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INVARIANT PIEZORESONANCE DEVICES BASED ON ADAPTIVE MULTIFREQUENCY SYSTEMS WITH A PREDICTIVE STANDARD

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Abstract. *The paper presents conceptual provisions for the construction of invariant multi-frequency piezoelectric resonance devices with a predictive reference model. The law of the optimal control of the system in real time is formulated, aimed at minimizing energy costs to ensure the trajectory of the system. The results of piezoelectric resonance system mathematical modelling in the conditions of temperature and vibration perturbations are presented.*

Keywords: invariant multi-frequency piezoelectric resonance system, optimal control, mathematical model

NIEZMIENNE URZĄDZENIA PIEZOREZONANSOWE NA PODSTAWIE ADAPTACYJNYCH WIELOCZĘSTOTLIWOŚCIOWYCH SYSTEMÓW Z PROGNOZOWANYM STANDARDEM

Streszczenie. *W artykule przedstawiono koncepcyjne zasady konstruowania niezmiennych wieloczęstotliwościowych piezoelektrycznych urządzeń z predykcyjnym modelem odniesienia. Zostało sformułowane prawo optymalnego sterowania systemem w czasie rzeczywistym, aby przy minimalnych stratach energii zapewnić trajektorię ruchu systemu. Przedstawiono wyniki matematycznego modelowania układu piezorezonansowego w warunkach zaburzeń temperatury i drgań.*

Słowa kluczowe: niezmienne wieloczęstotliwościowe układy piezoresonansowe, optymalne sterowanie, model matematyczny

Introduction

Modern piezoelectric resonance devices as part of infocommunication systems operate in considerable variation of temperature and vibrational-mechanical environment. This obstacle substantially complicates a problem of providing the invariance under a condition of parametrical non-stationarity and it requires special approaches to be solved.

Effective solving the problem dedicated to providing technical invariance of a piezoelectric resonance device (PRD) requires the transition to multi-frequency mode of oscillatory system excitation and representation of PRD like dynamic object. It allows formulating a novel algorithmic approach to problem-solving concerning providing the PRD invariance in respect to destabilizing and perturbation factors (DPF) by using a combination of the main, i.e. frequency defining and stabilizing the function of quartz resonator (QR) and additional measurement function that allows performing flowing PRD identification [1, 2].

1. Invariant PRD model in the form of adaptive system with the predictive standard

Let us consider a model of multi-frequency invariant PRD having controlled dynamics (IPRD/CD). Such model is represented in the form of an adaptive self-adjusting control system having predictive standard model (see Fig. 1). The main element of the system is the PRD core, i.e. multi-frequency oscillatory piezoelectric resonance system (MOPS) contained additional circles for control, matching, thermo- and vibro-stabilization and operating according to predictive standard model (see Fig. 1). The main element of the system is the PRD core, i.e. MOPS contained additional circles for control, matching, thermo- and vibro-stabilization influenced by destabilizing and perturbation factors (PF) [2, 3].

Optimal or suboptimal estimation and identification system forms the estimate of vector state $\hat{\mathbf{X}}_S$ and vector parameter estimate $\hat{\mathbf{X}}_P$ for mathematical model PRD on the basis of signal vector observation $\mathbf{Y}$. This approach corresponds to parametrical identification. Optimal control system forms the vector of controlling influences $\mathbf{u}$ on the basis of the standard mathematical model and a current estimate of the state vector PRD. It provides optimal system operating mode performed both at the stage of exit to the multi-frequency stable oscillation (terminal task) mode and at the stage of system state stabilization (technical invariance) according to given optimization criterion and limitations for $\mathbf{L}$ caused by a specific physical realization of the MOPS. Expanded vector of controlling influences $\mathbf{u}'$ also is used by optimal estimation and identification system.

