INFLUECE OF TEMPERATURE FLUCTUATIONS IN CRYSTAL OVEN ON SHORT-TERM STABILITY AND PHASE NOISE OF QUARTZ CRYSTAL OSCILLATORS

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***Abstract* - In paper are analyzed short-term frequency instability of high-stable OCXOs on the basis of small-sized, fast warm up quartz Resonator –Thermostat (RT). The analytical relations permitting to calculate a fluctuations of temperature of a RT and relevant to them to a fluctuation of frequency, stipulated by temperature-dynamic coefficient, of a quartz resonator are obtained. The limiting values of short-term instability of frequency of quartz resonators are estimated.**

Now in quartz oscillators for stabilization of temperature of a quartz resonator in basic are used having heated systems of a thermostatting with a thermocontroller circuit of a proportional type. In [1] the results of the analysis of short-term instability of frequency of the quartz resonator based on experimentally metered quantity of fluctuations of temperature in a thermostat and which is taking into account only a static temperature-frequency characteristic of the resonator are given. However, presence of temperature-dynamic effects of frequency of a quartz resonator give to essential to major frequency changes of the resonator, than it is stipulated by its static temperature-frequency characteristic. Use of resonators of a SC-cut allows considerably to reduce influence of fluctuations of temperature by frequency, however in new, small-sized quartz resonators thermostats with an directly heating of a crystal, at which the film heater is marked immediately on a crystal, this influence remains to considerable. Therefore it is represented expedient to find a theoretical estimation of fluctuations of temperature in a thermostat and fluctuations of frequency of a quartz resonator stipulated by temperature-dynamic effects in a quartz resonator.

For having heated a thermostat medial temperature of object of a thermostatting is determined by expression [2].

$$T_R = T_O + P \cdot R_t \qquad (1)$$

Where T_R - temperature of the resonator; P - power of heater on object of a thermostatting; R_t - blanket thermal resistance to a heat insulation of a thermostat.

If any parents call fluctuations of power oozed in a thermostat on quantity ΔP, fluctuation of temperature of object from (1)

$$\Delta T_R = \frac{\Delta P \cdot R_t}{1 + p \cdot \tau} \qquad (2)$$

Where τ - thermal time constant of a thermostat; p - laplacian.

It is possible to show, that for having heated a thermostat of a static type with a proportional thermocontroller circuit containing bridge temperature sensing device with use of a thermistor, direct-current amplifier, heater consisting of the regulating transistor and a resistor :

$$\Delta T_R = \frac{\Theta}{\mu \alpha R I K} \cdot \frac{\Delta U}{1 + p\tau} \quad , \qquad (3)$$

where Θ - $T_{max} - T_{min}$ - gamut of an operating temperature; μ - given static error of a thermocontroller; α- temperature coefficient of resistance of a thermistor; R - resistance of a thermistor; I - current through a thermistor; K - amplification constant an operational amplifier; ΔU - fluctuation of a voltage on an output an operational amplifier.

Figuring, that the fluctuations of a voltage on an output an operational amplifier are stipulated in the basic thermal and flicker noises of the bridge data unit and amplifier, the power spectral density of fluctuations of a voltage on an output an operational amplifier is determined by expression

$$S_{\Delta U}(f) = (4kT_R R + \frac{A}{f})K^2 \quad , \qquad (4)$$

where k - Boltzmann constant; T_R - temperature in a thermostat; A - coefficient a defining level of flicker fluctuations stipulated by noises of a temperature sensing device and amplifier, K - transfer ratio, defined value of thermal time constant τ of a thermostat. Then the power spectral density of fluctuations of temperature is equal

$$S_{TR}(f) = \frac{\Theta^2}{\mu^2 \beta^2} \cdot (4kT_R R + \frac{A}{f}) \cdot \frac{1}{1 + 4\pi^2 \tau^2 f^2} \quad , \qquad (5)$$

where $\beta = \alpha R I$ - temperature sensitivity of a temperature sensing device.

Let's estimate quantities of parameters, which are included in expression (5). The difference between the peak and underload operating temperature both is usually set by specifications and makes 130ºC (-60ºC-+ 70ºC). The precision of maintaining of temperature or static error of a thermo controller is picked about 0.01ºC for thermostats with the resonator of AT - cut and about 0.1ºC for thermostats with the resonator of SC-cut. The temperature coefficient of resistance of thermistors for different types would make quantity from 0.02 up to $0.04K^{-1}$. Temperature of a crystal usually makes 350-360K. The thermal time constant of a thermostat depending on a construction has quantity from several thousand seconds, for thermostats of a usual type up to tens and unities of seconds for small-sized resonator-thermostats with small warm up time. Coefficient A

