ISSN 2664-9969

UDC 355/359
DOI: 10.15587/2706-5448.2024.310043

Serhiy Hatsenko,
Ivan Vasylyaiko,
Dmytro Burlak

THE DEVELOPMENT OF A COMBINED SYSTEM OF FREQUENCY AUTOMATIC CONSTRUCTION OF RADIO MONITORING TOOLS WITH FIRST ASTATISM

At the present time, phase auto-adjustment systems are widely used, in which frequency stabilization and frequency tracking is achieved due to phasing of the reference (setting) and control voltages. Frequency auto-adjustment systems solve this problem as a result of direct measurement of the difference in frequencies of the reference and control voltages, and reduction of this difference. The scientific task solved in the research is to increase the dynamic characteristics of automatic tuning systems, to increase the dynamic accuracy and speed of frequency auto-tuning systems of radio monitoring devices with astatism. Therefore, the object of research is the system of automatic self-adjustment of military radio monitoring equipment. The subject of the research is the dynamic, root mean square errors of automatic self-tuning systems under different laws of change of the disturbing influence (input signal frequency deviation) and the speed of the systems. The methods of analysis and synthesis, the theory of complex technical systems and the theory of radio receiving devices were chosen as the basic mathematical apparatus in the proposed research. The research proposed a combined system of frequency auto-adjustment of radio monitoring devices with astatism, as well as basic mathematical expressions that describe its operation. In the process of research the following tasks were solved:

– an analysis of the dynamic characteristics of a static system of frequency auto-adjustment with the principle of deviation control was performed;

– a functional scheme and a mathematical model of a combined frequency auto-adjustment system with first-order astatism and increased speed were developed.

One of the important advantages of the proposed mathematical model is the increased efficiency of frequency tuning depending on the type of signal compared to known frequency autotuning. This is accepted not only in the case of changes in the disturbing influence according to deterministic laws, but also in the case of random disturbing influence.

The direction of further research should be considered the increase in dynamic accuracy (reduction of dynamic, root mean square errors) and speed of frequency auto-adjustment systems.

Keywords: *automatic autotuning systems, static frequency autotuning systems, first-order astatism.*

Received date: 06.06.2024
Accepted date: 08.08.2024
Published date: 15.08.2024

How to cite
Hatsenko, S., Vasylyaiko, I., Burlak, D. (2024). The development of a combined system of frequency automatic construction of radio monitoring tools with first astatism. Technology Audit and Production Reserves, 4 (2 (78)), 42–48. https://doi.org/10.15587/2706-5448.2024.310043

1. Introduction

The main tasks of the units of the Armed Forces of Ukraine that perform radio monitoring tasks include the search and detection of new enemy radio equipment, interception and registration of meaningful information, for the purpose of further processing and implementation. Currently, the enemy widely uses various devices of radio communication, both domestic and foreign, which in turn raises the requirements for the quality of radio receiving equipment used by units of the defense forces of Ukraine.

In order to organize hidden and stable communication, the enemy mainly uses radio stations with pseudo-random reconfiguration of the operating frequency (PROF), which is based on radio stations of the «Azart» (R-381P-1) and «Arahis» (R-392) type. The rate of change of the operating frequency in these radio stations ranges from 100 to several thousand jumps per second.

Based on this fact, the accuracy and speed of setting the radio receiving equipment of the radio monitoring units should be the same and even higher. The automatic frequency adjustment system (AFA) is a fairly important component of almost every radio receiving device and the quality of the signal we receive at the output of the radio receiving device depends on the speed and accuracy of its operation.

The topic of developing a fast and accurate AFA system based on the measurement of the frequency difference between the reference and control voltage frequencies and the reduction of this discrepancy is quite relevant at the moment [1–4]. Phase relationships between reference and control voltages are not taken into account.

In this way, the design of the radio receiving device is simplified, its reliability and speed of operation are increased, since the composition of the control link is reduced, which in turn leads to an increase in speed and reliability.

An important issue in the application of this AFA scheme is the accuracy and speed of measuring the frequency difference, which requires the use of modern and alternative methods of solving this problem. Because the use of a slow measurement method will negate all the advantages of an AFA system in contrast to a phase automatic frequency adjustment (PAFA) system.