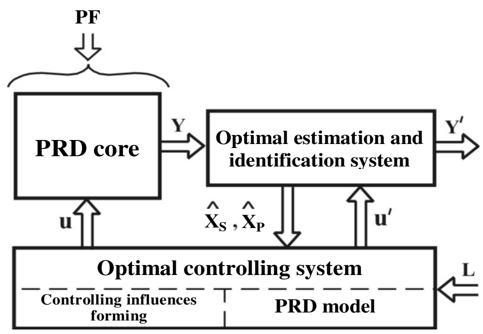

Fig. 1. Generalized structure of multi-frequency IPRD/CD

System operating is defined by standard predictive PRD model. The model allows defining the end time t_{set} and the exit trajectory $y_{mi}(t)$ for each oscillation excitation mode $\hat{y}_i(t)$ with given accuracy ε_i on the basis of a priory and current information about IPRD/CD as:

$$\left| y_{mi}(t) - \hat{y}_i(t) \right| \le \varepsilon_i \; ; \; i = \overline{1,n} \qquad (1)$$

according to minimum time criterion necessary for reconstruction of multi-frequency oscillations:

$$\tau_{\text{set}}^{\text{opt}} = \min_{\mathbf{L}\in\mathbf{D}} \max_{1\le i\le n} \tau_{\text{set}_i} \; , \qquad (2)$$

$$\mathbf{D} = \left\{ \mathbf{L} \in \Re^{\text{N}} : l_{j\min} \le l_j \le l_{j\max}, 1 \le j \le N \right\},$$

where τ_{set_i} is the set time for *i*-th oscillation mode which defined by given long-time frequency instability parameter δ_i; $\mathbf{L}_{\min} = \{ l_{1\min},..., l_{\text{N}\min} \}$, and $\mathbf{L}_{\max} = \{ l_{1\max},..., l_{\text{N}\max} \}$ are the vectors of minimum and maximum permissible values of core parameters given in IPRD/CD.

IPRD/CD structure comes near to optimal mode. It corresponds to the separation theorem and gives a possibility of separate optimization for estimation, identification and control system [2].

2. The basic equivalent circuit of multi-frequency core MOPS

The basic core architecture represents multi-frequency MOPS to have principles of creating filtering schemes implemented (Fig. 2). It incorporates passive multi-frequency quartz quadripole unit (MQU) on the base of quartz resonator with *m*-frequencies generating z_{qj} and n excitation channels embedding the generalized non-linear component (NLC) and phasing selective feedback circuit (FBC). The automatic bias circuits with complex equivalent resistance z_{b_i} are used for stabilizing NLC$_i$ operational mode. The selective non-linear circuits FBC with gain $K_{ji}\left(j\omega, u_{\Sigma}, \tau\right)$, $j=\overline{1,m}$, $i=\overline{1,n}$, except for their function to set required amplitude-phase ratio in excitation channels, provide significant reducing competition in oscillations due to their own selective properties $K_{ji}(j\omega)$ and also automatic adjustment $K_{ji}(u_{\Sigma})$ of oscillation amplitudes for fixing the specified (ultimately acceptable) power dissipation on QR.

