UDC 621.373.122

DETERMINATION OF AUTODYNE OSCILLATOR PARAMETERS BY THE BEATING METHOD

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The research results of oscillator internal parameters influence the features of dynamic autodyne characteristics formation in the case of external oscillator signal influence are presented. The equivalent circuit with a single-circuit oscillating system is considered as a model of the autodyne oscillator. Abbreviated equations are obtained by an averaging method and then they are linearized for small disturbances in a vicinity of the steady-state mode. The obtained characteristics for the beating mode are compared with characteristics of autodynes for short-range radar technology. The essential differences in behavior of the oscillator with acting the external oscillator and the oscillator with acting the own reflected signal have been found. The physical sense of the frequency dispersion phenomenon for the autodyne frequency deviation in the vicinity of hypothetical "zero" beating is discovered. The research results of dynamic autodyne characteristics in the frequency conversion mode of signals modulated on amplitude or frequency are given. It is shown that to suppress the spurious harmonics of the beating frequency, it is advisable to take additional measures for generated frequency stabilization in autodyne frequency converters, for instance, using the external feedback in the oscillator or using the external high-Q resonator. The adequacy of theoretical conclusions is confirmed by results of experimental investigations of the hybrid-integrated module of 8 mm-range made on the basis of the planar two-meza Gunn diode. Oscillator characteristics obtained by the beating method are compared with results of investigation fulfilled with the help of modulation characteristics. It is shown that errors in experimental determination of dynamic characteristics of autodyne oscillators caused by frequency limitations of a pin-diode typical for the modulation characteristic method can be eliminated. Problems of practical application of obtained results in real radar systems using autodyne oscillators are discussed.

Introduction

Autodynes or autodyne oscillators represent the open self-oscillating systems in which the oscillation amplitude and frequency as well as the average values of current and a voltage of an active element (AE) are varied under influence of the proper radiation reflected from some object or the radiation received from the external oscillator. These variations are registered by additional means as signals of external detection or signals of auto-detection in the AE bias circuit. Radio engineering systems built on the basis of the autodyne principle have the simplest construction of the receiver-transmitter module contained only of the antenna and the autodyne oscillator, which combines simultaneously functions of the transmitter and the receiver. Therefore, autodynes find the wide applications in the short-range radar and communication systems of different purposes, in the equipment of inspection and monitoring of technological parameters and in measuring engineering, where above-mentioned advantages of autodynes are determining [1—5].

Main characteristics of autodynes used in radar applications are dependences of instantaneous values of variations of the output auto-detection signals and oscillation amplitude and frequency variations as functions of delay time changes of the reflected signal [6, 7]. They have got names of the auto-detection characteristic, amplitude, frequency and amplitude-frequency characteristics respectively. These characteristics are widely used under analysis of formation peculiarities of the autodyne response on variations of oscillation amplitude and frequency at its auto-detection and at its extraction as a useful signal. Ratios of amplitude values of mentioned autodyne variations to the amplitude of electromagnetic radiation returned from the reflected object are significant parameters of the autodyne, which have the sense of coefficients of auto-detection, autodyne amplification, and frequency deviation respectively. These generalized parameters allow fulfillment of the analysis and optimization of autodyne oscillators with a purpose of the best variant choice.

Dynamical properties of the autodyne oscillator are determined by dependences of its characteristics and parameters versus the autodyne signal frequency and the movement velocity of the reflected object. The dynamic range of the oscillator is directly determined by its inertia properties characterized by the time constant of autodyne response [7]. Consideration of dynamic characteristics of radar autodynes is necessary in many practical applications, for example, in equipment for registration of fast-running processes in experimental physics, in practice of ground ballistic tests [1—4].

Experimental investigation of autodyne dynamic characteristics by the natural modeling conditions maximally closed to real ones is associated with significant financial expenses, complicity and inconvenience of the equipment [3]. At that, real radar objects are changed by their electrodynamic analogs called to simplify and essentially accelerate a process of product adjustment and to guarantee an achievement of required performance by simpler and cheaper means. However, application of signal equivalents which can be implemented by different methods is the most productive for such investigations in the laboratory conditions.

Among these research methods, the modulation characteristics method is well-known. The experimental deriving of these characteristics is significantly simpler than the autodyne characteristics obtaining [7, 8]. According to this method, the dependence of oscillator modulation ability is determined at fixed value of modulation parameter such as the modulus of reflection coefficient at high values of modulation frequency. Using this dependence, one can determine the time constant of the autodyne response.

Another method named as the method of external generator is based on the replace of the reflected signal by the signal from additional generator, which frequency is outside the synchronization band of the autodyne. This method has been successfully realized in widely used autodyne frequency converters for communication systems and radar technologies [9—11]. However, the substantiation of this method according to the research of dynamic properties of radar autodynes is absent in well-known literature. In many publications, these autodyne principles both are unreasonably identified as applied to radar and communication.

The purpose of this research is to develop the general approach to the theoretical investigation of autodynes and their experimental examination. To achieve this purpose, the results concerning the analysis of the oscillator inherent parameters influence on the features of the autodyne dynamic characteristics formation in the case of the external generator signals impact are obtained. The comparison of characteristics obtained by proposed approach with characteristics of operating radar autodynes is carried out. These data are compared to research results obtained by the modulation characteristics approach. The results of investigation of dynamic autodyne characteristics in the receiving mode of signals modulated on amplitude or frequency are given. The experimental data of the hybrid-integrated modules of 8-mm range fulfilled on the basis of the planar two-meza Gunn diodes are presented. These data confirm the correctness of conclusions of the theoretical investigations performed.

Equivalent circuit and main equations of the autodyne oscillator

Consider the main equations describing all known factors which define the formation of the autodyne response in the single-frequency single-circuit oscillator. As the model of such oscillators characterized by the main generalized parameters, we chose the UHF oscillator with hysteresis feedback between the active element (AE) current and the instantaneous voltage at self-oscillations.

As follows from oscillator theory, the volt-ampere characteristic of AE in general case has a hysteresis caused by finiteness of charges transfer time in the interaction space with the field of the resonator. It means that the instantaneous current i_e of AE is a function of the instantaneous voltage u and the speed of its variation $\dot{u} = du/dt$: $i_e = i_e(u,\dot{u})$. To simplify the following analysis, we assume that the relaxation time in AE is essentially less than characteristic time of generated oscillation amplitude variation.

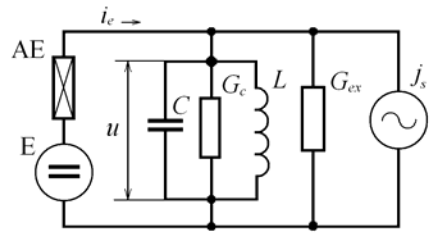


Fig. 1. Equivalent scheme of the single circuit autodyne.

The equivalent scheme of the single circuit autodyne is presented in Fig. 1. In this scheme, the UHF resonator operating near the oscillation frequency is presented by the simplest parallel oscillatory circuit including passive parameters of AE and consisting of the inductance L, the capacitance C and the total conductance G defined as $G = G_{res} + G_{ext}$, where G_{res} is the conductance of the resonator inherent loss; G_{ext} is the conductance of the external load. The current source $j_s(t)$ representing the influence of the external signal on the autodyne is connected in parallel to the resonator. This current can be expressed as follows:

$$j_s(t) = J_s \cos \omega t . \quad (1)$$

The AE having the nonlinear instantaneous volt-ampere characteristic of N-type is directly connected to the bias voltage source for DC and parallel to the resonator for AC. In a view of assumptions made for the circuit shown in Fig. 1, we can write the system of nonlinear differential equations with the retarded argument relatively to instantaneous voltages on capacitors:

$$d^2u/dt^2 + \omega_{nat}u = F(u,\dot{u},t); \qquad (2)$$

$$F(u,\dot{u},t) = -\frac{\omega_{nat}}{Q_L}\left\{\left[1+\frac{di_e(u,\dot{u})}{Gdu}\right]\frac{du}{dt} - \frac{dj_s(t)}{Gdt}\right\},$$

where $\omega_{nat} = (LC)^{-1/2}$, $Q_L = \omega_{nat}C/G$ are the natural frequency and the loaded Q-factor of the resonator, respectively.