determines a level of flicker fluctuations stipulated by an excess noise of resistors of a bridge temperature sensing device and an excess noise of an operational amplifier. Unfortunately, in the literature there are data on examination of noises of thermistors. For usual film and semiconductor resistors the quantity of coefficient A lays in limits 10^{-12} - 10^{-16}. For the majority of low noise operational amplifiers the level reduced to an inlet of excess noises on frequency 1 Hz is equal 0.5-2· 10^{-7}V/Hz$^{1/2}$, thus coefficient A has the order 10^{-14}. Let's receive for definiteness in expression (5) A=10^{-14}. In a fig. 1 the diagram of a power spectral density of fluctuations of temperature calculated on the formula (5) for the following values of parameters is submitted: Θ =130K, μ =0.1K, α =0.03K-1, R=10^4Ohm, I=10^{-4}A, A=10^{-14}, T_R=350K, τ =20s.

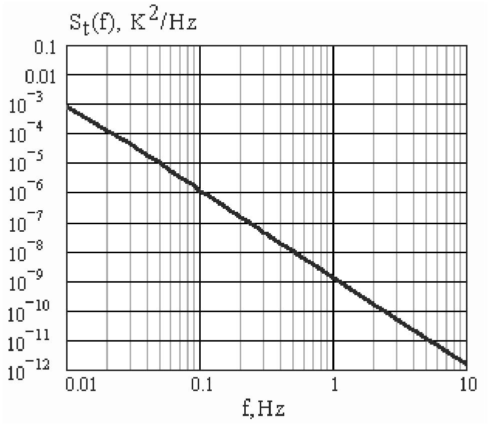


Fig. 1. A power spectral density of fluctuations of temperature in a thermostat

The values a standard deviation of fluctuations of temperature in a thermostat calculated for several values of parameters are given in the Table 1.

Table 1

	σ		
μ / τ	20s	200s	2000s
0.1	6.1· 10^{-3}	1.9· 10^{-3}	1.9· 10^{-4}
0.01	6.1· 10^{-2}	19· 10^{-3}	1.9· 10^{-3}

The results of calculations of value at under the order of quantities coincide with experimental data [1], which are obtained by immediate measuring of fluctuations of temperature in a thermostat.

The standard deviation of temperatures stipulated only by thermal noises at A=0, μ=0.1 and τ=20s is equal σ =6.10^{-5}K. The analysis of expression (5) and data of the table displays, that σ in a strong degree the accuracy of maintaining of temperature, or coefficient of regulation G= Θ/μ. There is some value G, at which the level of fluctuations of temperature exceeds a static error of a controller.

In paper [3] for an estimation of influence of prompt changes of temperature on frequency of a quartz resonator the temperature-dynamic performance of the resonator and temperature-dynamic coefficient is entered. The temperature-dynamic performance erects dependence of a frequency change of the resonator on quantity of change of temperature of its housing under the sine law from a stationary value by amplitude in one degree. Temperature-dynamic coefficient of a resonator frequency is a coefficient linking quantity of a frequency change of the resonator to amplitude of change of temperature of housing on the sine law.

The temperature-dynamic performance substantially depends on an edge of a crystal and design of the concrete resonator and is well approximated by the following expression

$$\Delta f = \gamma \cdot \Delta T_R \left(\frac{1+\eta}{1+4\pi^2 f^2 \tau_1^2} - \frac{1}{1+4\pi^2 f^2 \tau_2^2} \right)^{1/2}, \qquad (6)$$

where Δf a deviation of a resonator frequency, γ - temperature-dynamic coefficient of a resonator frequency, ΔT_R - deviation of temperature of the resonator, τ_1 and τ_2 - thermal time constants, defined construction of the concrete resonator, η - coefficient depending generally on a temperature-frequency characteristic of the resonator and from ΔT_R.

In a fig. 2 the experimentally metered temperature-dynamic performances of several quartz resonators with crystals of AT and SC - cut, different construction are submitted. The change in temperatures in a thermostat of a quartz resonator was carried out by an alternation of one of resistances of a bridge temperature-sensing device on quantity, at which the amplitude of change of temperature made 0.1ºC. The period of change of resistance varied from 0.5 about 1000 seconds. The deviation amplitude of frequency was determined through a frequency multiplier and frequency counter and then was given in amplitude of change of temperature equal 1ºC.