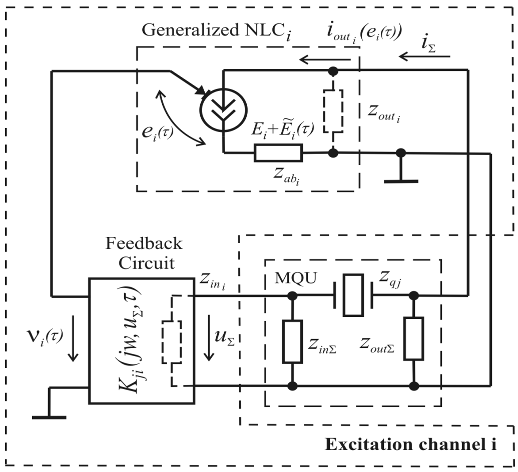

Fig. 2. The basic equivalent circuit of multi-frequency core MOPS

Figure 2 has the following symbols' identifications: $z_{\mathrm{in}\Sigma} = R_{\mathrm{in}\Sigma} \Big/ \left(1 + j\omega\tau_{\mathrm{in}\Sigma}\right)$, $R_{\mathrm{in}\Sigma}^{-1} = \sum_i R_{\mathrm{in}_i}^{-1}$, $C_{\mathrm{in}\Sigma} = \sum_i C_{\mathrm{in}_i}$ – the complex equivalent total resistance of partial FBC input circuits; $z_{\mathrm{out}\Sigma} = R_{\mathrm{out}\Sigma} \Big/ \left(1 + j\omega\tau_{\mathrm{out}\Sigma}\right)$, $R_{\mathrm{out}\Sigma}^{-1} = \sum_i R_{\mathrm{out}_i}^{-1}$, $C_{\mathrm{out}\Sigma} = \sum_i C_{\mathrm{out}_i}$ – the complex equivalent total resistance of output NLCi circuits; $z_{\mathrm{ab}_i} = R_{\mathrm{ab}_i} / \left(1 + j\omega\tau_{\mathrm{ab}_i}\right)$ – complex resistance of auto-bias circuit i; $\tau_{\mathrm{ab}_i} = R_{\mathrm{ab}_i} C_{\mathrm{ab}_i}$, $\tau_{\mathrm{in}\Sigma} = R_{\mathrm{in}\Sigma} C_{\mathrm{in}\Sigma}$, $\tau_{\mathrm{out}\,\Sigma} = R_{\mathrm{out}\,\Sigma} C_{\mathrm{out}\,\Sigma}$ – time constants; $i_{\Sigma} = \sum_i i_{\mathrm{out}_i}(e_i)$ – total current of NLCi; $e_i(\tau) = \sum_j v_i(\tau) + E_i + \widetilde{E}_i(\tau)$ – control voltage in NLCi input, where E_i, $\widetilde{E}_i(\tau)$ – constant and variable components of auto-bias voltage;

$u_{\Sigma}(\tau) = U_0(\tau) + \sum_j U_j(\tau) \cdot \cos[\omega_j t + \varphi_j(\tau)]$ – the total voltage in FBC circuit input, where $U_j(\tau)$, ω_j and $\varphi_j(\tau)$ – envelope, frequency and phase of oscillation j correspondently, $\tau = t - t_0$ – time interval from initial moment t_0 (MOPS start up moment).

3. General formulation of the task of the temperature and vibration measuring

Multi-frequency excitation of MPOS is necessary for combining the function of stabilizing the frequency with measuring function, which allows the simultaneous identification of influence factors (temperature, vibration) and allows defining MPOS as multi-dimensional object, in the model of which the controlled perturbations appear:

$$y_i(p) = y_{s_i}(p) + \Delta y_{c_i}(p) + \Delta y_{nc_i}(p) = W_{ii}(p) x_{s_i}(p) + \\ + \sum_{j=1, j\neq i}^{m} W_{ij}(p) x_{s_j}(p) + \sum_{k=1}^{n} A_{i_c}(p) x_{c_k}(p) + \Delta y_{nc_i}(p), \quad (3)$$

where $\mathbf{X}_s(p) = \left\{x_{s_i}\right\}_{j=1}^{m}$ – is the vector of control which is set; $\mathbf{X}_c(p) = \left\{x_{c_k}\right\}_{k=1}^{n}$ – is the vector of controlled perturbations; $\mathbf{W}(p)$, $\mathbf{A}(p)$ – are the transmission functions of direction channels and the channels of perturbations accordingly; $\Delta y_{nc_i}(p)$ is the additional movement by means of non-controlled perturbations.

Dependence of QR frequencies from temperature T and vibration acceleration G are presented as:

$$f_{REF} = f_{REF}^0 + a_{1T} T + a_{1G} G; \quad (4)$$

$$f_T = f_T^0 + a_{2T} T + a_{2G} G; \quad (5)$$

$$f_G = f_G^0 + a_{3T} T + a_{3G} G, \quad (6)$$

where f_{REF}^0, f_{T}^0, f_G^0 are nominal meanings of frequencies; $a_{1\mathrm{T}}$, $a_{2\mathrm{T}}$, $a_{3\mathrm{T}}$ – are coefficients of temperature sensitivity; $a_{1\mathrm{G}}$, $a_{2\mathrm{G}}$, $a_{3\mathrm{G}}$ – are the coefficients of vibration -sensitivity.

