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MODULATION CHARACTERISTICS OF MICROWAVE AUTODYNE OSCILLATORS

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General relations for the analysis of autodyne and modulation characteristics are obtained in the form of differential equations with the retarded argument. Solutions for characteristics of frequency response of autodyne variations of the oscillation amplitude and phase as well as the auto-detecting signal of UHF oscillator under influence of the proper reflected radiation are derived. The solution of the same equation system is given for frequency responses of the modulation deepness of oscillation amplitude and frequency as well as the auto-detecting signal in the case of the reflection factor modulation by the high-frequency signal. Calculations of autodyne and modulation characteristics are fulfilled at different values of inherent parameters of UHF oscillators. Non-isochronous and non-isodromous properties of autodyne oscillators are investigated. Phenomena of frequency auto-detecting are considered. A method for dynamic properties determination is substantiated according to its modulation characteristics at the oscillation amplitude registration. The results of theoretical analysis are confirmed by experimental data obtained on the example of hybrid-integrated oscillator of 8mm-range on the Gunn diode.

Introduction

For normal operation of autodyne short-range radar systems intended for registration of high-speed processes, the autodyne oscillators used in them should have the sufficient margin on dynamic characteristics [1—3]. Experimental investigation of these characteristics in full-scale or modeling conditions is connected with large material expenses, complexity and bulky equipment [4]. To simplify and essentially accelerate the manufacture process and ensure the achievement of required performance by simpler and cheaper means, the real radar objects are often replaced by their electrodynamics prototypes [5—7]. The most efficient techniques for these investigations in laboratory conditions are based on the usage of signal equivalents realizing by different methods.

A method of modulation characteristics is the simple way to determine the autodyne characteristics by experimental data as compared to other approaches based on determination of autodyne characteristics [7—9]. This method allows determining the frequency response of the oscillator modulation capability for fixed value of the modulating parameter (modulus of the reflection factor) at high values of the modulation frequency. Using this function, one can obtain the time constant of the autodyne response, which is the main parameter for the determination of dynamic properties of the oscillator [10, 11].

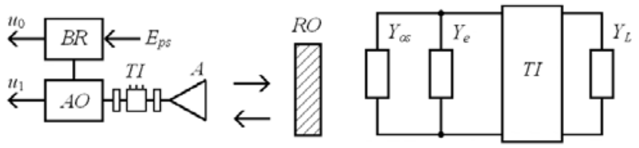
At substantiation of this method in [8], the relation between coefficients of autodyne amplification and the amplitude modulation capability of the non-isochronous oscillator has been obtained. However, modulation characteristics of the oscillation frequency and the auto-detecting signal of the non-isodromous autodyne remain unstudied in the known publications although they can have the practical interest.

In the present paper, the general approach to the autodyne analysis is developed for the case when the high modulation frequency in oscillators is carried out by means of variation of the reflection factor modulus. The relations between their autodyne and modulation parameters and characteristics are obtained. This approach allows consideration of not only non-isochronous but also non-isodromous properties of UHF oscillators and the phenomenon of the frequency auto-detection signal [6].

In conclusion of the paper, we present results of experimental studies of the hybrid-integrated modules of 8mm-range fulfilled on the basis of planar two-mesa Gunn diodes, which are described in [12] devoted to the analysis of the alternative beating method.

Main equations of the autodyne

The functional circuit of the simplest radar, which has an autodyne UHF oscillator *AO* directly connected with an antenna *A* through the impedance transformer *TI* without any decoupling elements, is presented in Fig. 1*a*. The operating bias for the active element *AE* of *AO* is supplied from the power source E_{ps} through the registration block *BR*. Electromagnetic oscillations generated in UHF oscillator *AO* are radiated by the receivetransmit antenna A in direction of the reflecting object RO. Reflected radiation returns through the antenna A in the oscillator AO causing the autodyne effect.



(a) (b)

Fig. 1. Functional (a) and equivalent (b) circuits of the single-circuit autodyne.

As a result, arising autodyne variations of average current or voltage in the AE power circuit of AO are transformed to the output signal voltage u_0 (auto-detecting signal) [13] by means of the simplest auto-bias circuit of the special circuit of BR. In some constructions of the autodyne radar, the useful signal is extracted by the additional circuit, which transforms the autodyne variations of amplitude or frequency into the output signal voltage u_1 (the signal of external detection) [14].

The equivalent circuit of the autodyne UHF oscillator is shown in Fig. 1b. In this high-frequency circuit, the oscillatory system is presented by frequency dependent conductance $Y_{os} = Y_{os}(\omega)$; $Y_L = Y_L(t,\tau)$ represents the load conductance of AO and its variations caused by influence of the reflected radiation, which is delayed on the propagation time $\tau = 2l/c$ to the reflecting object RO and back, where l is the distance to the object; c is the propagation velocity of electromagnetic radiation.

The electronic conductance of AE $Y_e = Y_e(A,\omega)$ averaged over the oscillation period in the general case depends on the amplitude A and the frequency ω of oscillations. Such dependence is typical for UHF oscillators implemented on AE with hysteresis caused by the phenomenon of main carrier's delay in the interaction space with the resonator field.

Assume that oscillations in AE are quasi-harmonic ones: $u(t) = \mathrm{Re}[A \exp j(\omega_0 t + \varphi)]$, where $A = A(t)$, $\varphi = \varphi(t)$ are slowly changing amplitude and phase in the current time moment t. Then, the balance equation for complex admittance of the circuit shown in Fig. 1b in accordance with the general theory of UHF oscillators [15] has the form:

$$Y_e(A,\omega) + Y_{os}(\omega) + Y_{rL}(t,\tau) = 0\,, \qquad (1)$$

where $Y_{rL}(t,\tau) = Y_L k_{ti}$ is the load conductance reduced to the AE plane; k_{ti} denotes the transfer coefficient of the impedance transformer TI.