Taking into account that the loaded Q-factor Q_L in UHF oscillators has the sufficiently high value, the approximate solution of equation (2) can be considered as the quasi-harmonic signal:

$$u = A\cos\Psi(t) = A\cos(\omega t + \varphi), \qquad (3)$$

where $A \equiv A(t)$, $\varphi \equiv \varphi(t)$ are slowly changing amplitude and phase of self-oscillations. Then

$$\dot{u} = -\omega A \sin\Psi(t), \qquad (4)$$

As follows from (3) and (4), variables A and φ must satisfy the equation [15]:

$$\dot{A}\cos\Psi(t) - A\,\dot{\varphi}\sin\Psi(t) = 0. \qquad (5)$$

Taking into account the small value of relative offset of the current frequency of oscillations ω and the frequency ω_{nat} defined by the inequality $(\omega^2 - \omega_{nat}^2)/\omega_{nat} << 1$, the initial equation (2) can be presented in the form:

$$d^2u/dt^2 + \omega^2 u = f(u,\dot{u},t); \qquad (6)$$

$$f(u,\dot{u},t) = -\frac{\omega_{nat}}{Q_L}\Big[\frac{du}{dt} + \frac{di_e(u,\dot{u})}{Gdu} - Q_L u\frac{\omega^2 - \omega_{nat}^2}{\omega_{nat}} - \frac{dj_s(t)}{Gdt}\Big].$$

Based on known energy relations for oscillators, one can obtain the relation $J_s = (8G_{in}P_s)^{1/2}$, where $P_s = \Gamma^2 P_{out}$ denotes the power of external oscillator signal influencing the initial generator; P_{out} is the output power of the autodyne oscillator; $\Gamma = A_s / A_{out} = (P_s / P_{out})^{1/2}$ is the coefficient defined as the ratio of input signal amplitude A_s and the inherent amplitude A_{out} of the autodyne oscillator. Taking into account the equation (4), we can express the derivative of the current of the dependent oscillator as follows:

$$dj_s(t)/dt = -2\Gamma G_{in} A\,\omega\sin\Psi(t). \qquad (7)$$

Substituting expressions (1), (3), (4) and (7) into (5), (6) and solving the resulting system of equations, we obtain equations for slowly changing variables A and φ. According to standard averaging method [12], these equations can be written in the following form:

$$\frac{dA}{dt} = -\frac{1}{Q_L\omega} f(A,\Psi,t)\sin\Psi(t); \qquad (8)$$

$$\frac{d\varphi}{dt} = -\frac{1}{Q_L A\,\omega} f(A,\Psi,t)\cos\Psi(t); \qquad (9)$$

$$f(A,\Psi,t) = -\omega_{nat}[-\omega A\sin\Psi(t)] + \omega_{nat}\frac{1}{G}\frac{di_e(u,\dot{u})}{du} - \omega_{nat}\left[Q_L\frac{\omega^2-\omega_{nat}^2}{\omega_{nat}}A\cos\Psi(t) - \frac{2\Gamma G_{in}}{G}\omega A\sin\Psi(t)\right].$$

Within limits of the quasi-harmonic approximation, equations (8) and (9) are equivalent to the initial equation (2) and have the great generality. Further their analysis usually leads to the abbreviated equations for amplitude and phase of oscillations. To obtain these abbreviated equations, we present the current of AE in the form of Fourier series:

$$i_e(u,\dot{u}) = I_0(A,\omega) + \sum_{n=1}^{\infty}[I_{n\mathrm{Re}}(A,\omega)\cos n\Psi(t) + I_{n\mathrm{Im}}(A,\omega)\sin n\Psi(t)]; \qquad (10)$$

$$I_0(A,\omega) = \frac{1}{2\pi}\int_0^{2\pi} i_e(u,\dot{u})d\Psi;$$

$$I_{n\mathrm{Re}}(A,\omega) = \frac{1}{\pi}\int_0^{2\pi} i_e(u,\dot{u})\cos n\Psi d\Psi;$$

$$I_{n\mathrm{Im}}(A,\omega) = \frac{1}{\pi}\int_0^{2\pi} i_e(u,\dot{u})\sin n\Psi d\Psi,$$

where $I_0(A,\omega)$, $I_{n\mathrm{Re}}(A,\omega)$, $I_{n\mathrm{Im}}(A,\omega)$ are the DC component and amplitudes of in-phase and orthogonal components of current harmonics through active element respectively.

Let us approximate the current $i_e(u,\dot{u})$ for these components by the first harmonic. Then, the active element can be presented as parallel connection of the resistive $G_e \equiv G_e(A,\omega) = I_{1\mathrm{Re}}(A,\omega)/A$ and the reactive $B_e \equiv B_e(A,\omega) = I_{1\mathrm{Im}}(A,\omega)/A$ conductances averaged per oscillation period. Taking into account the expansion (10), from (8) and (9) we obtain the system of abbreviated differential equations for amplitude and phase of the autodyne oscillator:

$$\frac{2GQ_L}{\omega_{nat}}\frac{1}{A}\frac{dA}{dt} + G_e + G = 2\Gamma\eta G\cos\varphi; \qquad (11)$$

$$\frac{2GQ_L}{\omega_{nat}}\frac{d\varphi}{dt} + B_e + 2GQ_L\frac{\omega - \omega_{nat}}{\omega_{nat}} = -2\Gamma\eta G\sin\varphi, \qquad (12)$$

where $\eta = Q_L / Q_{in}$, $Q_{in} = \omega_{nat} C / G_{in}$ are the efficiency and the external Q-factor of the oscillatory system, respectively.

Equations (11), (12) have been obtained within the limits of usual approximations used in the analysis of self-oscillating systems. They quite accurately describe the behavior of the autodyne oscillators under arbitrary values of influenced radiation amplitude, as well as the transient processes of the autodyne response establishment and its steady-state value.

Considering the processes of amplitude and frequency variations in the autodyne oscillator, one can distinguish quasi-static and dynamic operation modes. In the quasi-static mode, the transient processes in the oscillator occur quite slowly, so that derivatives in the left parts of equations (11), (12) can be neglected. In dynamic mode, such assumptions can not be made because all variations occur quite rapidly. Considering the first mode and supposing in expressions (11), (12) $dA/dt = d\varphi/dt = 0$, we obtain the equation which can be transformed to the following form using the concept of complex conductance:

$$Y_e + Y_{nat} + Y_{in} = 0, \tag{13}$$

where $Y_e = G_e + jB_e$, $Y_{nat} = G_{nat} + jB_{nat}$ are complex conductances of AE and the resonator, respectively; $B_{nat} = 2GQ_L(\omega - \omega_{nat})/\omega_{nat}$ is the reactive conductance of the resonator; $Y_{in} = 2\Gamma\eta G(\cos\varphi - j\sin\varphi)$ denotes the component of the load input conductance transformed to the oscillator, which is caused by the external signal action on the oscillator.