On the exit of Mixers the oscillations of difference frequencies are distinguished:

$$F_T = f_T - f_{REF} = \left(f_T^0 - f_{REF}^0\right) + a_1^* T + a_2^* G = F_T^0 + \Delta F_T; \quad (7)$$

$$F_G = f_G - f_{REF} = \left(f_G^0 - f_{REF}^0\right) + a_3^* T + a_4^* G = F_G^0 + \Delta F_G, \quad (8)$$

where $a_1^* = \left(a_{2T} - a_{1T}\right)$, $a_2^* = \left(a_{2G} - a_{1G}\right)$, $a_3^* = \left(a_{3T} - a_{1T}\right)$, $a_4^* = \left(a_{3G} - a_{1G}\right)$ are difference coefficients.

Solving together (7) and (8) we get a possibility of synchronous identification of temperature T and vibrational acceleration G [3]:

$$T = \frac{a_4^* \Delta F_T - a_2^* \Delta F_G}{a_1^* a_4^* - a_2^* a_3^*}; \; G = \frac{a_1^* \Delta F_G - a_3^* \Delta F_T}{a_1^* a_4^* - a_2^* a_3^*}. \quad (9)$$

3. Strategy of optimal control for software trajectory motion of PRD with predictive model

The designed concept for invariant PRD like adaptive system with predictive standard requires solving inverse dynamics problem. It requires determination of the dynamic system motion and its parameters under a condition of performing of the motion corresponding to given trajectory. In accordance to specificity of development and exploiting IPRD/CD control process is performed by two stages.

The first stage is the oscillation forming. Control impacts are formed in each exciting channels. The impacts provide the output to the stationary mode under a minimum time of set of stable multi-frequency oscillatory mode.

Second stage is the oscillation stabilization. Control of IPRD/CD is directed to support of generated oscillations stability under influence of destabilizing factors, i.e. providing technical invariance [2].

We will carry out the construction of optimal or sub-optimal control law according to generalized work criterion that has good results at the stage of analytical construction during a designing period. Using this approach allows not only simplifier the procedure of obtaining the optimal control laws, but often do not obtain the functional dependences due to the cumbersomeness and complexity related to control laws. In such case, solving a problem comes to an end with an algorithm which performs optimization during system functioning and it is convenient from the point of view of a realization of microprocessor control.

Let us consider controlled process in the form of

$$\dot{y}_i + f_i\left(x_1, \ldots, x_n, y_1, \ldots, y_m, t\right) = 0, \; \dot{x}_j = u_j, \quad (10)$$

where f_i is differentiable or piecewise differentiable functions; $\mathbf{x} = \left(x_1, \ldots, x_n\right)$ is the state vector of the control elements; $\mathbf{y} = \left(y_1, \ldots, y_m\right)$ is the state vector of the control object; $\mathbf{u} = \left(u_1, \ldots, u_m\right)$ is the control vector, $i = \overline{1,n}$, $j = \overline{1,m}$.

In considered case, the control of the rates related to the variations of controlled elements is performed. Object non-stationarity can be taken into account by extension its state vector.

Equation of system free movement (3) can be written as

$$\dot{\mathbf{y}} + f(\mathbf{x}, \mathbf{y}, t) = 0, \; \dot{\mathbf{x}} = 0, \quad (11)$$

e.g. free system movement is the movement under fixed locations of the control elements.

For the task formulated by using an expression (3), we have expanded state vector $(\mathbf{x},\mathbf{y})$. According to optimal controlling the minimum of the functional

$$I = V_{\text{set}}(\mathbf{x}(t_2),\mathbf{y}(t_2)) + \int_t^{t_2} Q(\mathbf{x},\mathbf{y},t)dt + \frac{1}{2}\int_t^{t_2}\sum_{j=1}^{m}\frac{u_j^2 + u_{jopt}^2}{k_j^2}dt \quad (12)$$

provides the control of the form of

$$u_j = u_{jopt} = -k_j^2 \frac{\partial V}{\partial x_j}, \quad (13)$$

where $V = V(y,t)$, is the solving the following equation

$$\frac{dV}{dt} - \sum_{i=1}^{n} f_i \frac{dV}{dy_i} = -Q, \quad (14)$$

under boundary condition of $V_{t=t_2} = V_{\text{set}}$; f_i, Q, where V_{set} are given uninterrupted functions; $k_j^2 > 0$ are given coefficients.