In the case of autodyne functioning in conditions, when the amplitude of natural oscillations $A(t)$ essentially exceeds the amplitude of returned oscillations from the object (from system pre-history) $\Gamma A(t,\tau)$, so that the following condition is fulfilled $\Gamma << 1$, where Γ is the coefficient characterizing the radiation damping at its propagation to the object and back, the equation for $Y_{rL}(t,\tau)$ in (1) can be represented in the form:

$$Y_{rL}(t,\tau) = G_{rL} + \Delta Y_{rL}(t,\tau)\,, \qquad (2)$$

where $\Delta Y_{rL}(t,\tau) = -\Delta G_{rL}(t,\tau) + \mathrm{j}\Delta B_{rL}(t,\tau)$ is the varying part of the reduced to the AE plane complex load conductance caused by the action of the reflected wave; $\Delta G_{rL}(t,\tau) = 2G_{rL}\Gamma(t,\tau)\cos\delta(t,\tau)$, $\Delta B_{rL}(t,\tau) = 2G_{rL} \times \times\Gamma(t,\tau)\sin\delta(t,\tau)$ are its active and reactive components; $\Gamma(t,\tau) = \Gamma[A(t,\tau)/A(t)]$, $\delta(t,\tau) = \Psi(t) - \Psi(t,\tau)$ denote the modulus and the phase of the instantaneous reflection factor; $\Psi(t)$, $\Psi(t,\tau)$ are the total oscillation phase in the current time moment t and in the moment $(t-\tau)$, respectively. For the steady-state mode of the autonomous oscillator, when $\Gamma = 0$, $\omega = \omega_0$, $A = A_0$, it follows from (1):

$$Y_e(A_0,\omega_0) + Y_{os}(\omega_0) + G_{rL} = 0\,. \qquad (3)$$

In the equation (1), the oscillation amplitude can be presented as $A = A_0 + \Delta A$, where ΔA are the autodyne variations of the amplitude, at that, $\Delta A << A_0$. The phenomenon of auto-detecting of the autodyne response at fixed bias $E = E_0$ consists in autodyne variations of the average value of the current $I_e = I_e(A,\omega)$ of AE. Extraction of these variations with regard to the quiescent point $I_{e0} = I_e(A_0,\omega_0)$ and the linear detection of amplitude variations ΔA ensure the possibility to obtain the output signals $u_0 = Z_{it}\Delta I_e$ and $u_1 = k_d \Delta A$ (see Fig. 1a), where $\Delta I_e = I_e(A,\omega) - I_e(A_0,\omega_0)$; Z_{it} is the impedance of transformation of current variations into the voltage of BR; k_d denotes the transfer function of the detector.

Following the Kurokawa method [15], for perturbed oscillator, when in (2) $\Gamma \neq 0$, we should replace ω in the expression for $Y_{os}(\omega)$ in equation (1) by $\omega_0(1+\chi) - j(1/A)(dA/dt)$, where $\chi = (1/\omega_0)(d\varphi/dt) = = \Delta\omega/\omega_0$ defines the relative autodyne variations of the frequency. Taking into consideration the slowness of functions $\varphi(t)$ and $A(t)$, we may assume that $d\varphi/dt$ and $(1/A)(dA/dt)$ are reasonably small compared with ω_0. Assuming the linearity of functions $G_e(A,\omega)$, $B_e(A,\omega)$ and $I_e(A,\omega)$ versus oscillation amplitude A and frequency ω, expressions for $Y_{os}(\omega)$ and $Y_e(A,\omega)$ in (1) as well as $I_e(A,\omega)$ can be expanded in the Taylor series. Limiting at that by two first terms, we obtain:

$$Y_{os}(\omega) = Y_{os}(\omega_0) + \left(\frac{\partial Y_{os}(\omega)}{\partial\omega}\right)_0 \left(\frac{d\varphi}{dt} - j\frac{1}{A}\frac{dA}{dt}\right); \quad (4)$$

$$Y_e(A,\omega) = Y_e(A_0,\omega_0) + \left(\frac{\partial Y_e(A,\omega)}{\partial A}\right)_0 \Delta A + \left(\frac{\partial Y_e(A,\omega)}{\partial\omega}\right)_0 \Delta\omega; \quad (5)$$

$$I_e(A,\omega) = I_{e0}(A_0,\omega_0) + \left(\frac{\partial I_e(A,\omega)}{\partial A}\right)_0 \Delta A + \left(\frac{\partial I_e(A,\omega)}{\partial\omega}\right)_0 \Delta\omega, \quad (6)$$

where the index "0" near large parenthesis denotes that the partial derivatives are taken in the vicinity of the stationary point.

Substituting (4), (5) in (1), taking into account (2), (3) and excluding variables of the second order of smallness, we obtain the equation, from which we can extract the real and imaginary parts. After elementary transformations, taking into consideration expansions (4)—(6), we obtain the system of linearized differential equations with retarded argument for relative variations of the amplitude $a_1 = \Delta A/A_0$ and the frequency $\chi = \Delta\omega/\omega_0$ of oscillations as well as the phase of the instantaneous reflection factor $\delta(t,\tau)$ and relative current value $i_0 = \Delta I_e/I_{e0}$ of AE:

$$\frac{\xi_{11}}{\omega_0}\frac{da_1}{dt} + \alpha_{11}a_1 + \varepsilon_{11}\chi = \Gamma(t,\tau)\eta\cos\delta(t,\tau); \quad (7)$$

$$\beta_{11}a_1 + \xi_{11}\chi = -\Gamma(t,\tau)\eta\sin\delta(t,\tau); \quad (8)$$