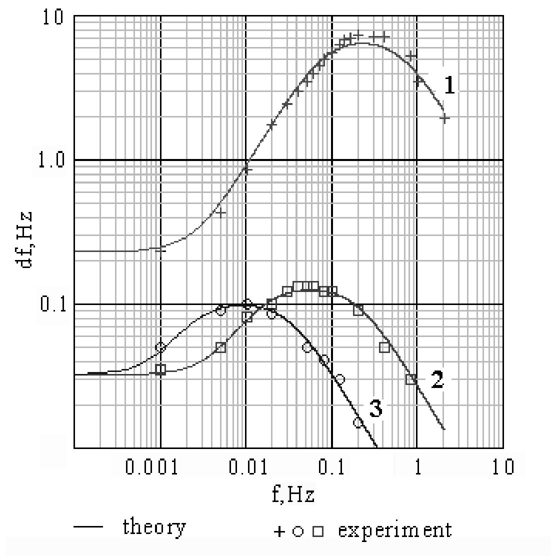


Fig. 2. The temperature-dynamic performances of quartz resonator-thermostats

The diagram 1 corresponds to a quartz resonator-thermostat with a crystal of an AT - cut of the rectangular shape on frequency 10 MHz operating on 5 overtone. The heater as a film resistor is marked on perimeter of a crystal. The diagram 2 corresponds to a quartz resonator-thermostat with a crystal SC - cut of the rectangular shape on frequency 10 MHz operating on 3 overtone. The crystal is located on a ceramic substrate playing a role of the cabinet of a thermostat. The heater consists of a film resistor located on a crystal and the transistor, located on a ceramic substrate. The diagram 3 corresponds to a quartz resonator-thermostat with a crystal SC - cut of the round shape on frequency 10 MHz operating on 3 overtone. The crystal is located in the cylindrical can, which has been carried out from metal. The heater is served by the transistor located on the can of a thermostat. In the table 2 the numerical values of parameters of quartz resonators of thermostats are given.

Table 2

	1	2	3
	AT	SC	SC
Θ_i =	7.2	0.13	0.1
$\Delta_1$13	0.25	0.8	5
$\Delta_2$13	2.0	10	60
η	0.001	0.06	0.1

Using (5) and (6) it is possible to receive expression for a power spectral density of fluctuations of frequency of the oscillator stipulated by fluctuations of temperature in a thermostat

$$S_f(f) = \gamma^2 \cdot \frac{\Theta^2}{\mu^2 \beta^2}(4kT_R R + \frac{A}{f}) \cdot K^2(f) \qquad (7)$$

where

$$K(f) = \left(\frac{1+\eta}{1+4\pi^2 f^2 \tau_1^2} - \frac{1}{1+4\pi^2 f^2 \tau_2^2} \right)^{1/2}$$

And for a power spectral density of phase noise

$$S_\varphi(f) = \frac{S_f(f)}{f^2} \qquad (8)$$

In a fig. 3 the settlement diagrams of phase noise L(f) =10· log($S\varphi$(f)/2) quartz oscillators with resonator-thermostats are submitted, which parameters are given in the Table 2.

The diagrams 1,2,3 accordingly for resonator-thermostats 1, 2 and 3. The diagram 4 represents a phase noise imported by an electronic circuit of the self-oscillator. The rectangles mark fields of experimental data obtained by results of measuring of phase noise of a batch of industrially released OCXOs.

As is known, the performance of short-term instability of frequency of a quartz oscillators is the two-sample variance, or Allen variance, defined according to expression (9)

$$\sigma_y^2(\tau) = \frac{2}{(\pi\nu\tau)^2} \int_0^\infty S_\varphi(f) \sin^4(\pi f \tau) df, \qquad (9)$$

where Δ - time of averaging, ν - frequency of a quartz oscillator.

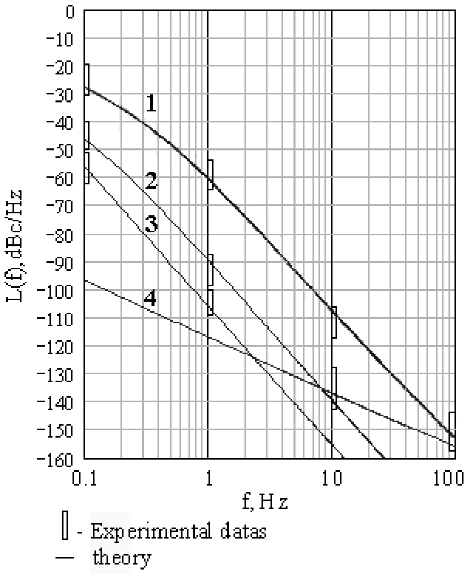


Fig. 3. A power spectral density of phase noise.

The results of calculations of Allen variance for surveyed above generators at Δ=1 and results of experimental measuring are given in the table 3.