In order to provide prediction of object behavior, model of free movement must operate in faster mode as $t' = t/\chi$, where $\chi = \text{const} >> 1$. Then, the equation of prediction model can be written as

$$\frac{d\mathbf{y}_{\text{м}}}{dt'} + \chi \cdot f(\mathbf{x}_{\text{м}},\mathbf{y}_{\text{м}},\chi t') = 0, \quad \frac{d\mathbf{x}_{\text{м}}}{dt'} = 0. \quad (15)$$

A prediction model has to provide the integration of free movement during total optimization interval from $t = t_1$ till to t_2 by using faster rate under initial conditions given by control (estimation) system. Integration rate that defined by χ value is selected in such a manner that for each cycle of Δt_c (in many times less than $t_2 - t$) several runs of a free movement were performed during the interval of $t_2 - t$. The latter procedures are necessary for numerical evaluation the partial derivations $\partial V / \partial y_i$. Because of this, the values χ in real-life control of a process must be of the value equal to dozens, hundreds and even thousands units.

The beginning of each cycle coincides with current time moment t with accuracy equal to Δt_c. At the beginning of each cycle, control and estimation system operating with real-life controlled process defines the state vector $\mathbf{x}(t)$ and gives initial conditions for free movement model (13). As a result, the following equality is provided for beginning of each cycle

$$\mathbf{y}_{\text{м}}(t) = \mathbf{y}(t). \quad (16)$$

Under free movement of the system, the left part of (7) transforms to the total derivative under time as

$$\dot{V} = -Q. \quad (17)$$

Therefore, we obtain

$$V(\mathbf{y}_{\text{м}}(t_2)) - V(\mathbf{y}_{\text{м}}(t_1)) = -\int_{t_1}^{t_2} Q(\mathbf{y}_{\text{м}},t)dt, \quad (18)$$

and for a terminal task:

$$V(\mathbf{y}_{\text{м}}(t_2)) = V_{\text{set}}(\mathbf{y}_{\text{м}}(t_2)). \quad (19)$$

Thus, for free movement system mode under predictive model, the following computations must be performed

$$V = V_{\text{set}}(\mathbf{x}_{\text{м}}(t_2'),\mathbf{y}_{\text{м}}(t_2')) + \chi \int_{t'=t/\chi}^{t_2'=t_2/\chi} Q(\mathbf{x}_{\text{м}},\mathbf{y}_{\text{м}},\chi t')dt'. \quad (20)$$

In order to evaluate by using numerical technique the partial derivations $\partial V / \partial x_j$, the variability of initial requirement related to $\mathbf{x}_{\text{м}}$ is performed for each run of the model (15).

Let us consider the features necessary for selection of integrand for minimizing functional $Q(\bullet)$ given in the form (12). The features depend on the difference between output vector $\mathbf{y}_{\text{м}}$ contained in the model (8) and the estimate of the control process state $\hat{\mathbf{y}}$:

$$Q = Q\left(\mathbf{y}_{\text{м}} - \hat{\mathbf{y}}\right). \quad (21)$$

Let us introduce the square functional as:

$$Q = \left(\mathbf{y}_{\text{м}} - \hat{\mathbf{y}}\right)^{\text{T}} \boldsymbol{\beta} \left(\mathbf{y}_{\text{м}} - \hat{\mathbf{y}}\right), \quad (22)$$

where $\boldsymbol{\beta}$ is the diagonal matrix contained the elements that are proportional to the maximum errors related to the corresponding coordinates (principle of the contribution of the errors).