$$\delta(t,\tau) = \Psi(t) - \Psi(t,\tau); \quad (9)$$

$$i_0 = \alpha_{01}a_1 + \varepsilon_{01}\chi, \quad (10)$$

where $\alpha_{01} = (A_0/I_{e0})(\partial I_e/\partial A)_0$ denotes the dimensionless parameter considering the auto-detecting phenomenon for oscillation amplitude variations; $\varepsilon_{01} = (\omega_0/I_{e0})(\partial I_e/\partial\omega)_0$ is the parameter of "frequency detection" defining the contribution of the frequency variations into variations of the power source current of AE; $\alpha_{11} = (A_0/2G)(\partial G_e/\partial A)_0$ is the reduced slope of the oscillator increment specifying the regeneration degree and the solidity of its limit cycle; $\varepsilon_{11} = \varepsilon_{os} + \varepsilon_e$ is the parameter defining the oscillator non-isodromous properties and taking into account influence of frequency variations on the oscillation amplitude through variations of active conductance parameters of oscillatory system $\varepsilon_{os} = (\omega_0/2G)(\partial G_{os}/\partial\omega)_0$ and the electronic conductance of AE $\varepsilon_e = (\omega_0/2G)(\partial G_e/\partial\omega)_0$; $\beta_{11} = (A_0/2G)(\partial B_e/\partial A)_0$ is the parameter defining the oscillator non-isochronous properties; $\xi_{11} = \xi_{os} + \xi_e$ is the parameter of frequency stabilization considering the frequency slope of reactive conductances of the oscillatory system $\xi_{os} = (\omega_0/2G)(\partial B_{os}/\partial\omega)_0$ and AE $\xi_e = (\omega_0/2G)(\partial B_e/\partial\omega)_0$, which can be presented as the loaded Q-factor of single circuit oscillatory system $\xi_{os} = Q_L$ and the Q-factor of the "electronic" conductance of AE $\xi_e = Q_e$, respectively; $\eta = G_{rL}/G = Q_L/Q_{ex}$ is the efficiency of the oscillatory system; Q_{ex} is its external Q-factor; $G = G_{os} + G_{rL}$ is the load conductance taking into account the reduced load.

In the case of the single circuit oscillatory system, for which $\varepsilon_{os} = 0$, the parameter ε_{11} is mainly defined by the frequency slope of the active conductance of AE $\varepsilon_{11} = \varepsilon_e$. Usually this parameter is comparably small in oscillators of the centimeter wavelength range, and we can neglect it in the system (7)—(10). However, in oscillators of the millimeter range and especially in oscillators stabilized by the additional external cavity [16], the consideration of the parameter ε_{11} as well as the parameter of frequency detection ε_{01} is necessary for adequate description of autodyne and modulation characteristics. Moreover, due to the inequality $\xi_{os} >> \xi_e$ fulfillment for the real UHF oscillators, we assume further that $\xi_{11} = Q_L$.

It can be seen from equations (7)—(10) that the main inertia property of the autodyne system is connected with oscillation amplitude variations. Combining equations (7), (8) at excluding of variable χ, we have:

$$\frac{da_1}{dt} + \frac{1}{\tau_a}a_1 = \Gamma(t,\tau)\eta\frac{\omega_0\sqrt{1+\rho^2}}{Q_L}\cos[\delta(t,\tau) - \psi_1], \quad (11)$$

where $\psi_1 = \arctan(\rho)$ is the angle of the phase shift of autodyne amplitude variations; $\rho = \varepsilon_{11}/Q_L$ is the non-isochronous property coefficient; τ_a is the characteristic time constant (relaxation time of the amplitude) of the autodyne response defined by the relation:

$$\tau_a = \frac{Q_L}{\alpha_{11}\omega_0(1-\gamma\rho)}. \quad (12)$$

In contrast to formulas obtained in [10, 11], the relation (12) takes into account the coefficients of non-isochronous $\gamma = \beta_{11}/\alpha_{11}$ and non-isodromous ρ properties of UHF oscillators. The time constant of the autodyne response τ_a is the main parameter determining properties of dynamic characteristics of the autodyne oscillator.

Dynamic characteristics of autodyne oscillators

In the most practical cases, the autodynes operate in the mode of the small signal, when the distortion parameter $p_a << 1$. Under these conditions, if the period $T_D = 2\pi / \Omega_D$ of the Doppler signal is much more than the delay time of reflected radiation $T_D >> \tau$, we may put in (7)—(9) $\Gamma(\tau,t) = \Gamma$, $\delta(\tau,t) = \Omega_D t$, and examine the stationary (smooth) processes of oscillation parameter variations. Then, by solving the system of equations (7)—(10), we obtain expressions describing the amplitude and phase relations between relative quasi-harmonic in time variations of the amplitude $a_1(t)$ and the frequency $\chi(t)$ of oscillations as well as the current $i_0(t)$ of AE:

$$a_1(t) = \Gamma K_a K_{1\Omega} \cos(\Omega_D t - \psi_{1\Omega}); \quad (13)$$

$$\chi(t) = -\Gamma L_a L_{a\Omega} \sin(\Omega_D t + \theta_\Omega); \quad (14)$$

$$i_0(t) = \Gamma K_0 K_{0\Omega} \cos(\Omega_D t - \psi_{0\Omega}), \quad (15)$$

where K_a, L_a, K_0 are coefficients of the autodyne amplification, the oscillation frequency deviation and the auto-detection:

$$K_a = \eta \frac{1}{\alpha_{11}} \frac{\sqrt{1+\rho^2}}{1-\gamma\rho}; \quad (16)$$

$$L_a = \eta \frac{1}{Q_L} \frac{\sqrt{1+\gamma^2}}{1-\gamma\rho}; \quad (17)$$

$$K_0 = \eta \frac{\alpha_{01}}{\alpha_{11}} \frac{1-\kappa_{fd}\gamma}{1-\gamma\rho} \sqrt{1+\kappa_d^2}, \quad (18)$$

$K_{1\Omega}$, $L_{a\Omega}$, $K_{0\Omega}$ are the normalized (with respect to eigenvalues at $\Omega_D = 0$) frequency-dependent components of coefficients of the autodyne amplification, the frequency deviation and the auto-detection, respectively:

$$K_{1\Omega} = \frac{1-\rho\Omega_{Dr}}{\sqrt{1+\rho^2}(1+\Omega_{Dr}^2)\cos\psi_{1\Omega}}; \quad (19)$$

$$L_{a\Omega} = \frac{1+\gamma\Omega_{Dr} + (1-\gamma\rho)\Omega_{Dr}^2}{\sqrt{1+\gamma^2}(1+\Omega_{Dr}^2)\cos\theta_\Omega}; \quad (20)$$

$$K_{0\Omega} = \frac{(1-\rho\Omega_{Dr})}{\sqrt{1+\kappa_d^2}(1+\Omega_{Dr}^2)\cos\psi_{0\Omega}}; \quad (21)$$