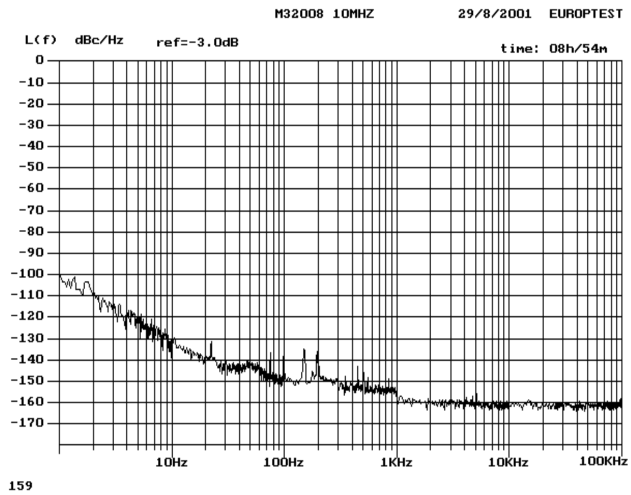
Table 3

	1	2	3
$\sigma_y(\Delta$ theory	1.6· 10^{-10}	1.6· 10^{-11}	4.5· 10^{-12}
$\sigma_y(\Delta$ experiment	(1-2) · 10^{-10}	(1-2)· 10^{-11}	(2-6)· 10^{-12}

On the basis of obtained data it is possible to make the following deductions. The settlement results are well compounded with experimental data. On frequencies of the analysis f smaller then 10 Hz the basic mechanism formative a phase noise of the oscillator, is the transformation of fluctuations of temperature of a thermostat in a fluctuation of frequency stipulated by temperature-dynamic sensitivity of a quartz resonator. The level of phase noise is proportional to coefficient of regulation of a thermo controller circuit G, therefore it is impossible simultaneously to receive a low level of phase noise and low temperature instability of frequency. A level of phase noise and accordingly short-term instability of frequency have essential quantity even for quartz resonators SC - cut. For a quartz resonator with one-step oven quantity of Allen variance $\sigma_y(\Delta$ =(1-2) · 10^{-12} apparently, is limiting.

Thus, the drop short-term instability of the quartz oscillator up to magnitude smaller 1· 10^{-12} represents a serious problem and can be solved by use of a double oven system of a thermostatting. Really coefficient of regulating of the first and second step can be small enough, at which the necessary exactitude of maintaining of temperature of the resonator and simultaneously low level of fluctuations of temperature is ensured. The analysis shows that at G < 10 phase noise stipulated by temperature-dynamic effects lower of a level of phase noise of the electronic circuit of the oscillator. There are optimum relations of parameters of an external and internal oven at which the minimum level of fluctuations of temperature and adequate accuracy of a thermostat is achieved.

In view of the obtained results two model of OCXOs designed on the basis of the small-sized, fast warm up resonator-thermostat. First, with a single oven system of a thermostatting is carried out on the basis of the quartz resonator-thermostat with directly heating crystal. The oscillator has the following performances: frequency 10 MHz, stabilization time of frequency less than 15 seconds with exactitude 10^{-7} in standard conditions, power consumption 250 mW,



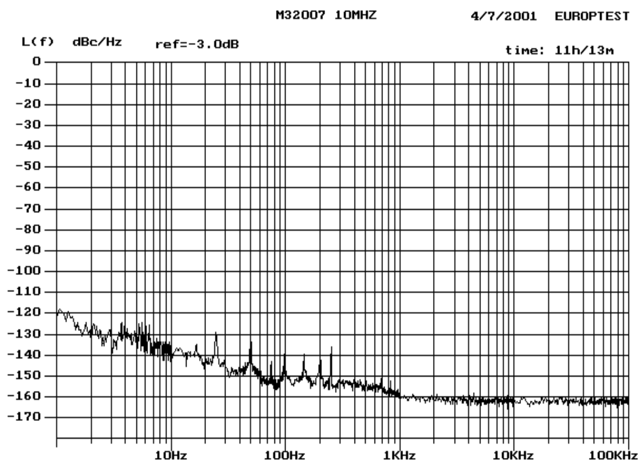


Fig. 4. Performance of phase noise of a quartz oscillators M32008 and M32007.

instability of frequency $\pm 5.10^{-8}$, in an interval of temperatures -60ºC - +70ºC, short-term instability $A_y(\tau)$ = 5.10^{-12}.

Second, with double oven system, has a stabilization time of frequency of 3 minutes, instability of frequency $\pm 2.10^{-10}$, in an interval of temperatures -30ºC - +70ºC, aging < 1.10^{-10}/day, power consumption 1 W and short-term instability of frequency $A_y(\tau)$ = 5.10^{-13}.

The performances of phase noise of generators are submitted in a fig. 4.

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