At $\Gamma = 0$ equations (11) — (13) determine the operation of the autonomous oscillator. Supposing in expressions (11), (12) $dA/dt = d\varphi/dt = 0$, the steady-state oscillation parameters of this oscillator can be obtained for $B_e = B_{e0}$, $G_e = G_{e0}$, $\omega = \omega_0$ as follows:

$$G + G_{e0} = 0;\; B_{c0} + B_{e0} = 0;\; I_0 = I_{00}, \tag{14}$$

where $G_{e0} = G_e(A_0, \omega_0)$, $B_{e0} = B_e(A_0, \omega_0)$; $B_{c0} = 2\times$ $\times GQ_L\chi_0$ denotes the reactive component of the passive part of the oscillating system on frequency ω_0; $\chi_0 = (\omega_0 - \omega_c)/\omega_c$ is the relative offset of the resonator frequency ω_{nat} with respect to frequency of steady-state oscillations ω_0 of the autonomous oscillator; I_{00} means the average value of the AE current. The frequency ω_0 can be calculated using (13):

$$\omega_0 = \omega_{nat}(1 + \tan\Theta / 2Q_L), \tag{15}$$

where $\Theta = \arctan(B_{e0} / G_{e0})$ is the delay angle in AE.

Equations (14), (15) of the steady-state mode are well known in the self-oscillations theory for determination of amplitude and frequency of the autonomous oscillator.

To analyze the autodyne effect in the most simple manner, we use the small-signal approximation when $\Gamma << 1$. For this, we present amplitude, frequency and average value of AE current in the form: $A = A_0 + a$; $\omega = \omega_0 + \Delta\omega$; $I_0 = I_{00} + \Delta I_0$, where a, $\Delta\omega = d\varphi/dt$ and ΔI_0 are appropriate autodyne variations of the oscillator steady-state parameters. At that, the average value of the AE current I_0, as well as parameters G_{e0} and B_{e0} included in the equation (14) get the appropriate increments. Assuming that external force is small enough, so that $a << A_0$, $\Delta\omega << \omega_0$, $\Delta I_0 << I_0$, we can write mentioned parameters taking into account the first expansion terms in Taylor series in the vicinity of steady-state mode:

$$G_e = G_{e0} + \left(\frac{\partial G_e}{\partial A}\right)_0 a + \left(\frac{\partial G_e}{\partial \omega}\right)_0 \Delta\omega; \tag{16}$$

$$B_e = B_{e0} + \left(\frac{\partial B_e}{\partial A}\right)_0 a + \left(\frac{\partial B_e}{\partial \omega}\right)_0 \Delta\omega; \tag{17}$$

$$I_0 = I_{00} + \left(\frac{\partial I_0}{\partial A}\right)_0 a + \left(\frac{\partial I_0}{\partial \omega}\right)_0 \Delta\omega, \tag{18}$$

where index “0” near large parenthesis indicates that the partial derivatives are taken in the vicinity of steady-state mode.

Substituting (16), (17) into (11), (12) and taking into consideration (14), (15) and (18), we obtain the system of non-autonomous linearized equations for determination of the relative autodyne variations of amplitude $a_1 = a/A_0$ and phase φ of oscillations as well as variations of the AE current $i_0 = \Delta I_0 / I_{00}$:

$$\frac{Q_L}{\omega_0}\frac{da_1}{dt} + \alpha_{11}a_1 + \varepsilon_{11}\frac{1}{\omega_0}\frac{d\varphi}{dt} = \Gamma\eta\cos\varphi; \tag{19}$$

$$\beta_{11}a_1 + Q_L\left(\chi_{id} + \frac{1}{\omega_0}\frac{d\varphi}{dt}\right) = -\Gamma\eta\sin\varphi; \tag{20}$$

$$\alpha_{01}a_1 + \varepsilon_{01}\frac{1}{\omega_0}\frac{d\varphi}{dt} = i_0, \tag{21}$$

where $\chi_{id} = \Delta\omega_{id}/\omega_0$ denotes the relative value of the initial difference $\Delta\omega_{id} = \omega - \omega_0$ of the external signal frequency ω and the autonomous oscillator frequency ω_0; $\alpha_{11} = (A_0/2G)(\partial G_e/\partial A)_0$ is the reduced slope of the oscillator increment causing the regeneration degree and its limit cycle permanence; $\varepsilon_{11} = \varepsilon_c + \varepsilon_e$ signifies the non-isodromic property parameter taking into account the influence of frequency variations on the oscillation amplitude through variations of resistive conductance parameters of the oscillating system

$\varepsilon_c = (\omega_0/2G)(\partial G_c/\partial\omega)_0$ and the AE electronic conductance $\varepsilon_e = (\omega_0/2G)(\partial G_e/\partial\omega)_0$; $\beta_{11} = (A_0/2G)(\partial B_e/\partial A)_0$ is the parameter defining non-isochronous properties of the oscillator; $\xi_{11} = \xi_c + \xi_e$ is the coefficient of the oscillator frequency stabilization considering the frequency slope of reactive parts of the oscillating system admittance $\xi_c = (\omega_0/2G)(\partial B_c/\partial\omega)_0$ and of the AE $\xi_e = (\omega_0/2G)(\partial B_e/\partial\omega)_0$; $\alpha_{01} = (A_0/I_0)(\partial I_0/\partial A)_0$ is the parameter considering the auto-detection phenomenon of the oscillation amplitude variations; $\varepsilon_{01} = (\omega_0/I_0)(\partial I_0/\partial\omega)_0$ is the frequency detection coefficient defining the contribution of oscillation frequency variations into variations of the AE supply current. The values ξ_c, ξ_e can be interpreted as the loaded Q-factor of the single-circuit oscillating system $\xi_c = Q_L$ and the Q-factor of the AE electronic conductance $\xi_e = Q_e$, respectively. Due to fulfillment of the inequality $\xi_c >> \xi_e$ in real UHF oscillators, we assume for further analysis that $\xi_{11} = Q_L$.

The equations (19)—(21) have sufficiently wide generality since they provide possibility to analyze phenomena both inside and outside of the lock-in range as well as the autodyne effect in UHF oscillators with any type of AE (tunnel diodes, Gunn diodes, field-effect and bipolar transistors). At that, such inherent parameters of the oscillator as non-isochronous and non-isodromous properties, amplitude and frequency detection factors can be taken into account. In the case of UHF oscillators performed on IMPATT diodes having the S-type volt-ampere characteristic, the obtained results are also valid under condition of the dual replacement of the main concepts: current ↔ voltage, conductance ↔ resistance, etc.