Taking into account the advantages and disadvantages of each of the approaches to adjusting the indicators of radio receiving equipment, there is an urgent scientific task in substantiating the composition of the system of frequency auto-adjustment of radio receiving equipment of radio monitoring units.

The aim of research is the development of a system of automatic self-adjustment of military radio monitoring equipment.

2. Materials and Methods

The objects of research are the systems of automatic self-adjustment of military radio monitoring equipment.

The subjects of research are dynamic, root mean square errors of automatic self-adjustment systems of military radio monitoring devices under different laws of change of disturbing influence (input signal frequency deviation) and system speed.

The research problem is the development of a system of frequency auto-adjustment of radio receiving equipment of radio monitoring units. Modeling was carried out using MathCad 14 (USA). Aser Aspire based on the AMD Ryzen 5 processor was used as the hardware. The basic mathematical apparatus in the proposed research was chosen to be the methods of analysis and synthesis, the theory of complex technical systems, and the theory of radio receiving devices.

3. Results and Discussion

3.1. Combined frequency autotuning system with first-order astatism. The functional scheme of the combined AFA system is shown in Fig. 1.

Eliminate the error $\Delta\omega_{PR}(t)$ with a gradual change $\Delta\omega_C(t)$ and limit it in the case of a linear change $\Delta\omega_C(t)$ it is possible by making the system astatic with first-order astatism using the feedback of the disturbing influence $\Delta\omega_C(t)$, so by building a combined AFA system. To transform a static system into an astatic one of the first order of astatism, it is enough to use a provoking feedback to send a signal to the system proportional to this provocation [5].

To measure the provocative effect $\Delta\omega_C(t)$ a frequency discriminator FD tuned to the nominal frequency ω_{C0} is used input signal. On the functional diagram, the frequency discriminator FD is presented in the form of a set of comparison element CE, which performs the subtraction operation $\Delta\omega_C(t)=\omega_{C0}-\omega_C(t)$ and the deviation converter signal frequency (disturbing effect) in voltage: $u_{FD}=k_{FD}\,\Delta\omega_C(t)$.

According to the work [3], the time of the transition process t_P of the system is determined by the slowly fading component and the transient component of the error. Increasing the speed of the system can be achieved by compensating this slowly decaying component. For this, it is necessary to apply the first derivative of this influence to the system, in addition to the voltage proportional to the disturbing influence [6, 7], thus, a correction device (CD) should be included in the compensation link, which would pass a signal proportional to the disturbing influence $\Delta\omega_C$ and its first derivative [8]. To increase the output voltage of the correction device, an amplifier is used which (thus, the voltage from the output of the compensation link) is fed to the adder, where it is composed of the voltage of the error signal $u_{FD}(t)$ of frequency discriminator FD included in the closed circuit of the system.

Before the introduction of disturbing communication when changing the step frequency of the signal $\Delta\omega_C(t)=\omega_0$ there was an error that was fixed $\Delta\omega_{PR}(t)=\Delta\omega_C/(1+k_R)$, from which the voltage $u_Y(t)$ was formed at the input of the control generator CG. When the connection $u_Y(t)$ is turned on, the voltage is formed from the sum of voltages $u_\Sigma(t)=u_{FD}(t)+u_{US}(t)$, where $u_{US}(t)$ in the established mode, as well as $u_{FD}(t)$, proportionally. While increasing (due to the gain of the amplifier) error voltage $u_{FD}(t)$ decreases for a certain value an increase in frequency $\Delta\omega_G(t)$ is required CG voltage, equal to $\Delta\omega_G(t)=\Delta\omega_C$ is achieved only due to the voltage of the compensating connection $u_{US}(t)$.

System error at the same time $\Delta\omega_{PR}(t)=0$. With further increase tends to exceed the value and therefore an error of another sign appears. It is obvious that you should choose the gain of the amplifier such that in the case of a gradual change in the frequency of the signal error $\Delta\omega_{PR}(t)=0$.

The operation of the combined AFA system with a linear change in the signal frequency by developing the appropriate mathematical model of the system.