$\psi_{1\Omega}$, θ_Ω, $\psi_{0\Omega}$ are frequency-dependent angles of the phase shifts of autodyne variations of the amplitude and the frequency as well as the auto-detection signal, respectively:

$$\psi_{1\Omega} = \arctan[(\rho + \Omega_{Dr})/(1-\rho\Omega_{Dr})]; \quad (22)$$

$$\theta_\Omega = \arctan \frac{\gamma(1-\rho\Omega_{Dr})}{1+\gamma\Omega_{Dr} + (1-\gamma\rho)\Omega_{Dr}^2}; \quad (23)$$

$$\psi_{0\Omega} = \arctan\{[\rho - \kappa_{fd} + (1-\kappa_{fd}\gamma)\Omega_{Dr} - \kappa_{fd}(1-\gamma\rho)\Omega_{Dr}^2]/(1-\kappa_{fd}\gamma)(1-\rho\Omega_{Dr})\}; \quad (24)$$

$\Omega_{Dr} = \Omega_D \tau_a$ is normalized frequency of the autodyne response; $\kappa_{fd} = \varepsilon_{01}\alpha_{11}/\alpha_{01}\xi_{11}$ is the coefficient of frequency detection of autodyne frequency variations into variation of the average values of the AE current; $\kappa_d = [(\rho - \kappa_{fd})/(1-\kappa_{fd}\gamma)]$ is the coefficient of amplitude-frequency displacement of the auto-detection signal of non-isodromous ($\rho \neq 0$) and non-isochronous ($\gamma \neq 0$) oscillator.

Obtained equations (19)—(24) have the reasonably complicate form, therefore, we fulfill their analysis with attraction of numerical methods. Fig. 2 shows the frequency dependences of autodyne characteristics and angles of its phase shifts calculated by formulas (19)—(24) at $\gamma = 1.2$; $\kappa_{fd} = -0.5$ for different values of ρ: $\rho = -0.5$ (curves *1*); $\rho = 0$ (curves *2*); $\rho = 0.5$ (curves *3*).

The frequency dependence of the coefficient $K_{1\Omega}$ shown in Fig. 2*a* is the symmetric function with regard to $\Omega_D = 0$. Its view reminds the amplitude-frequency characteristic of the oscillatory circuit, and it does not depend upon coefficients γ and ρ. At that, the angle of phase shift $\psi_{1\Omega}$ is determined by non-isodromous property ($\rho \neq 0$) causing its displacement along the ordinate axis.

In contrast to the frequency dependence of $K_{1\Omega}$, the function $L_{a\Omega}$ shown in Fig. 2*b* under condition $\gamma \neq 0$ is not symmetric one with regard to $\Omega_D = 0$, and has a dispersion form in the vicinity of this frequency. The view of this function is substantially determined by the values and the signs of non-isochronous γ and non-isodromous ρ coefficients. In the case of the isochronous oscillator only ($\gamma = 0$), the autodyne frequency deviation does not depend upon the frequency Ω_D as shown by the curve *4* in Fig. 2*b*.

The analysis of calculated characteristics $L_{a\Omega}$ showed that two main factors influence the value of autodyne frequency deviation. The first one is connected with the impact of reflected radiation, and it is determinative. The second one is caused by transformation of autodyne amplitude variations $a_1(t)$ into variations of oscillation frequency due to non-isochronous property. If these factors are added in-phase and the frequency Ω_D grows with the same sign, the autodyne deviation increases. Otherwise, in the case of anti-phase combination, if the frequency Ω_D grows with another sign, the autodyne deviation decreases. These circumstances define the physical sense of the frequency dispersion phenomena of frequency deviation, which was discovered for non-isochronous oscillators in [17]. In the considered case of the non-isodromous oscillator ($\rho \neq 0$), the component caused by its non-isochronous property is determined by another additional factor, which is connected with the presence of the inherent feedback in the oscillator [6].

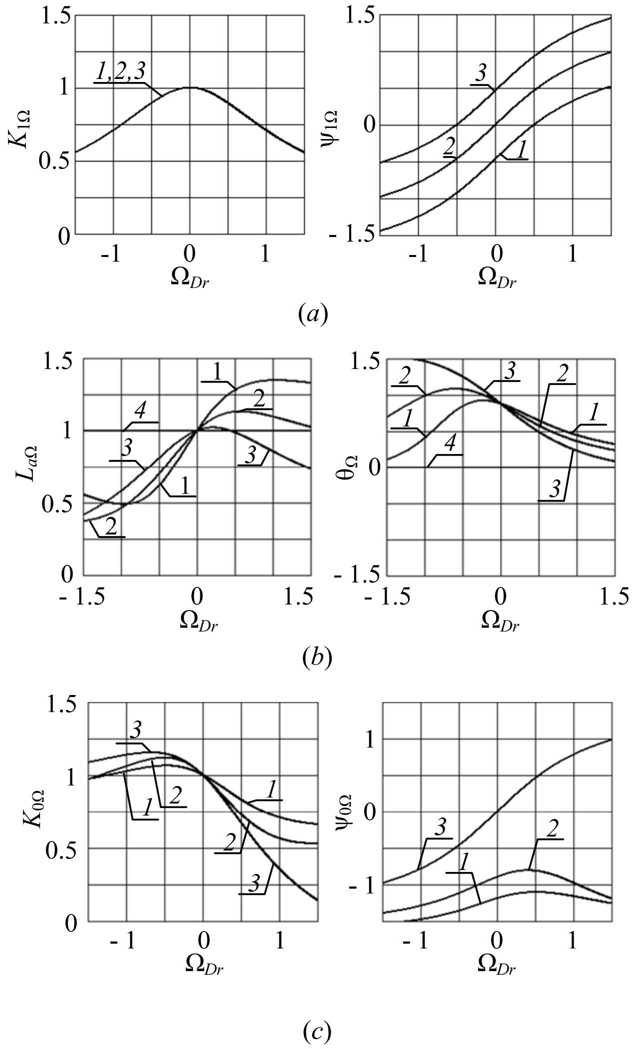


Fig. 2. Diagrams of normalized coefficients of the frequency functions $K_{1\Omega}$ (*a*), $L_{a\Omega}$ (*b*), $K_{0\Omega}$ (*c*) and phase shift angles $\psi_{1\Omega}$ (*a*), θ_Ω (*b*), $\psi_{0\Omega}$ (*c*).