Dynamic characteristics of autodyne oscillators in the beating mode and in the mode of frequency conversion of an input signal

Considering the steady-state mode, derivatives in the left sides of equations (19)—(21) can be equaled to zero. As a result, we obtain

$$a_1 = \Gamma K_a \cos(\varphi - \psi_1); \quad (22)$$

$$\chi_{id} = -\Gamma L_a \sin(\varphi + \theta); \quad (23)$$

$$i_0 = \Gamma K_0 \cos(\varphi - \psi_0), \quad (24)$$

where K_a, L_a, K_0 are coefficients of autodyne amplification, oscillation frequency deviation and auto-detection, which can be defined as

$$K_a = \eta \frac{1}{\alpha_{11}} \frac{\sqrt{1+\rho^2}}{1-\gamma\rho}; \quad (25)$$

$$L_a = \eta \frac{1}{\xi_{11}} \frac{\sqrt{1+\gamma^2}}{1-\gamma\rho}; \quad (26)$$

$$K_0 = \eta \frac{\alpha_{01}}{\alpha_{11}} \frac{1-\kappa_{fd}\gamma}{1-\gamma\rho} \sqrt{1+\kappa_{ad}^2}; \quad (27)$$

$\psi_1 = \arctan(\rho)$, $\theta = \arctan(\gamma)$, $\psi_0 = \arctan(\kappa_{ad})$ are angles of phase offset of autodyne amplitude variations, oscillations frequency variations and variations of auto-detection, respectively; $\kappa_{ad} = [(\rho - \kappa_{fd})/(1-\kappa_{fd}\gamma)]$; $\kappa_{fd} = \varepsilon_{01}\alpha_{11}/\alpha_{01}\xi_{11}$ is the parameter of frequency detection of autodyne frequency variations into variations of the average value of the AE current; $\Gamma L_a = \Delta\omega_c/\omega_0 = (\omega - \omega_0)/\omega_0 = \chi_c$ denotes the relative maximal deviation of the frequency $\omega = d\Psi/dt$ of disturbed oscillator versus autonomous oscillation frequency ω_0 under influence of the external signal.

As it is known [13], the behavior of the phase φ including in equations (22)—(24) depends on the ratio of initial offset values χ_{id} and χ_c. According to this reference, two variants of these equation solutions can exist. If the inequality $\chi_{id} > \chi_c$ is fulfilled, there is the beating mode in the system. In this case, the phase φ continuously changes and the value $\Delta\omega_c$ determines the maximal deviations of frequency ω from ω_0. When the opposite inequality $\chi_{id} < \chi_c$ is fulfilled, we obtain the oscillation locking mode. At that, the maximal frequency deviation $\Delta\omega_c$ is equaled to the half of the synchronization band.

In the beating mode, when the strong inequality $\Delta\omega_{id} >> \Delta\omega_c$ is fulfilled, the phase φ in (22)—(24) increases practically in the linear manner with the growth of beating frequency Ω_p as it follows from the equality $\varphi \equiv \varphi(t) = \Omega_p t$ [13]. Then, excluding cases of multiple ratio of frequencies Ω_p and ω_0, the solutions of the equations (19)—(21) system for dynamic relative variations of amplitude $a_1(t)$ and frequency $\chi(t)$ as well as the auto-detection signal $i_0(t)$ can be essentially simplified.

After transformation, these simplified solutions take the form:

$$a_1(t) = \Gamma K_a K_a(\Omega_p) \cos[\Omega_p t - \psi_1(\Omega_p)]; \quad (28)$$

$$\chi(t) = \Gamma L_a L_a(\Omega_p) \sin[\Omega_p t + \theta(\Omega_p)]; \quad (29)$$

$$i_0(t) = \Gamma K_0 K_0(\Omega_p) \cos[\Omega_p t - \psi_0(\Omega_p)], \quad (30)$$

where $K_a(\Omega_p)$, $L_a(\Omega_p)$, $K_0(\Omega_p)$ are normalized parameters of the frequency dependences of autodyne amplification coefficient, oscillation frequency deviations and the auto-detection signal defined by relations:

$$K_a(\Omega_p) = \sqrt{\frac{(1-\rho\,\Omega_{pn})^2 + (\rho + \Omega_{pn})^2}{(1+\rho^2)[1+\Omega_{pn}^2]^2}}\,; \quad (31)$$

$$L_a(\Omega_p) = \frac{1+\gamma\,\Omega_{pn} + (1-\gamma\rho)\,\Omega_{pn}^2}{\sqrt{(1+\gamma^2)(1+\Omega_{pn}^2)}\cos\theta(\Omega_p)}\,; \quad (32)$$

$$K_0(\Omega_p) = \frac{(1-\rho\,\Omega_{pn})}{\sqrt{1+\kappa_{ad}^2}\,(1+\Omega_p^2)\cos\psi_0(\Omega_p)}\,; \quad (33)$$

$\psi_1(\Omega_p)$, $\theta(\Omega_p)$, $\psi_0(\Omega_p)$ are angles of relative phase offsets of autodyne amplitude variations, beating frequency and the auto-detection signal which can be expressed as follows:

$$\psi_1(\Omega_p) = \arctan\frac{\rho+\Omega_{pn}}{1-\rho\,\Omega_{pn}}\,; \quad (34)$$

$$\theta(\Omega_p) = \arctan\frac{\gamma(1-\rho\,\Omega_{pn})}{1+\gamma\,\Omega_{pn} + (1-\gamma\rho)\,\Omega_{pn}^2}\,; \quad (35)$$

$$\psi_0(\Omega_p) = \arctan\delta_0(\Omega_p)\,; \quad (36)$$

$$\delta_0(\Omega_p) = \frac{\rho - \kappa_{fd} + (1-\kappa_{fd}\gamma)\,\Omega_{pn} - \kappa_{fd}(1-\gamma\rho)\,\Omega_{pn}^2}{(1-\kappa_{fd}\gamma)(1-\rho\,\Omega_{pn})}\,,$$

where $\Omega_{pn} = \Omega_p\tau_a$ is the normalized beating frequency; τ_a denotes the characteristic time constant (relaxation time) of the autodyne response defined by expression:

$$\tau_a = \frac{Q_L}{\alpha_{11}\omega_0(1-\gamma\rho)}\,. \quad (37)$$

Comparing the obtained equations (28)—(37) for the autodyne in the mode of frequency conversion with the appropriate equations (1)—(13) obtained for the case of the radar autodyne [14], one can see their complete formal coincidence. Nevertheless, physical phenomena lying in the basis of its operation are substantially different. In the first case, the autodyne output signal frequency determining in accordance with the Doppler effect by the relative velocity of radar and object movement can change from zero (the object is fixed) up to the maximal limiting frequency $\Omega_{\lim}$ [14, 15]). In contrast to considered phenomenon, in the case of the autodyne frequency conversion, the beating frequency is limited from below by the value of lock-in band $\Delta\omega_c$ determined, as it follows from (29), by the value of autodyne frequency deviation which can be represented in the form $\Delta\omega_c = \Gamma L_a L_a(\Omega_p)\omega_0$. The simultaneous presence of amplitude (28) and frequency (29) modulations of autodyne oscillations inevitably complicates the output signal waveform. However, the character of these distortions is principally different and it does not link with the delay phenomenon of the reflected signal as it occurs in the case of radar autodynes [7, 15, 16].

It should be noted that obtained equations (31)—(36) at the assumption $\Omega_{pn} = 0$ fully correspond to the similar ones of the paper [8] derived at quasi-static description of autodyne operation.

For further analysis, it is important to consider conditions of asynchronous reception of AM and FM signals. Examining the case of AM signals, we must assume in initial equations $J_s(t) = J_{s0}(1 + m_{am}\cos\Omega_m t)$. Then, the system of equations (19), (20) takes the form:

$$\frac{Q_L}{\omega_0}\frac{da_1}{dt} + \alpha_{11}a_1 + \varepsilon_{11}\frac{1}{\omega_0}\frac{d\varphi}{dt} = \Gamma_0\eta(1+m_{am}\cos\Omega_m t)\cos\varphi\,; \quad (38)$$

$$\frac{Q_L}{\omega_0}\frac{d\varphi}{dt} + Q_L\chi_{id} + \beta_{11}a_1 = -\Gamma_0\eta(1+m_{am}\cos\Omega_m t)\sin\varphi\,, \quad (39)$$

where $\Gamma_0 = A_{c0}/A_0$; A_{c0} is the amplitude of the radiation acting on the oscillator.