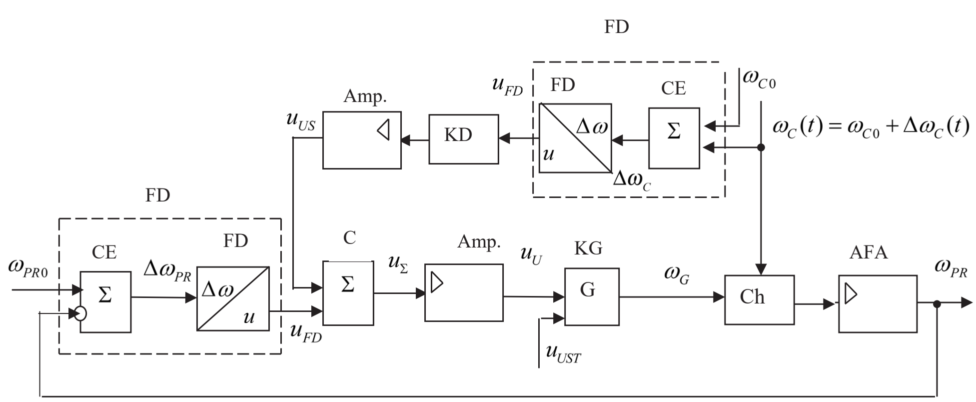

Fig. 1. Functional diagram of the combined system of the radio-receiving equipment of the radio monitoring units

3.2. Mathematical model of the combined system of AFA with astatism of the first order. The mathematical model of the combined AFA system with astatism of the first order according to the functional scheme (Fig. 1) while using the equations in the deviations are given below.

Transfer function:

– frequency discriminator FD:

$$K_{FD}(p)=\frac{u_{FD}(p)}{\Delta\omega_{PR}(p)}=\frac{k_{FD}}{T_{FD}p+1},\ k_{FD}=1,\ T_{FD}=0.005\ \text{s};$$

– amplifier Amp.:

$$K_A(p)=\frac{u_A(p)}{u_\Sigma(p)}=k_A,\ k_A=4;$$

– controlled generator CG:

$$K_G(p)=\frac{\Delta\omega_G(p)}{u_P(p)}=\frac{k_G}{T_Gp+1},\ k_G=1,\ T_G=0.1\ \text{s};$$

– frequency discriminator FD:

$$K_{FD}(p)=\frac{u_{FD}(p)}{\Delta\omega_C(p)}=\frac{k_{FD}}{T_{FD}p+1},\ k_{FD}=1,\ T_{FD}=0.005\ \text{s};$$

– correction device CD:

$$K_{CD}(p)=\frac{u_{CD}(p)}{u_{FD}(p)};$$

– amplifier Amp.:

$$K_A(p)=\frac{u_A(p)}{u_{CD}(p)}=k_A;$$

– compensatory provoking connection:

$$K_C(p)=\frac{u_P(p)}{\Delta\omega_C(p)}=K_{FD}(p)K_{CD}(p)K_A(p).$$

Parameters of transfer functions $K_{CD}(p)$ and $K_A(p)$ are determined as a result of the synthesis of the connection of disturbing influence in accordance with the conditions of increasing the dynamic accuracy and speed of the system.

Reduction of dynamic and root-mean-square errors of the AFA system [1] can be achieved by transforming a static system with respect to the disturbing influence into an astatic system with first-order astatism [2, 4, 7]. An increase in the quality indicators of the transient process (in particular, an increase in the performance of the system) can be achieved thanks to the compensation of the slowly decaying component of the transient process, which is caused by a change in the provoking influence.

To transform a static system with respect to a provoking influence $\Delta\omega_C(t)$ [5, 9] in a system with first-order astatism, it is necessary to introduce a voltage proportional to the disturbing influence into the system with the help of the disturbing influence connection. To compensate for the weakly damping component of the induced transient $\Delta\omega_C(t)$, it is necessary to enter into the system one first derivative of $\Delta\omega_C(t)$ [2, 10, 11].