The frequency function $K_{0\Omega}$ shown in Fig. 2*c* has some asymmetry of the characteristic, which is connected with the phenomenon of frequency detection ($\kappa_{fd} \neq 0$). The phase shift $\psi_{0\Omega}$ of the autodyne response has also the complicate dependence versus the frequency Ω_D. When signs of coefficients γ and κ_{fd} changes, functions $\psi_{0\Omega}$ become similar to characteristics $\psi_{1\Omega}$. Their differences consist in the presence of additional phase shifts along the ordinate axis due to frequency detection.

From equation (19) under condition $K_{1\Omega} = 1/2^{1/2}$, one can define the boundary value $\Omega_{\lim}$ of the autodyne signal frequency:

$$\Omega_{\lim} = \frac{1}{\tau_a} = \frac{\alpha_{11}\omega_0(1-\gamma\rho)}{Q_L} = \frac{\omega_0\sqrt{1+\rho^2}}{K_a Q_{ex}}. \qquad (25)$$

Using (25) and taking into account the formula for the Doppler frequency $\Omega_D = 2\nu_r\omega_0 / c$, where ν_r is the radial component of the movement relative velocity of the reflecting object and short-range radar, we obtain the limitation on this velocity:

$$\nu \le v_{\lim} = \frac{c\alpha_{11}(1-\gamma\rho)}{2Q_L} = \frac{c\sqrt{1+\rho^2}}{2K_a Q_{ex}}. \qquad (26)$$

The limiting velocity $v_{\lim}$ obtained by (26) does not depend on the oscillation frequency ω_0 and is determined by inherent parameters of the autodyne. At that, the values of K_a and Q_{ex} included in the second part of formula (26) can be easily measured whereas the value of ρ is sufficiently small and can be neglected. It implies that excessive growth of the autodyne amplification coefficient K_a and the external *Q*-factor Q_{ex} can lead to signal limitation in the autodyne at high velocity ν_r of movement. For example, the limiting velocity $v_{\lim}$ obtained by (26) at values $K_a = 1000$ and $Q_{ex} = 200$ is $v_{\lim} = 750$ m/s. Therefore, the mentioned characteristics should be taken into account at choosing the oscillator type for the autodyne short-range radar and its operation mode. This example shows that for experimental determination of autodyne dynamic characteristics, it is suitable to use indirect methods based, as we already noted, on examination of modulation characteristics.

Modulation characteristics of oscillators in the case of reflection factor modulation

The time constant of the autodyne response usually can be determined experimentally according to modulation characteristics of UHF oscillator [7, 8]. These characteristics can be investigated on the usual experimental bench for studying autodynes, in which the electromechanical imitator of the Doppler signal is replaced by the pin-diode modulator operating on the reflection. At that, the operating point on the pin-diode characteristic is chosen in the middle of the linear part of the opening bias. At the supply on the pin-diode of the harmonic signal with small amplitude with modulation frequency Ω_M, these conditions provide reflection factor variations according to the law:

$$\Gamma(\tau) = \Gamma(t) = \Gamma_0(1 + m_\Gamma \sin\Omega_M t), \qquad (27)$$

where Γ_0 is the average value of the reflection factor; m_Γ is its modulation index.

As can be seen from explication of (2) according to this case, the active $\Delta G_{rL}(\tau)$ and reactive $\Delta B_{rL}(\tau)$ components of the load variations influencing the oscillation amplitude an frequency variations, respectively, will depend not only on time t, but on the initial phase δ_0 of reflection factor:

$$\Delta G_{rL}(\tau) = \Delta G_{rL}(\delta_0, t) =$$
$$= -2G_{rL}\Gamma_0 \cos\delta_0 - 2G_{rL}\Gamma_0 m_\Gamma \cos\delta_0 \sin\Omega_M t; \quad (28)$$
$$\Delta B_{rL}(\tau) = \Delta B_{rL}(\delta_0, t) =$$
$$= 2G_{rL}\Gamma_0 \sin\delta_0 + 2G_{rL}\Gamma_0 m_\Gamma \sin\delta_0 \sin\Omega_M t. \quad (29)$$

First terms in (28), (29) have the sense of some DC components depending on the phase δ_0 only. They are in m_Γ times more than the alternating components presented by the second terms. Because of this, autodyne variations of the amplitude and the frequency as well as the AE current become also dependent on both the phase δ_0 and time t: $a_1 \equiv a_1(\delta_0, t)$; $\chi \equiv \chi(\delta_0, t)$; $i_0 \equiv i_0(\delta_0, t)$. The solution of the system (7), (8), (10) with consideration (27)—(29) for this case gives the following expressions for components of the autodyne response under investigation:

$$a_1(\delta_0, t) = a_{10}(\delta_0) + \tilde{a}_1(t); \quad (30)$$
$$\chi(\delta_0, t) = \chi_0(\delta_0) + \tilde{\chi}(t); \quad (31)$$
$$i_0(\delta_0, t) = i_{00}(\delta_0) + \tilde{i}_0(t), \quad (32)$$

where $a_{10}(\delta_0)$, $\chi_0(\delta_0)$, $i_{00}(\delta_0)$ are the DC components of the autodyne response caused by first terms in (28), (29):

$$a_{10}(\delta_0) = \Gamma_0 K_a \cos(\delta_0 - \psi_1); \quad (33)$$
$$\chi_0(\delta_0) = -\Gamma_0 L_a \sin(\delta_0 + \theta); \quad (34)$$
$$i_{00}(\delta_0) = \Gamma_0 K_0 \cos(\delta_0 - \psi_0); \quad (35)$$

$\tilde{a}_1(t)$, $\tilde{\chi}(t)$, $\tilde{i}_0(t)$ are alternating components caused by the modulation process and defined by second terms in (28), (29):

$$\tilde{a}_1(t) = \Gamma_0 m_\Gamma K_a K_{1\Gamma} \cos(\delta_0 - \psi_1)\cos(\Omega_M t - \psi_{1\Gamma}); \quad (36)$$
$$\tilde{\chi}(t) = -\Gamma_0 m_\Gamma L_a \sin(\delta_0 + \theta) L_\Gamma \cos(\Omega_M t - \theta_\Gamma); \quad (37)$$
$$\tilde{i}_0(t) = \Gamma_0 m_\Gamma K_0 \cos(\delta_0 - \psi_0) K_{0\Gamma} \cos(\Omega_M t - \psi_{0\Gamma}); \quad (38)$$