When the inequalities $\Delta\omega_{id} >> \Delta\omega_c$, $\Omega_p >> \Omega_m$ are fulfilled, solutions of the system (38), (39) and also (21) have the form:

$$a_1(t) = \Gamma_0 K_a K_a(\Omega_p)(1+m_{am}\cos\Omega_m t)\cos[\Omega_p t - \psi_{1p}(\Omega_p)]\,; \quad (40)$$

$$\chi(t) = -\Gamma_0 L_a L_a(\Omega_p)(1+m_{am}\cos\Omega_m t)\sin[\Omega_p t + \theta_p(\Omega_p)]\,; \quad (41)$$

$$i_0(t) = \Gamma_0 K_0 K_0(\Omega_p)(1+m_{am}\cos\Omega_m t)\cos[\Omega_p t - \psi_0(\Omega_p)]\,. \quad (42)$$

In the case of FM signal reception with the single-tone modulation, the equation (1) takes the form:

$$j_s(t) = J_{s0}\cos[\omega t + m_{fm}\sin\Omega_m t]\,, \quad (43)$$

where $m_{fm} = \Delta\omega_{fm}/\Omega_m$ is the FM index; $\Delta\omega_{fm}$ is the frequency deviation. Taking into consideration (43) in (20) $\chi_{id} \equiv \chi_{id}(t) = [\omega - \omega_0 + \omega_{fm}\sin\Omega_m t]/\omega_0$, the solution of the formed equation under accepted assumptions can be derived as follows:

$$a_1(t) = \Gamma_0 K_a K_a(\Omega_p)\cos[\Omega_{p0}t + m_{fm}\sin\Omega_m t - \psi_{1p}(\Omega_p)]\,; \quad (44)$$

$$\chi(t) = -\Gamma_0 L_a L_a(\Omega_p)\sin[\Omega_{p0}t + m_{fm}\sin\Omega_m t + \theta_p(\Omega_p)]\,; \quad (45)$$

$$i_0(t) = \Gamma_0 K_0 K_0(\Omega_p)\cos[\Omega_{p0}t + \\ + m_{fm}\sin\Omega_m t - \psi_0(\Omega_p)], \quad (46)$$

where $\Omega_{p0} = \omega - \omega_0$ is the average beating frequency.

As follows from equations (40), (41) and (44), (45), in the autodyne frequency converter operating in the beating mode, the amplitude and frequency modulations of oscillations occur with the beating frequency Ω_p. At that, there is practically the linear transfer of the received spectrum to the beating frequency. However, the presence of mixed modulation and dependence of the beating frequency Ω_p itself upon the oscillation frequency $\chi(t)\omega_0$ defined by the expression $\Omega_p \equiv \Omega_p(t) = -[\omega - \omega_0 + \chi(t)\omega_0]$ in accordance with (41) and (45) causes distortions of beating signals extracted according to variations of oscillation amplitude in the AE auto-detection circuit. These distortions cause the appearance of additional harmonics on frequencies multiple to the main beating frequency Ω_p, the increase of combination components level and narrowing the dynamic range of the radio receiving set [17].

These peculiarities of output signals distinguish the autodyne frequency converters from the usual frequency converters, in which functions of the local oscillator and the mixer are functionally separated. To eliminate mentioned disadvantages of autodyne frequency converters, it is necessary to make additional measures to stabilize the oscillation frequency, for instance, using the external feedback in the oscillator circuit [18] or the external high-Q resonator [19].

Influence of oscillator inherent parameters on the dynamic autodyne features

The product of coefficients γ and ρ including in obtained equations (22)—(30), (40)—(42), (44)—(46) has the physical sense of "loop amplification" in the oscillator as the system with feedback. The influence of this feedback loop parameters and other inherent properties of the oscillator such as a parameter of frequency detection κ_{fd} on quasi-static and dynamic characteristics of radar autodynes has been considered in publications [5—7]. Here, we analyze the influence of inherent parameters on the dynamic characteristics autodynes-receivers of signals from the external oscillator. In this case, as follows from equations (31)—(46), the value of time constant τ_a of the autodyne response (37) influences the formation of UHF oscillators autodyne response. This time constant, in turn, also depends from inherent parameters of the oscillator.

Define the value τ_a in (37) as $\tau_a = \tau_{ai}\tau_{ao}$, where $\tau_{ai} = Q_L/\alpha_{11}\omega_0$ is the time constant of the autodyne response of the usual isodromous oscillator [7] and $\tau_{ao} = \tau_a/\tau_{ai} = 1/(1-\gamma\rho)$ is the time constant normalized with respect to τ_{ai}. The bulk diagram showing dependence of the normalized time constant τ_{ao} upon coefficients of non-isochronous γ and non-isodromous ρ properties is presented in Fig. 2. As follows from this diagram, both non-isochronous and non-isodromous properties cause essential amendments in the value of τ_{ao} compared to the case of autodyne oscillator in which $\gamma = \rho = 0$. These amendments are especially perceptible in the case of identical signs of coefficients γ and ρ. In this case, when the value of loop amplification $\gamma\rho$ tends to unity, the essential growth of the time constant τ_a can observe that is unwanted in a number of applications since it limits the speed performance of autodyne systems.

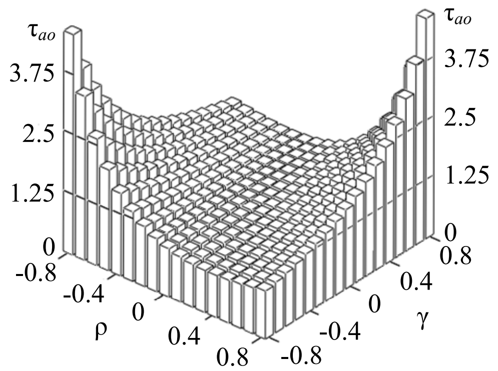


Fig. 2. The bulk diagram of the normalized value of the autodyne response time constant τ_{ao}.

Equations (31)—(36) obtaining autodyne parameters have sufficiently complicate form. Therefore, we perform their analysis with attraction of numerical methods for variation of parameters. Frequency dependences of autodyne parameters and their phase shift angles calculated in accordance with (31)—(36) for different values of coefficients γ, ρ and κ_{fd} are presented in Fig. 3 — Fig. 5.

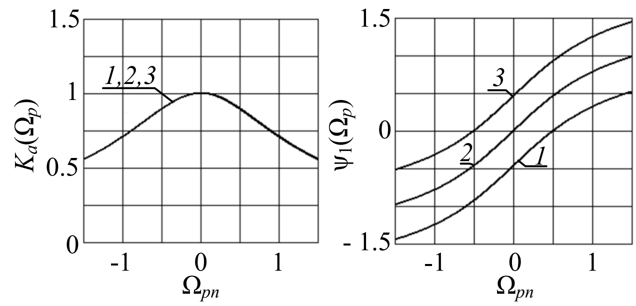


Fig. 3. Diagrams of frequency dependences of the autodyne amplification coefficient $K_a(\Omega_p)$ and the phase shift angle $\psi_1(\Omega_p)$ calculated for $\gamma = 1.2$ and different values of non-isodromous coefficient ρ: $\rho = -0.5$ (curves *1*); $\rho = 0$ (curves *2*); $\rho = 0.5$ (curves *3*).