In accordance with these requirements, the physically implemented transfer function of the disturbing influence connection should have the form:

$$K_{CT}(p)=\frac{u_A(p)}{\Delta\omega_C(p)}=\frac{\tau_1p+k_C}{\tau_2p+1}. \quad (1)$$

According to the mathematical model of the combined AFA system, the transfer function of the connection of the provoking influence is equal to:

$$K_C(p)=K_{FD}(p)K_{CD}(p)K_A(p)=\frac{k_{FD}(p)}{T_{FD}p+1}K_{CD}(p)k_A. \quad (2)$$

To determine the transfer function of the correction device $K_{FD}(p)$ the right-hand sides of expressions (1) and (2) are equated:

$$\frac{k_{FD}}{T_{FD}p+1}K_{CD}(p)k_A=\frac{\tau_1p+k_C}{\tau_2p+1},$$

where

$$K_{CD}(p)k_A=\frac{\tau_1p+k_C}{\tau_2p+1}\cdot\frac{T_{FD}p+1}{k_{FD}}. \quad (3)$$

Transfer function $K_A(p)$ (3) physically unrealized (the degree of the numerator is greater than the degree of the denominator). The transfer function, which is physically implemented, has the form:

$$K_{CD}(p)k_A=\frac{(T_{FD}p+1)(\tau_1p+k_C)}{(\tau_2p+1)k_{FD}(\tau_3p+1)}. \quad (4)$$

In this case, the transfer function of the connection with the disturbing influence will be equal to:

$$K_C(p)=\frac{u_A(p)}{\Delta\omega_C(p)}=$$
$$=\frac{k_{FD}(\tau_1p+k_C)(T_{FD}p+1)}{(T_{FD}p+1)(\tau_2p+1)k_{FD}(\tau_3p+1)}=\frac{\tau_1p+k_C}{(\tau_2p+1)(\tau_3p+1)}. \quad (5)$$

To define parameters τ_1, k_C, τ_2 and τ_3 of the communication transfer function under the influence (5), it is necessary to first find the form of the transfer function of the combined AFA system. For this purpose, according to the mathematical model of the system, the following system of equations was compiled:

$$\Delta\omega_{PR}(p)=\Delta\omega_C(p)-\Delta\omega_G(p),$$
$$\Delta\omega_G(p)=K_{CD}(p)K_A(p)K_G(p)\Delta\omega_{CD}(p)+$$
$$+K_S(p)K_A(p)K_G(p)\Delta\omega_S(p).$$

Excluded from the system $\Delta\omega_G(t)$, it is possible to receive:

$$\left(\Delta\omega_C(p)-\Delta\omega_{PR}(p)\right)=$$
$$=K_{CD}(p)K_A(p)K_G(p)\Delta\omega_{PR}(p)+$$
$$+K_S(p)K_U(p)K_G(p)\Delta\omega_S(p),$$
$$\left[1+K_{CD}(p)K_A(p)K_G(p)\right]\Delta\omega_{PR}(p)=$$
$$=\left[1-K_C(p)K_A(p)K_G(p)\right]\Delta\omega_C(p),$$

where is the transfer function of the system:

$$K_{\Delta\omega_{PR}}(p)=\frac{\Delta\omega_{PR}(p)}{\Delta\omega_C(p)}=\frac{1-K_C(p)K_A(p)K_G(p)}{1+K_{CD}(p)K_A(p)K_G(p)}, \quad (6)$$

or

$$K_{\Delta\omega_{PR}}(p)=\frac{\Delta\omega_{PR}(p)}{\Delta\omega_C(p)}=\frac{1-\dfrac{(\tau_1 p+k_C)k_A k_G}{(\tau_2 p+1)(\tau_3 p+1)(T_G p+1)}}{1+\dfrac{k_{CD}k_A k_G}{(T_{CD}p+1)(T_G p+1)}}=$$

$$=\frac{\begin{bmatrix}(\tau_2 p+1)(\tau_3 p+1)(T_G p+1)-\\-(\tau_1 p+k_C)k_A k_G\end{bmatrix}(T_{CD}p+1)(T_G p+1)}{\begin{bmatrix}(T_{CD}p+1)(T_G p+1)+\\+k_{CD}k_A k_G\end{bmatrix}(\tau_2 p+1)(\tau_3 p+1)(T_G p+1)}=$$

$$=\frac{\begin{bmatrix}(\tau_2 p+1)(\tau_3 p+1)(T_G p+1)-\\-(\tau_1 p+k_C)k_A k_G\end{bmatrix}(T_{CD}p+1)}{\begin{bmatrix}(T_{CD}p+1)(T_G p+1)+\\+k_{CD}k_A k_G\end{bmatrix}(\tau_2 p+1)(\tau_3 p+1)}=\frac{D_{\Delta\omega_{PR}}(p)}{F_{\Delta\omega_{PR}}(p)}, \quad (7)$$

