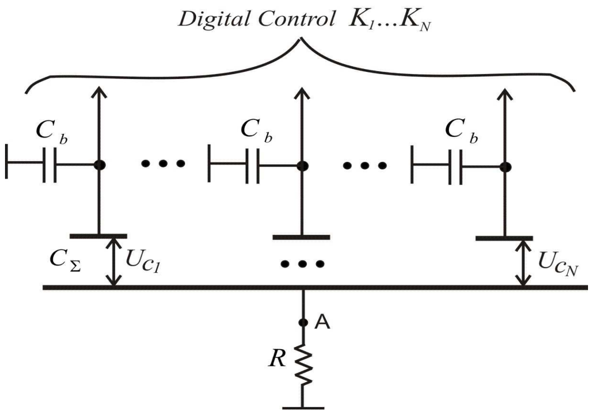

***Figure 15.** Scheme of activating of MEMS - capacity: R - Shift resistor; C_b -Blocking capacity, $\tilde{N}_{\Sigma}$ - Equivalent capacity of matrix active electrode, $U_{c_1} \dots U_{c_N}$ - Control voltage.*

formed. Signals $U_{c_1} \dots U_{c_N}$, which are given on elementary electrodes through functional transducers $K_1 \dots K_N$ (fig. 15), define single state of each electrode, in which active electrode has minimal gap with static one, and which in line with (10), for providing flat - parallel shift can be not less than 1/3 of value of shift in initial condition. Under $U_c = 0$ this gap is maximal (initial condition), and under $U_c = \max$ – it is minimal (single condition). Functional transducers $K_1 \dots K_N$ provide creating necessary law of voltage change on each electrode $U_{c_1} \dots U_{c_N}$ on basis of digital control code of microcontroller N_{cod}. Such technical solution allows receiving practically any law of capacity control under considerably less level of noise compared with electronic- convertible capacity on varicap [28].

6. Conclusion

The work proposes the new approach to building primary measuring transducers "physical parameter- frequency" based on controlled frequency- compensated piezoresonance oscillation systems. The peculiarity of present PMT is using capacity of decompensation of the AFC system as output information parameter of measuring transducer. At the same time there appears the possibility of achieving high linearity of through characteristic of transformation, as opposed to classical piezoresonance PMT with frequent output, for which present characteristic has substantially non- linear character.

On the example of using FCPOS as primary measuring transducer of humidity of the discrete substances, the procedure of choosing optimal parameters of PMT is studied. As a result of analysis of mathematical model of POS it is established, that, in spite of including low- quality dielcometric coaxial cell into POS, by means of using high- quality element- quartz resonator and optimal connection between it and low- quality capacity (coaxial cell) in oscillation system, it is possible to provide residual quality $\widetilde{Q}$ on the level not less than several thousands. This allows to achieve substantially better precision characteristics of PMT based on POS of present type as compared with other ones, for example, self oscillator (active oscillator) of PMT LC- type.

The possibility of minimization of non- linearity of characteristics $\vartheta_n(\mathbf{x})$ by means of bidirectional search of optimal meanings of central frequency of quartz discriminator $f_q + \Delta F_D$ and initial shift on the varicap U_{bias} of connection element POS is shown. Result of parameters optimization leads to the advantage on equivalent quality $\widetilde{Q}$, which equals from one and half to four times more, which under typical meanings of QR parameters (dynamic inductivity – L_q= 7.96 mH, capacity $\tilde{N}_q$=0.0318 pF; resistance R_q=10 Ohm; parallel capacity C_0=5 pF; own resonance frequency – f_q=10 MHz and quality factor – $Q_{No\ Load}$ = $50 \cdot 10^3$) gives the increase of equivalent quality of POS from 5000 to 10000 units.

The possibility of improvement of FCPOS be means of applying the matrix, controlled by the capacity, MEMS converters as the connection elements, has been studied. Separate control over each active electrode allows realizing multi- level mode of control, under which the capacity of control of each elementary capacitor $U_{c_1}(t) \neq U_{c_N}(t)$ is changed, and the variable geometry of matrix active electrode in general is formed. Such technical solution allows achieving practically any law of control over the capacity under considerably less noise level, as compared with electron- rearranged capacity on varicap, as well as forming the single (unified) approach to building the system of FCPOS.

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