By exploiting the optimal Kalman filter or suboptimal estimation procedure, it is necessary to define the following

$$\boldsymbol{\beta} = \hat{\mathbf{R}}^{-1}, \quad (23)$$

where $\mathbf{R}$ is the error covariance matrix or their estimates $\hat{\mathbf{R}}$.

It is also interesting an approach to forming the sequence of quality functional which describes the energy of system movement, for example, the minimum of acceleration energy as

$$Q = \left(\ddot{\mathbf{y}}_{\text{м}} - \hat{\ddot{y}}\right)^{\text{T}} \boldsymbol{\beta} \left(\ddot{\mathbf{y}}_{\text{м}} - \hat{\ddot{y}}\right). \quad (24)$$

This approach allows improving the dynamic accuracy for control of transmission processes in IMPRD/CD on the stage of oscillation reconstruction.

Several limitations exist for solving the task (10) – (15) according to physical peculiarities and functional assignment of PRD, particularly, for oscillation magnitude U_i, initial frequency run-out $\Delta\omega_i$, total power of quartz resonator excitation $P_{\text{osc}\Sigma}$ in multi-frequency mode and rate of its variations [2, 5]:

$$U_{\min} \le U_i \le U_{\max};$$
$$\Delta\omega_i \le \Delta\omega_{\max}, \; i = \overline{1,n}; \quad (25)$$
$$P_{\text{osc}\Sigma} \le P_{\max}; \; \frac{dP_{\text{osc}\Sigma}}{dt} \le K_{\text{dyn}}^{(P)}$$

In order to give limitations, expanded state vector $(\mathbf{x},\mathbf{y})$ can be represented in the form of some space state domain G, which we will consider as enclosed and simply-connected. Let us give the penalty function $Q_{\text{f}}(\mathbf{x},\mathbf{y})$, which is equal to zero inside and on the borders of the domain G and rather fast accrue in given domain. Assuming that the domain G is described by the equation $Q_{\text{f}}(\mathbf{x},\mathbf{y})$=0, we represent the integrand function of the functional of quality related to generalized work (12) as

$$Q = Q_{\text{opt}} + Q_{\text{f}}, \quad (26)$$

for what inside the domain of limitations $Q = Q_{\text{opt}}$. The function Q_{opt} is determined by the limitations of (22) – (24) given inside the domain G, and the limitations of (25) are given for the minimized functional (19) with help of the penalty function Q_{f} (26).

It should be noted that described above algorithm corresponds to the terminal (quasi-terminal) control state $V_{t=t_{\text{set}}} = V_{\text{set}}$ which is related to the first control stage, e.g. forming stable and multi-frequency oscillating mode in IMPRD/CD. However, it can be simply transformed to the non-terminal algorithm of control by using transition to "sliding" optimization interval for which optimization interval is given as $t_2 = t + T_{\text{set}}$, where T_{set} is the given optimization interval. According to that, predictive model performs integration of the equations (15) within the interval from t/χ till to $(t + T_{\text{set}})/\chi$. As the function of V_{set} can be selected, an arbitrary function, including $V_{\text{set}} \equiv 0$.

After achievement the terminal state (19), stabilization of location of the system relatively given state is performed $V_0 \equiv V_{\text{ST}}$. For this reason, transition to the "sliding" optimization interval T_{ST} is executed.

Let us define productivity of control microprocessor system necessary for realization of technical invariance principle in PRD using adaptive system with predictive standard. If under condition of single-entry numerical integration for optimization interval equal to T_{ST} necessary N operations, then performance of microprocessor device can be approximately estimated as follows

$$n_M = \frac{m+1}{2\Delta t_c} N . \tag{27}$$

It was assumed here that number of components of influence vector which give control process is equal to m and binary system of numerical differentiation is exploited. Value of Δt_c is defined by a necessary velocity of the update for given influences. For example, for $m = 3$, $\Delta t_c = 0.5\,\text{s}$, $N = 2 \cdot 10^5$ microprocessor device must provide productivity in the level of $n_M = 8 \cdot 10^5$ operations per one second [2].