The region of frequency dependences of autodyne parameters and their phase shift angles calculated in accordance with (31)–(36) for different values of coefficients γ, ρ and κ_{fd} in the vicinity of value $\Omega_p = 0$ in diagrams is presented hypothetically.

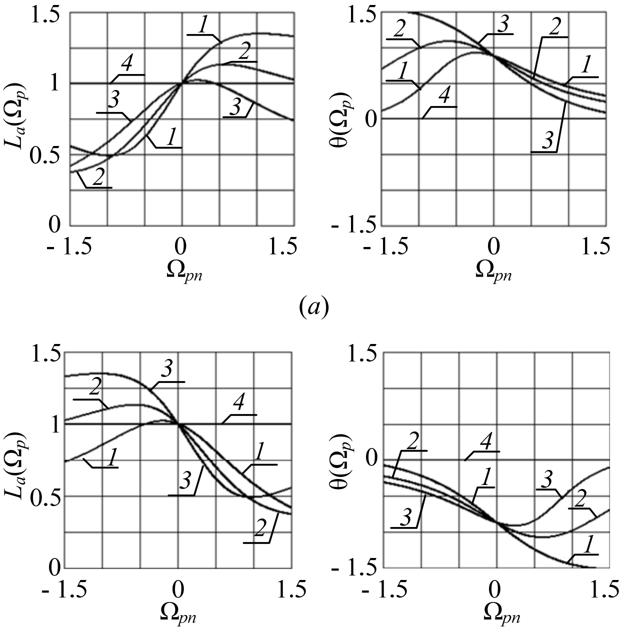
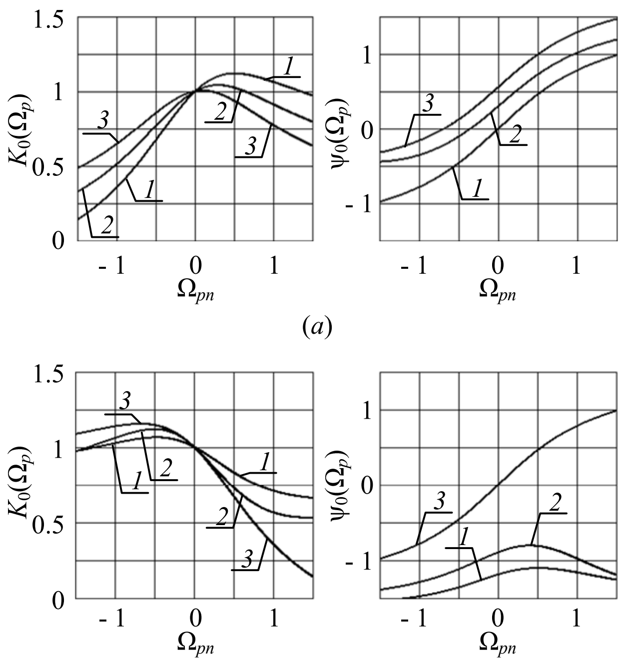


Fig. 4. Diagrams of frequency dependences of the normalized coefficient of the frequency deviation $L_a(\Omega_p)$ and the phase shift angle $\theta(\Omega_p)$ calculated for $\gamma = 1.2$ (*a*) and $\gamma = -1.2$ (*b*) for different values of the non-isodromous coefficient ρ: $\rho = -0.5$ (curves *1*); $\rho = 0$ (curves *2*); $\rho = 0.5$ (curves *3*); (diagrams *4* are received for $\gamma = 0$).



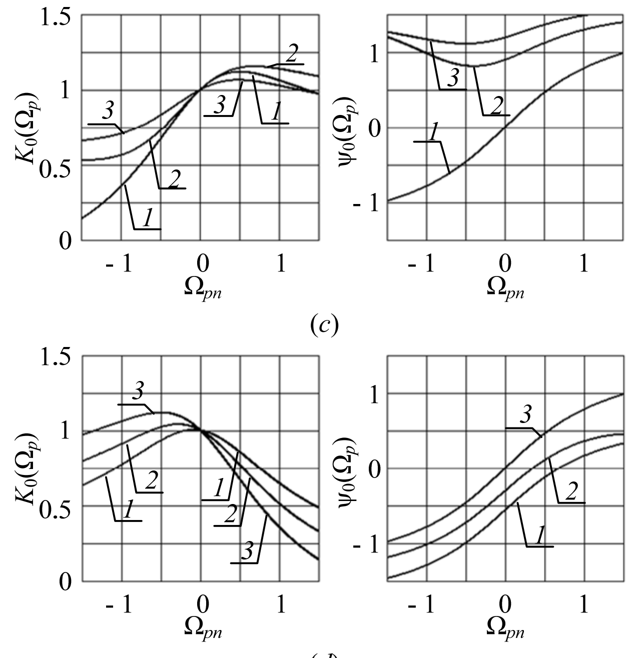


Fig. 5. Diagrams of frequency dependences of normalized coefficient of auto-detection $K_0(\Omega_p)$ and the phase shift angle $\psi_0(\Omega_p)$ calculated for different values of coefficients γ, κ_{fd}: (*a*) $\gamma = 1.2$, $\kappa_{fd} = -0.5$; (*b*) $\gamma = 1.2$, $\kappa_{fd} = 0.5$; (*c*) $\gamma = -1.2$, $\kappa_{fd} = -0.5$; (*d*) $\gamma = -1.2$, $\kappa_{fd} = 0.5$ and the non-isodromous coefficient ρ: $\rho = -0.5$ (curves *1*); $\rho = 0$ (curves *2*); $\rho = 0.5$ (curves *3*).

As follows from Fig. 3, the frequency dependence of the normalized coefficient of autodyne amplification $K_a(\Omega_p)$ caused by inertia property of oscillation amplitude is the symmetrical function with respect to $\Omega_p = 0$. This dependence reminds the amplitude-frequency characteristic of oscillating circuit and it does not depend on values of coefficients γ and ρ. At that, the phase shift angle of the characteristic $\psi_1(\Omega_p)$ is determined by non-isodromic property of the oscillator $(\rho \neq 0)$ causing its offset along the ordinate axis. The dependence $K_a(\Omega_p)$ as a function of coefficients γ and ρ is tracked in absolute values of the frequency of the autodyne response Ω_p.

As follows from expression (31), if the inequality $2\pi / \Omega_p < \tau_a$ is fulfilled, the amplitude value of the autodyne signal $a_1(t)$ is strongly decreased since the autodyne has no time to react on the fast variation of the phase φ.

From (31) under condition $K_a(\Omega_p) = 1/2^{1/2}$, we can obtain the limiting value of the autodyne signal frequency

$$\Omega_{\lim} = \frac{1}{\tau_a} = \frac{\alpha_{11}\omega_0(1-\gamma\rho)}{Q_L} = \frac{\omega_0\sqrt{1+\rho^2}}{K_a Q_{ex}}, \qquad (47)$$

which is fully coincides with expression for the limiting frequency of the Doppler signal of the radar autodyne (see formula (14) from [14]).