or

$$K_{\Delta\omega_{PR}}(p)=\frac{\Delta\omega_{PR}(p)}{\Delta\omega_C(p)}=\frac{a_0p^4+a_1p^3+a_2p^2+a_3p+a_4}{b_0p^4+b_1p^3+b_2p^2+b_3p+b_4}, \quad (8)$$

where

$a_0=T_{CD}T_G\tau_2\tau_3;$

$a_1=T_{CD}T_G\tau_2+T_{CD}T_G\tau_3+T_{CD}\tau_2\tau_3+T_G\tau_2\tau_3;$

$a_2=T_{CD}T_G+\tau_2\tau_3+T_{CD}(\tau_3+\tau_2)+$
$+T_G(\tau_2+\tau_3)-k_A k_G\tau_1 T_{CD};$

$a_3=T_{CD}+T_G+\tau_2+\tau_3-k_A k_G\tau_1-k_A k_G k_C T_{CD};$

$a_4=1-k_C k_A k_G;$

$b_0=T_{CD}T_G\tau_2\tau_3;$

$b_1=T_{CD}T_G\tau_2+T_{CD}T_G\tau_3+T_{CD}\tau_2\tau_3+T_G\tau_2\tau_3;$

$b_2=T_{CD}T_G+\tau_2\tau_3+T_{CD}\tau_3+T_{CD}\tau_2+T_G\tau_2+$
$+T_G\tau_3+\tau_2\tau_3 k_{CD}k_A k_G;$

$b_3=T_{CD}+T_G+\tau_2+\tau_3+(\tau_2+\tau_3)k_{CD}k_A k_G;$

$b_4=1+k_{CD}k_A k_G=1+k_A.$

According to the expression (8), the combined system of AFA in the general case (at an arbitrary value of the coefficient k_C) is static, as well as the system without connection with the provoking influence.

The condition for transforming a static system into a system with first-order astatism is:

$$a_4=1-k_C k_A k_G=0, \quad (9)$$

where

$$k_C=\frac{1}{k_U k_G}=\frac{1}{4\cdot 1}=0.25. \quad (10)$$

When the condition (9) is fulfilled, the transfer function of system (8) takes the form:

$$K_{\Delta\omega_{PR}}(p)=\frac{a_0p^4+a_1p^3+a_2p^2+a_3p}{b_0p^4+b_1p^3+b_2p^2+b_3p+b_4}, \quad (11)$$

thus, the system becomes astatic with first-order astatism.

Parameters τ_1, τ_2, τ_3, which are included in the transfer function $K_C(p)$ (5), disturbing connections (as well as in the transfer functions (7), (8)), were determined in accordance with the requirements for increasing the quality indicators of the transient process, in particular, the time τ_1 constant for the first derivative of the disturbing influence – in accordance with the condition of increasing the speed of the system.

At the same time, it is possible to adhere to the following method:

1. Write down the transfer function (7) of the combined system when condition (10) is fulfilled:

$$K_{\Delta\omega_{PR}}(p)=\frac{\Delta\omega_{PR}(p)}{\Delta\omega_C(p)}=$$

$$=\frac{(T_{CD}p+1)\begin{bmatrix}(\tau_2 p+1)(\tau_3 p+1)(T_G p+1)-\\-(k_A k_G\tau_1 p+1)\end{bmatrix}}{\begin{bmatrix}(T_{CD}p+1)(T_G p+1)+\\+k_{CD}k_A k_G\end{bmatrix}(\tau_2 p+1)(\tau_3 p+1)}=\frac{D_{\Delta\omega_{PR}}(p)}{F_{\Delta\omega_{PR}}(p)}. \quad (12)$$

It can be seen from expression (12) that the parameters τ_2,τ_3 connection with the disturbing influence are not included in the characteristic equation $(T_{CD}p+1)(T_G p+1)+k_{CD}k_A k_G=0$ of the closed part of the system and therefore affect its stability. However, when the open connection of the provoking influence is introduced, new roots appear in the characteristic equation of the system $F_{\Delta\omega_{PR}}$ (p=0), equal $p_{2C}=-(1/\tau_2)$ and $p_{3C}=-(1/\tau_3)$. New components $A_{2C}e^{p_{2C}t}$ and $A_{3C}e^{p_{3C}t}$ will correspond to these roots and the transient component of the error caused by a change in the disturbing influence. In order for these components not to have a significant negative effect on the quality of the transient, it is desirable that they decay quickly, at least faster than the slowly decaying components.