4. Experimental result

The main contribution to the dynamic of variations of oscillation frequency is made by the Quartz Resonator self-heating up, here at the thermo-dynamic component of instability of QR can exceed the meaning $(0.5 \ldots 1) \cdot 10^{-5}$. At the same time the vibration instability on this stage of oscillations is one or two degrees less. After establishing the temperature balance of Quartz Resonator for $t > (80 \ldots 100)$ s the dynamics of frequency shifts is defined mainly by vibration-dynamic component.

The similar character of dependences can be observed also for the third harmonic component of QR oscillations, which is determined by the localization of mechanic oscillations of resonator in one capacity and proves high correlation dependence between the oscillations of the first and third mechanic frequency of QR. Temperature and vibration components of instability of QR frequency in the form of difference dependences is shown in Fig. 3.

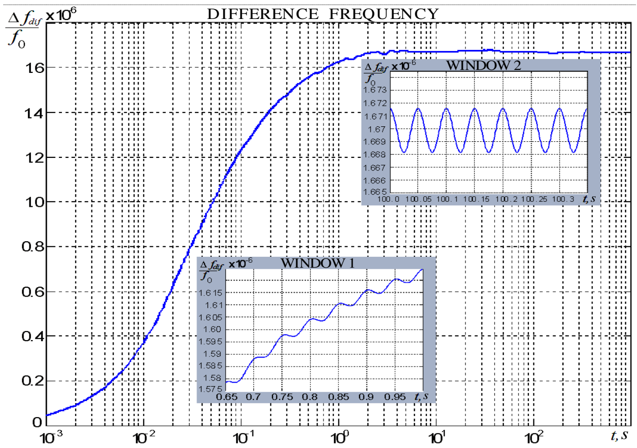

Fig. 3. Difference frequency in POS

It can be seen that for the difference component δf_{dif} because of high correlation of shifts of oscillation frequencies f_1, f_3 the sharp shortening of the process of establishing the frequency of difference oscillation f_{dif} (approximately by a degree) with synchronic decrease of vibration-dynamic instability to a value $(0.3 \ldots 0.5) \cdot 10^{-8}$ can be observed (Fig. 3, Window 2).

On the basis of frequencies of difference oscillations ΔF_T (7), ΔF_G (8) the scheme of formation the signal of compensation (Fig. 1) provides the currant identification of temperature and vibration influences onto Quartz Resonator in accordance with (9) and the formation of correcting code $N(T,G)$ for Digital Synthesizer of Direct Synthesis in accordance with (4) [4, 5].

5. Conclusion

Using of suggested conceptual states related to design invariant multi-frequency piezoelectric resonance devices with controlled dynamics (IMPRD/CD) in the form of adaptive-self-tuning systems with the fast operating predictive standard provided creation of novel class invariant PRD which accuracy performance is of maximum close to potentially possible level. Control the trajectory operating in a real-time environment is performed on the basis of predictive numerical analysis of the core dynamics in MOPS. Model parameters are given corresponding to the results of identification of current state QR under multi-mode excitation and taking into account the constructive peculiarities of PRD concrete type.

In order to provide given system operation mode under its incomplete parametrical distinctness (robustness), two-stage interval-approximation control law has been developed. The law provides dividing the process into the sequence interval-local approximation tasks within the limits of two stages for restoration and stabilization of multi-mode oscillation mode. During the first stage, adaptive control task is solved for each separate mode of MOPS in order to provide operating the system under stationary oscillation mode in minimum time. During the second stage, control influences are formed. The latter ones are directed to the system stabilization under influence of destabilizing factors, i.e. providing technical invariance. Criteria for an optimal control in IMPRD/CD are analytically designed. That provides for each stage the minimization of energy expenses for optimal system operating trajectory. Local and global stability of interval-approximation control technique IMPRD/CD is demonstrated. Estimate of productivity of digital control system in IMPRD/CD confirms opportunity of physical realization of given conception by using wide spread ARM processes.

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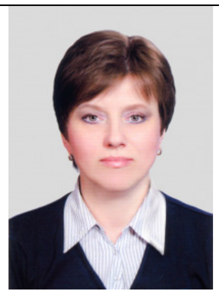

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