In contrast to behavior of $K_a(\Omega_p)$, the frequency dependence $L_a(\Omega_p)$ under condition $\gamma \neq 0$ is not the symmetrical function with respect to $\Omega_p = 0$, but it has near zero dispersion form, as illustrated in Fig 4. The view of this hypothetical function in a great extent is determined by the value and the sign of non-isochronous γ and non-isodromious ρ coefficients. When the sign of the coefficient γ is changed, curves $L_a(\Omega_p)$ in diagrams in vicinity of $\Omega_p = 0$ change also the sign of derivatives, as follows from comparison of appropriate curves in Fig. 4*a* and Fig. 4*b*. At that, curves $\theta(\Omega_p)$ are rotated on the angle, which is approximately equals to π with respect to origin of coordinates as the point of central symmetry. The slope S_Ω of dispersion dependence $L_a(\Omega_p)$ in vicinity of zero frequency $\Omega_p = 0$

$$S_{\Omega=0} = \left(\frac{dL_a(\Omega_p)}{d\Omega_{pn}} \right)_{\Omega=0} = \frac{\gamma(1-\gamma\rho)}{1+\gamma^2} \qquad (48)$$

has the greatest value under $\gamma = \pm 1$, as it has been shown in [14] for the case of the radar autodyne. At that, the oscillator non-isodromous property increases the slope $S_{\Omega=0}$ under condition when signs of coefficients γ and ρ are different. For other values of the coefficient γ the effect of frequency dispersion appears in the lesser extent. In the case of the isochronous oscillator $(\gamma = 0)$, it is completely absent and the phase shift $\theta(\Omega_p) = 0$, as illustrated by curves shown in Fig. 4.

Thus, two main factors influence the value of autodyne frequency deviation. The first factor as determinative one relates to variations of the oscillation frequency. The second one is specified by conversion of autodyne amplitude variations $a_1(t)$ into variations of oscillation frequency due to non-isochronous property. In the case of in-phase combining of these factors at frequency Ω_{pn} growth of the same sign, the autodyne deviation increases. Otherwise, in the case of anti-phase combination under frequency Ω_{pn} growth of another sign, it decreases. These regulations designate the physical sense of the phenomenon of frequency dispersion of autodyne frequency deviation, as has been shown for the radar autodynes in [14]. In the considered case of non-isodromous oscillator $(\rho \neq 0)$, the component caused by its non-isochronous property is defined by another additional factor associated with the presence of the inherent feedback discussed above.

Characteristics $K_0(\Omega_p)$ and $\psi_0(\Omega_p)$ shown in Fig. 5 illustrate the result of amplitude-phase combining the response (22) on amplitude variations $a_1(t)$ extracted in the bias circuit of AE and detection of the response (23) on frequency variations $\chi(t)$, that can be ensued from equation (21). Therefore, in the general case, the frequency dependence of $K_0(\Omega_p)$ also has some asymmetry of characteristic caused by phenomenon of frequency detection $(\kappa_{fd} \neq 0)$. The phase shift $\psi_0(\Omega_p)$ of the autodyne response also has the complicated dependence upon frequency Ω_{pn}. At that, for different signs of coefficients γ and κ_{fd}, dependences $\psi_0(\Omega_p)$ shown in Fig. 5*a* and Fig. 5*d* are similar to characteristics $\psi_1(\Omega_p)$ depicted in Fig. 3. Their differences consist of the presence of additional phase shifts along the ordinate axis due to frequency detection. In the case of different signs of coefficients γ and κ_{fd}, these characteristics have more complicated view determined in a great extent by the value of the coefficient ρ as can be seen in Fig. 5*b* and Fig. 5*c*. Naturally, at the absence of the phenomenon of oscillator frequency detection $(\kappa_{fd} = 0)$ the characteristics $K_0(\Omega_p)$, $\psi_0(\Omega_p)$ coincide with characteristics $K_1(\Omega_p)$ and $\psi_1(\Omega_p)$.

Peculiarities of beating signal formation revealed here restrict the application of the external generator method to its usage for investigations of sensitivity and noise properties of the autodyne as the radio receiver, for measurements of coefficients of autodyne amplification K_a, frequency deviation L_a, auto-detection K_0. The considered method can be also applied to derive the time constant of the autodyne response starting from the definition of the limiting frequency $\Omega_{\lim}$ at measurement of characteristic $K_a(\Omega_p)$. It should be noted that the beating waveform definition does not associate with peculiarities of signal formation in the autodyne short-range radar.

Results of experimental investigations

The functional scheme of experimental installation for inspection of dynamic characteristics of UHF oscillators is presented in Fig. 6. The autodyne oscillator *AO* under investigation was connected to the modulator *Mod* on the pin-diode through the double-arm directional coupler *DC*, the variable attenuator *Att* with the damping factor of −15 dB and the circulator *C*. The length of the waveguide path from the autodyne oscillator to pin-diode-modulator *Mod* was equal to 0.22 m. The third arm of the circulator was loaded by the waveguide short-circuiter *SC*. The sinusoidal signal with constant bias was supplied to the control input of the modulator *Mod* from the radio-frequency oscillator *RO*. The side arms of the directional coupler *DC* were connected to the spectrum analyzer *SA* and the output of the microwave oscillator *MO* through isolating gates.

The autodyne oscillator *AO* under investigation was supplied from the stabilized voltage source *PS*. The oscillator module "Tigel-08" performed by the hybrid-integrated technology on the planar two-meza Gunn diode of 8mm wave range was used as an object under investigation [20].

To compare methods of experimental estimation of the autodyne response time constant, the modulation characteristic of the UHF oscillator was studied [8]. For this purpose, the operating point on the characteristic of the pin-diode was chosen in the middle of the linear sector of the direct bias. It permits to ensure the reflection coefficient variation according to the law $\Gamma(t)=\Gamma_0(1+m\sin\Omega_m t)$, where $m<<1$, if the sinusoidal signal of small amplitude with frequency Ω_m is supplied on the pin-diode. The choice of the appropriate phase of the reflection coefficient by the waveguide short-circuiter *SC* ensures the maximal deep of the amplitude modulation of *AO*. The chosen value of the modulation deep of the reflection coefficient was $m=0.1$

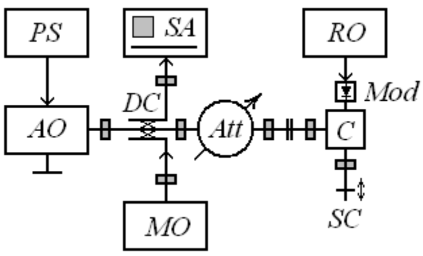


Fig. 6. Functional scheme of experimental installation

The deep of amplitude modulation was checked by the spectrum analyzer *SA*. The form of modulation characteristic for this oscillator in the normalized view measured in the frequency $\Omega_m/2\pi$ range from 10 to 300 MHz is presented by the curve *1* in Fig. 7.

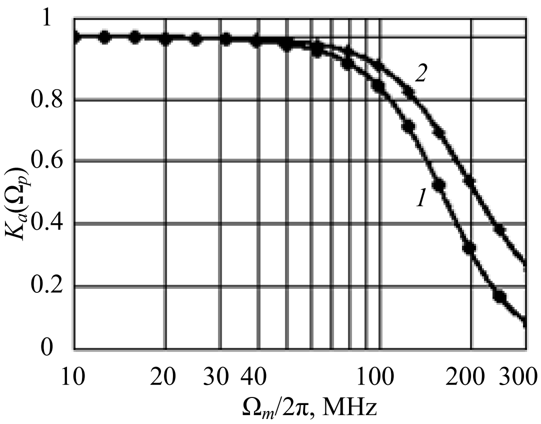


Fig. 7. Diagrams of frequency dependences of the normalized coefficient of autodyne amplification of the oscillator on the Gunn diode of 8mm range.

After that, the attenuator *Att* was switched to position of maximal attenuation, and the signal of the constant level –40 dBm was supplied to the input of the autodyne oscillator *AO* from the output of the microwave oscillator *MO* through the directional coupler *DC* with transfer attenuation –10 dB in the same range of frequency offset with respect to the oscillation frequency. The structure of frequency dependence of the beating signal checked by the spectrum analyzer *SA* is presented by the curve *2* in Fig. 7.