$K_{1\Gamma}$, L_Γ, $K_{0\Gamma}$ are the normalized (with regard to the eigenvalues for $\Omega_M = 0$) frequency-dependent components of coefficients of modulation transformation into variations of oscillation amplitude and frequency as well as into the AE bias circuit (the auto-detection signal):

$$K_{1\Gamma} = 1\Big/\sqrt{1+\Omega_{Mr}^2}; \quad (39)$$
$$L_\Gamma = \frac{\gamma\cos\delta_0 + [1+(1-\gamma\rho)\Omega_{Mr}^2]\sin\delta_0}{(\gamma\cos\delta_0 + \sin\delta_0)(1+\Omega_{Mr}^2)\cos\theta_{\Gamma\Omega}}; \quad (40)$$
$$K_{0\Gamma} = [(1+\Omega_{Mr}^2)(1-\kappa_{fd}\gamma)\sqrt{1+\kappa_d^2}\,]^{-1} \times$$
$$\times\{\sqrt{1+\rho^2}\cos(\delta_0 - \psi_0) + \kappa_{fd}[1+(1-\gamma\rho)\Omega_{Mr}^2]\sin\delta_0 -$$
$$-\kappa_{fd}\gamma\cos\delta_0\} / \cos(\delta_0 - \psi_0)\cos\psi_{0\Omega}; \quad (41)$$

$\psi_{1\Gamma}$, θ_Γ, $\psi_{0\Gamma}$ are frequency-dependent angles of the phase shift of modulation variations of amplitude, frequency, and the auto-detection signal, respectively:

$$\psi_{1\Gamma} = \arctan\Omega_{Mr}; \quad (42)$$
$$\theta_\Gamma = \arctan\frac{\gamma\Omega_{Mr}(\cos\delta_0 + \rho\sin\delta_0)}{\gamma\cos\delta_0 + [1+(1-\gamma\rho)\Omega_{Mr}^2]\sin\delta_0}; \quad (43)$$
$$\psi_{0\Gamma} = \arctan[\Omega_{Mr}(1-\gamma\kappa_{fd})\sqrt{1+\rho^2} \times$$
$$\times\cos(\delta_0 - \psi_0) / \{\kappa_{fd}[1+(1-\gamma\rho)\Omega_{Mr}^2 + \sqrt{1+\rho^2} \times$$
$$\times\cos(\delta_0 - \psi_0) - \kappa_{fd}\gamma\cos\delta_0]\sin\delta_0\}]; \quad (44)$$

$\Omega_{Mr} = \Omega_M \tau_a$ is the normalized modulation frequency.

As can be seen from (30)—(32), the oscillator response components on the modulation of the reflection factor contain the DC components in its structure: $a_{10}(\delta_0)$, $\chi_0(\delta_0)$, $i_{00}(\delta_0)$ depending, as follows from (33)—(35), on the reflection factor phase δ_0, values of initial phases ψ_1, θ, ψ_0 caused by inherent properties of the oscillator, and also alternating components: $\tilde{a}_0(t)$, $\tilde{a}_1(t)$, $\tilde{\chi}(t)$. As follows from (36)—(38), amplitude values of the last components depend on the value of the modulation index m_Γ, the phase shift δ_0, the value of initial phases ψ_1, θ, ψ_0 and the modulation frequency Ω_{Mr}. The product of normalized coefficients $K_{1\Gamma}$, L_Γ, $K_{0\Gamma}$ and trigonometric functions included in these equations gives the appropriate functions of normalized amplitudes of the modulation deepness versus the phase δ_0 of the reflection factor: $k_{1\Gamma} = K_{1\Gamma} \times \cos(\delta_0 - \psi_1)$; $l_\Gamma = L_\Gamma \sin(\delta_0 + \theta)$; $k_{0\Gamma} = K_{0\Gamma}\cos(\delta_0 - \psi_0)$. Graphs of these functions are shown in Fig. 3.

As can be seen from the obtained graphs, "zeros" of the modulation deepness and its maximums are observed for different values of the reflection factor phase δ_0. Therefore, for experimental determination of the required characteristics, it is necessary to choose the appropriate phase δ_0.

So, to examine the characteristic $K_{1\Gamma}$, it is necessary to satisfy the condition $\delta_0 = \psi_1$; for determination of L_Γ, it is required $\delta_0 = \pi/2 - \theta$; to define $K_{0\Gamma}$, we need to select the phase $\delta_0 = \psi_0$. At that, by fixing appropriate positions of the short-circuit piston in the waveguide path, it is possible to determine these shift angles $\psi_{1\Gamma}$, θ_Γ and $\psi_{0\Gamma}$ experimentally. The accuracy of these measurements is higher if we register zeros instead of maximums of modulation.

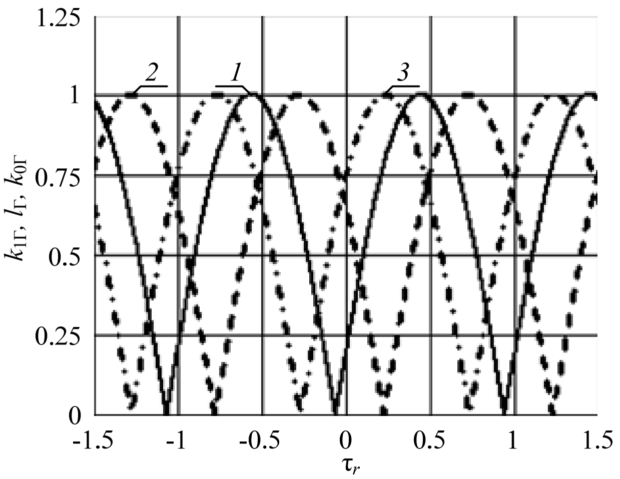


Fig. 3. Graphs of normalized amplitudes of modulation signals of the amplitude $k_{1\Gamma}$ (curve *1*), the frequency l_Γ (curve *2*) and auto-detection signal $k_{0\Gamma}$ (curve *3*) versus the normalized phase $\tau_r = \delta_0/2\pi$ of the refection factor.