2. The roots of the characteristic equation of the AFA system with the principle of deviation control is equal to: $p_1=-72.9843788$; $p_2=-137.0156212$.

With the selected parameters k_C (look at (10)), τ_2 and τ_3 transfer function $K_{\Delta\omega_{PR}}(p)$ (12) will take the form:

$$K_{\Delta\omega_{PR}}(p)=\frac{\Delta\omega_{PR_K}(p)}{\Delta\omega_C(p)}=$$

$$=\frac{a_0p^4+a_1p^3+a_2p^2+a_3p}{b_0p^4+b_1p^3+b_2p^2+b_3p+b_4}=\frac{D_{\Delta\omega_{PR}}(p)}{F_{\Delta\omega_{PR}}(p)}, \quad (13)$$

where

$a_0=T_{CD}T_G\tau_2\tau_3=1\cdot 10^{-9};$

$a_1=T_{CD}T_G\tau_2+T_{CD}T_G\tau_3+T_{CD}\tau_2\tau_3+T_G\tau_2\tau_3=1.71\cdot 10^{-6};$

$a_2=T_{CD}T_G+\tau_2\tau_3+T_{CD}(\tau_3+\tau_2)+T_G(\tau_2+\tau_3)-$
$-k_U k_G\tau_1 T_{CD}=8.17\cdot 10^{-4}-0.02\cdot\tau_1;$

$a_3=T_{CD}+T_G+\tau_2+\tau_3-k_U k_G\tau_1-$
$-k_U k_G k_C T_{CD}=0.103-4\cdot\tau_1;$

$b_0=T_{CD}T_G\tau_2\tau_3=1\cdot 10^{-9};$

$b_1=T_{CD}T_G\tau_2+T_{CD}T_G\tau_3+T_{CD}\tau_2\tau_3+T_G\tau_2\tau_3=1.71\cdot 10^{-6};$

$b_2=T_{CD}T_G+\tau_2\tau_3+T_{CD}\tau_3+T_{CD}\tau_2+T_G\tau_2+$
$+T_G\tau_3+\tau_2\tau_3 k_{CD}k_U k_G=0.000825;$

$b_3=T_{CD}+T_G+\tau_2+\tau_3+(\tau_2+\tau_3)k_{CD}k_U k_G=0.12;$

$b_4=1+k_{CD}k_U k_G=1+k_R=5.$

3. Coefficient τ_1 (look at (5)) at the first derivative of the disturbing influence. Value determine, in accordance with the requirements of increasing one of the indicators of the quality of the transition process – speed, which corresponds to the time of the transition process (time of regulation t_P). One of the methods of increasing the speed of automatic

control systems, as mentioned, is the method of compensating weakly damped components of the transient error component by means of communication with disturbing influence. The possibility of compensating the weakly damped components of the transient process is explained by the fact that, as can be seen from (12), the parameter τ_1 is included in the numerator of the transfer function. With the appropriate selection of this parameter, the weakly damping components of the transient process can be compensated, and therefore, the speed of the system is increased.

To increase the speed of the system, it is possible to make a decision to compensate for this weakly decaying component of the transient component of the error by connection devices with a disturbing influence.

The transient component of the error of the combined system $\Delta\omega_{PR\,K}(t)$ according to the roots of the characteristic equation of its closed part and the roots p_{2C} and p_{3C}, introduced by the perturbing connection (13), is described by the expression:

$$\Delta\omega_{PR\,K}(t)=A_1e^{p_1t}+A_2e^{p_2t}+A_{2C}e^{p_{2C}t}+A_{3C}e^{p_{3C}t}.$$

The initial value of the i-th component of the transient error component under a disturbing influence $\Delta\omega_C(p)=$ $=D_{\Delta\omega_C}(p)/F_{\Delta\omega_C}(p)$ is equal to:

$$A_i=\frac{D_{\Delta\omega_{PR}}(p_i)D_{\Delta\omega_C}(p_i)}{F'_{\Delta\omega_{PR}}(p_i)F_{\Delta\omega_C}(p_i)}. \quad (14)$$