The limiting frequency $\Omega_{\lim}/2\pi$ of these characteristics by the level 0.707 is 126 MHz in the first case and 164 MHz in the second case. As follows from these data, the relaxation time constant values of amplitude of the autodyne oscillator under investigation respectively constitute $\tau_a=1/\Omega_{\lim}\approx1.26\cdot10^{-9}$ in the first case and $\tau_a=1/\Omega_{\lim}\approx1\cdot10^{-9}$ in the second case. The discrepancy of obtained values can be explained by the inherent cut of the frequency response by the pin-modulator having switching time about 1 ns.

Inherent parameters values $\rho=-0.187$; $Q_L=55$; $\gamma=0.92$; $\omega_0/2\pi=37.5$ GHz have been obtained in [8] for this oscillator. In accordance with (25) and (47) these data were used to calculate the autodyne amplification coefficient $K_a=5.4$ and the parameter $\alpha_{11}=0.15$ characterizing the limit cycle permanence in the chosen operation mode.

The results of performed investigations indicate that the external generator method is more accurate when determining the time constant of the autodyne response.

Conclusion

Results of fulfilled investigations confirm that frequency dependence of the normalized coefficient of autodyne amplification of the oscillator situated under influence of the external oscillator signal is the symmetrical function with respect to zero beating frequency. At that, in the general case of non-isochronous and non-isodromous oscillator, frequency characteristics of coefficients of autodyne frequency deviation and auto-detection have more complicate form caused by phase relations of autodyne variations of amplitude and frequency oscillations.

It is shown that the external oscillator method provides the measurement of not only such autodyne oscillator parameters as coefficients of autodyne amplification, the autodyne frequency deviation and auto-detection but also the time constant of the autodyne response and other inherent parameters of the oscillator starting from definition of limiting frequency at measurement of the amplitude characteristic. It is evident that this method can be used for measurement of the sensitivity and noise characteristics of the autodyne as a radio receiving set.

The results of fulfilled analysis can be useful under determination of the response time of the UHF autodyne to influence of the external asynchronous signal and also at the solution of optimal signal reception tasks and processing in the beating mode in different systems. As compared with the modulation characteristic method, the developed method has no error caused by frequency limitations of the used modulator. Additional advantage of the external oscillator method is its simplicity and availability of equipment which is especially important at fulfillment of laboratory researchers of large number of different oscillators with the purpose of type choice and optimization of the oscillation mode of autodyne oscillators.

The developed method can be successfully used in the solution of the problem of autodyne operating speed estimation used as a transceiver on-board of the sounding balloon for the interrogator in the promising system of atmosphere radio-sounding. In these systems the autodyne oscillator should have the necessary operating speed at reception of radio-pulses of the interrogator to provide required accuracy of distance measurement to the sounding balloon.

This research is fulfilled under financial support of the Ministry of Education and Science of Russian Federation in accordance with Government decree No. 218 dated April 09, 2010.

References

1. Rocket F. Proximity fuze // Electronics. — 1945. — N. 11. — P. 110—111.

2. Hunton R. D., Miller B. J. Generator-powered proximity fuze // Electronics. — 1945. — N. 12. — P. 98—103.

3. Page C. H., Astin A. V. Survey of proximity fuze development // American Journal of Physics. — 1947. — Vol. 15, N. 2. — P. 95—110.

4. Zakarlyuk N. M., Noskov V. Ya., Smolskiy S. M. Onboard autodyne velocity sensors for aeroballistic inspections // Proceedings of 20th International Crimean Conference “Microwave & Telecommunication Technology”, September 13—17, 2010. — Sevastopol: Weber. — 2010. — Vol. 2. — P. 1065—1068.

5. Komarov I. V., Smolskiy S. M. Fundamentals of short–range FM radar // Norwood: Artech House, 2003. — 290 p.

6. Takayama Y. Doppler signal detection with negative resistance diode oscillators // IEEE Transactions on Microwave Theory and Techniques. — 1973. — Vol. 21, N. 2. — P. 89—94.

7. Votoropin S. D., Noskov V. Ya., Smolskiy S. M. Modern hybrid-integrated autodyne oscillators of microwave and millimeter ranges and their application. Part 2. Theoretical and experimental investigations // Advantages in modern radio electronic engineering. — 2007. — N. 7. — P. 3—33 [in Russian].

8. Resonance of relaxation oscillations in autodyne oscillators / E. M. Gershenzon, V. M. Kalygina, B. I. Levit, B. N. Tumanov // Radiophysics and Quantum Electronics. – 1981. — Vol. 24, N. 8. — P. 1028—1034 [in Russian].

9. Nagano S., Akaiwa Y. Behavior of Gunn diode oscillator with a moving reflector as a self-excited mixer and a load variation detector // IEEE Transactions on Microwave Theory and Techniques. — 1971. — Vol. 19, N. 12. — P. 906—910.

10. Pantoja F. R., Calazans E. T. Theoretical and experimental studies of gain compression of millimeter-wave self-oscillating mixers // IEEE Transactions on Microwave Theory and Techniques. — 1985. — Vol. 33, N. 3. — P. 181—186.

11. Lazarus M. J., Novak S., Bullimore E. D. New millimeter-wave receivers using self-oscillating Gunn diode mixers // The Microwave Journal. — 1971. — N. 7. — P. 43—45.

12. Bogoliubov N. N., Mitropolsky Yu. A. Asymptotic methods in the theory of nonlinear oscillations. — Moscow: Nauka, 1974. — 504 p. [in Russian].

13. Kurokawa K. Injection locking of microwave solid-state oscillators // Proceedings of the IEEE. — 1973. — Vol. 61, N. 10. — P. 1386—1410.

14. Votoropin S. D., Noskov V. Ya. UHF autodyne signals for tracking the parameters of moving objects // Russian Physics Journal. — 2000. — Vol. 43, N. 7. — P. 576—581.

15. Votoropin S. D., Zakarlyuk N. M., Noskov V. Ya., Smolskiy S. M. On principal impossibility of auto-synchronization of an autodyne by radiation reflected from a moving target // Russian Physics Journal. — 2007. — Vol. 50, N. 9. — P. 195—206.

16. New direction-of-motion Doppler detector / M. J. Lazarus, F. P. Pantoja, M. Somekh, at al. // Electronic Letters. — 1980. — Vol. 16, N. 25. — P. 953—954.

17. Minaev M. I. Low-frequency spectrum of autodyne frequency converter // Electronic Engineering. Series UHF Electronics. — 1989. — N. 7 (421). — P. 12—14 [in Russian].

18. Minaev M. I., Tsentsiper B. L. Research of the autodyne frequency mixer on Gunn diode with large dynamic range of the external signal power variation // Electronic Engineering. Series UHF Electronics. — 1987. — N. 4 (398). — P. 30—33 [in Russian].

19. Noskov V. Ya., Ignatkov K. A., Smolskiy S. M. Analysis of signals of stabilized autodynes // Telecommunication Sciences. — 2011. — Vol. 2, N. 1, January — June. — P. 5 — 16.

20. Votoropin S. D., Noskov V. Ya., Smolskiy S. M. Modern hybrid-integrated autodyne oscillators of microwave and millimeter ranges and their application. Part 1. Technological achievements // Advantages in modern radio electronic engineering. — 2006. — N. 12. — P. 3—30 [in Russian].

Received in final form December 14, 2011