Let us rewrite equations (40) and (43) for the case when the reflection factor phase $\delta_0 = \pi/2 - \theta$, and (41), (44) when it is equal to ψ_0:

$$L_\Gamma = \frac{(1+\gamma^2)+(1-\gamma\rho)\Omega_{Mr}^2}{(1+\gamma^2)(1+\Omega_{Mr}^2)\cos\theta_\Gamma}; \quad (45)$$

$$K_{0\Gamma} = \left\langle 1+\rho\kappa_d - \kappa_{fd}\{\gamma+[1+(1-\gamma\rho)\Omega_{Mr}^2]\kappa_d\}\right\rangle / (1+$$

$$+\Omega_{Mr}^2)\sqrt{1+\kappa_d^2}\sqrt{(1-\kappa_{fd}\gamma)^2+(\rho-\kappa_{fd})^2}\cos\psi_{0\Gamma}; \quad (46)$$

$$\theta_\Gamma = \arctan\{\Omega_{Mr}\gamma(\gamma+\rho)/[1+\gamma^2+(1-\gamma\rho)\Omega_{Mr}^2]\}; \quad (47)$$

$$\psi_{0\Gamma} = \arctan\frac{\Omega_{Mr}(1-\gamma\kappa_{fd})(1+\rho\kappa_d)}{1+\rho\kappa_d-\kappa_{fd}\{\gamma+[1+(1-\gamma\rho)\Omega_{Mr}^2]\kappa_d\}}. \quad (48)$$

Since the equations (39)–(48) have sufficient complicate form, we use the numerical method for their analysis.

The modulation characteristic of variations of oscillation amplitude $K_{1\Gamma}$ has the simplest form similar to the characteristic of oscillatory circuit. Fig. 4 shows the coefficient $K_{1\Gamma}$ and its phase characteristics $\psi_{1\Gamma}$ calculated by formulas (39) and (42). Comparing curves presented in Fig. 4 and Fig. 2*a*, we see that characteristics for modulus of coefficients $K_{1\Gamma}$ and $K_{1\Omega}$ completely coincide.

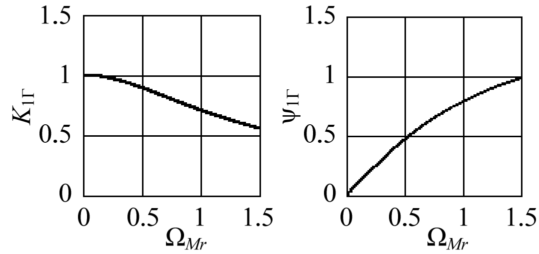


Fig. 4. Graphs of frequency responses of normalized transfer functions of amplitude modulation $K_{1\Gamma}$ and its angles of the phase shift $\psi_{1\Gamma}$.

In these figures, the difference between phase characteristics $\psi_{1\Gamma}$ and $\psi_{1\Omega}$ is observed. These characteristics reflect the permanent phase shifts of the autodyne response depending on inherent properties of the oscillator. It should be noted that in the case of reflection factor modulation, such dependences are absent. The boundary frequency on the level 0.707 with respect to modulation deepness maximum is determined by the autodyne response time constant $\Omega_{\lim} = 1/\tau_a$ and is connected with inherent parameters of the oscillator according to (12).

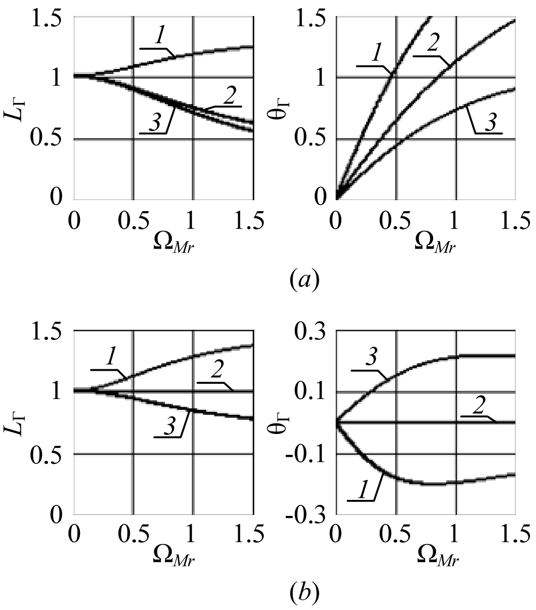


Fig. 5. Graphs of frequency responses of normalized coefficients of modulation frequency deviation L_Γ and angles of the phase shift θ_Γ calculated at $\gamma = 1.2$ for different values of reflection factor phases δ_0 (*a*): $\delta_0 = \arctan\rho - 0.3$ (curves *1*); $\delta_0 = \arctan\rho$ (curves *2*); $\delta_0 = \arctan\rho + 0.3$ (curves *3*) and the non-isochronous property coefficient γ (*b*): $\gamma = -0.5$ (curves *1*); $\gamma = 0$ (curves *2*); $\gamma = 1.2$ (curves *3*).

In contrast to characteristics of the autodyne frequency deviation L_Ω shown in Fig. 2*b*, characteristics of the frequency modulation L_Γ are symmetric functions of the frequency Ω_{Mr} in accordance with (40), (45). Graphs of the frequency responses of the $L_\Gamma = L_\Gamma(\Omega_{Mr})$ modulus and the phase $\theta_\Gamma = \theta_\Gamma(\Omega_{Mr})$ are presented in Fig. 5. Curves in Fig. 5*a* are obtained according to (40) and (43) for phase variations δ_0 of the reflection factor, as well as curves in Fig. 5*b* are carried out by relations (45), (47) for variation of non-isochronous property coefficient γ. As can be seen from these graphs, both the sign and the value of non-isochronous property coefficient γ, and the reflection factor phase δ_0 essentially influence the value of frequency modulation as well as the character of this function at high values of modulation frequency Ω_{Mr}. With modulation frequency Ω_{Mr} growth, the frequency deviation may increase (curves *1*) or decrease (curves *3*) for definite values of the phase δ_0 and the coefficient γ. Only in the case of isochronous oscillator, where $\gamma = 0$, the frequency dependence of L_Γ and θ_Γ is absent as illustrated by curves *2* in Fig. 5*b*.

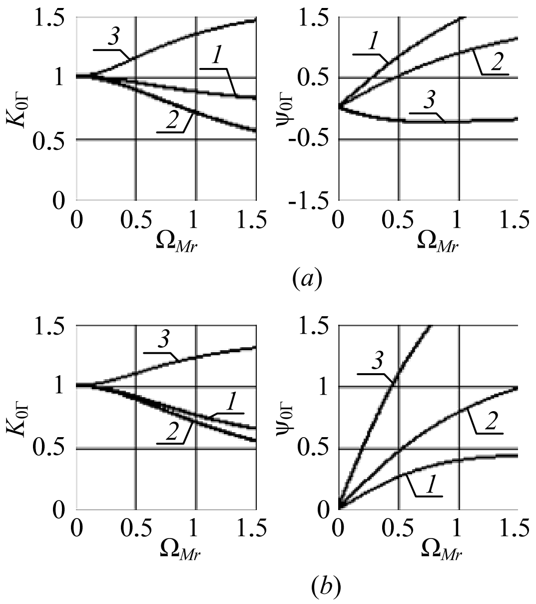


Fig. 6. Graphs of frequency responses of normalized transfer coefficients of modulation into the auto-detecting circuit of AE $K_{0\Gamma}$ and angles of the phase shift $\psi_{0\Gamma}$ calculated for $\gamma = 1.2$ and different values of the reflection factor phase δ_0 ($\kappa_{fd} = 0.4$) (*a*): $\delta_0 = \arctan\rho - 0.8$ (curves *1*); $\delta_0 = \arctan\rho$ (curves *2*); $\delta_0 = \arctan\rho + 1.7$ (curves *3*) and different values of frequency detection coefficient κ_{fd} (*b*): $\kappa_{fd} = -0.5$ (curves *1*); $\kappa_{fd} = 0$ (curves *2*); $\kappa_{fd} = 0.2$ (curves *3*).

The analysis of equations (45) and (47) shows that the boundary frequency $\Omega_{\lim}$ of the function $L_\Gamma = L_\Gamma(\Omega_{Mr})$ on level 0.707 from the maximal value depends on coefficients γ and ρ. To provide the damping characteristics of $L_\Gamma(\Omega_{Mr})$, it is necessary to fulfill the condition $x > 1$, where $x = (1+\gamma^2)^2/2(1-\gamma\rho)$. Under this condition, the value of the normalized (with respect to the boundary frequency $\Omega_{r\lim} = \Omega_{\lim}\tau_a$) autodyne response can be calculated by the formula: $\Omega_{r\lim} = [(x+1)/(x-1)]^{1/2}$. Using this formula at values $\gamma = 1.2$ and $\rho = -0.2$, we obtain $\Omega_{r\lim} = 1.55$.

Graphs of the functions of the auto-detection signal coefficients module $K_{0\Gamma}$ and their phase characteristics $\psi_{0\Gamma}$ versus the frequency Ω_{Mr} of modulation impact calculated according to (41) and (44) for different phases δ_0 of the reflection factor are shown in Fig. 6*a*. The similar graphs calculated according to (46) and (48) at variations of the frequency detection coefficient κ_{fd} are presented in Fig. 6*b*. These graphs show that in this case, as in the case of modulation of the oscillation frequency considered above, with frequency Ω_{Mr} growth, the modulation value of the auto-detection signal can increase (curves *3*) or decrease (curves *1* and *2*) at definite values of mentioned parameters δ_0 and κ_{fd}. When the frequency detection phenomenon is absent ($\kappa_{fd} = 0$), the form of characteristics $K_{0\Gamma}$ and $\psi_{0\Gamma}$ completely coincides with one of characteristics $K_{1\Gamma}$ and $\psi_{1\Gamma}$ as illustrated in Fig. 4.

The analysis of modulation characteristics calculated at oscillator reflection factor modulation shows that the characteristic of amplitude modulation coincides with the autodyne amplitude characteristics and can be used for determination of the time constant of the autodyne response. The behavior of other characteristics to a great extent depends on inherent oscillator parameters and the phase of the reflection factor. Therefore, they cannot be used for this purpose.

It is interesting to compare the method of experimental estimation of the time constant of the autodyne response by modulation characteristics under consideration with the beating method based on application of the signal from the measuring oscillator [12]. The oscillator module "Tigel-08" implemented on the planar two-mesa Gunn diode of 8mm-range [16] by the hybrid-integrated technology was used as the object under investigation. The autodyne characteristics were studied in the frequency $\Omega_M / 2\pi$ range from 10 to 300 MHz.

The boundary frequency $\Omega_{\lim} / 2\pi$ of autodyne characteristics on the level 0.707 determined by these two methods respectively constitute 126 MHz in the first case and 164 MHz in the second case. According to these frequencies, the values of the relaxation time constant for the amplitude of studied autodyne oscillator are: $\tau_a = 1/\Omega_{\lim} \approx 1.26 \cdot 10^{-9}$ in the first case and

$\tau_a = 1/\Omega_{\lim} \approx 1 \cdot 10^{-9}$ in the second case. Insignificant discrepancy of obtained values is explained by the proper slope of the frequency response by the pin-modulator having the switching time about 1 ns. To determinate the value of τ_a by the method of modulation characteristics more accurate, it is necessary to use the reflection factor modulus modulators having essentially less switching time than the measuring time constant of the autodyne response.

Conclusion

Based on the general approach to the autodyne analysis, the formation of their dynamic autodyne and modulation characteristics has been considered. These characteristics were obtained by using the variation of the reflection factor modulus. At that, such inherent properties of UHF oscillators as the non-isochronous property, the non-isodromous property and the frequency detection were taking into consideration. It is proved that under condition of fast reflector movement the inertia property of oscillation amplitude variations affects the frequency function of amplitudes of autodyne and modulation characteristics as well as additional phase shifts of the autodyne response components. Influence of these inherent properties on the shape of the autodyne response at high speeds is demonstrated under conditions of high values of the distortion parameter commensurable with unity.

The analysis of autodyne and modulation characteristics showed that the only characteristic of oscillation amplitude modulation coincides with the autodyne amplitude characteristic and can be used for determination of the time constant of the autodyne response. The behavior of frequency and auto-detection characteristics to a great extent depends on inherent oscillator parameters and the phase of the reflection factor. Therefore, they cannot be used for the determination of the autodyne response time constant.

Obtained results can be applied at determination of the time response of the autodyne UHF oscillator on the influence of reflected radiation. They are also useful for solution of optimal signal processing problems in various short-range radar systems.

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