For the case of a change in influence according to the law of a unit step function:

$$\Delta\omega_C(t)=1,\ \Delta\omega_C(p)=\frac{1}{p}=\frac{D_{\Delta\omega_C}(p)}{F_{\Delta\omega_C}(p)}, \quad (15)$$

where $D_{\Delta\omega_C}(p)=1$, $F_{\Delta\omega_C}(p)=p$. $F_{\Delta\omega_C}(p)$ is described:

$$A_i=\frac{a_0p_i^4+a_1p_i^3+a_2p_i^2+a_3p_i}{4b_0p_i^3+3b_1p_i^2+2b_2p_i+b_3p_i}\cdot\frac{1}{p_i}=$$
$$=\frac{a_0p_i^3+a_1p_i^2+a_2p+a_3}{4b_0p_i^3+3b_1p_i^2+2b_2p_i+b_3p_i}. \quad (16)$$

Thus, the synthesis of the open compensating connection with the disturbing influence of the combined AFA system is performed in accordance with the condition of reducing dynamic, root mean square errors (the condition of the transformation of the static AFA system into a system with first-order astatism) and the condition of increasing the speed (compensation of the slowly decaying components of the transient process).

As for the system with the principle of deviation control, it is possible to determine the established dynamic errors of the combined system with step, linear and quadratic laws of change of disturbing influences:

$$\Delta\omega_C(t)=\omega_0\cdot 1(t),\ \Delta\omega_C(t)=\omega_0+\omega_1t,$$

$$\Delta\omega_C(t)=\omega_0+\omega_1t+\omega_2t^2.$$

The error of the combined system) is determined by the expression:

$$\Delta\omega_{PRK}(p)=K_{\Delta\omega_{PR}}(p)\Delta\omega_C(p). \quad (17)$$

Fixed a dynamic error $\Delta\omega_{PRK}(p)$ of the combined system according to the theorem of operational calculation about the final value of the function is equal to:

$$\Delta\omega_{PRK}(t)=\lim_{p\to 0}p\,\Delta\omega_{PRK}(p). \quad (18)$$

If the disturbing influence varies according to a linear law $\Delta\omega_C(t)=\omega_0+\omega_1t$, then an error in the regime will have a disturbing effect $\Delta\omega_C(p)=\omega_0/p+\omega_1/p^2$:

$$\Delta\omega_{PRK}(t)=\lim_{p\to 0}p\frac{a_0p^4+a_1p^3+a_2p^2+a_3p}{b_0p^4+b_1p^3+b_2p^2+b_3p+b_4}\times$$
$$\times\left[\frac{\omega_0}{p}+\frac{\omega_1}{p^2}\right]=\frac{0_3}{b_4}\omega_1, \quad (19)$$

thus, instead of a growing error in a system with the principle of control by deviation, in a combined system the speed error has a finite value.

When the disturbing influence changes according to the quadratic law $\Delta\omega_C(t)=\omega_0+\omega_1t+\omega_2t^2$, whose description looks like $\Delta\omega_C(p)=\omega_0/p+\omega_1/p^2+2!\omega_2/p^3$, the error in the set mode is equal to:

$$\Delta\omega_{PRK}(t)=\lim_{p\to 0}p\frac{a_0p^4+a_1p^3+a_2p^2+a_3p}{b_0p^4+b_1p^3+b_2p^2+b_3p+b_4}\times$$
$$\times\left[\frac{\omega_0}{p}+\frac{\omega_1}{p^2}+\frac{2!\omega_2}{p^3}\right]=\infty, \quad (20)$$

thus, in the combined AFA system, as well as in the system with the principle of deviation control [7], the error in the set mode tends to infinity.

The transfer function of the connection with the disturbing influence of $K_C(r)$ is synthesized according to the condition of transformation of the static system of the AFA into a system with first-order astatism (parameter k_C) and the condition of increasing speed (parameter) system.

As shown in the work [8], the value of the coefficient when the first derivative of the perturbing automatic control system, synthesized according to the condition of increasing the order of astatism of the system, is equal to the optimal value τ_{1OPT}, at which the root mean square deviation (RMS) takes the minimum value. (This provision is also valid for the case of the synthesis of communication parameters with disturbing influence). The value of RMS under random disturbing influence is described by the expression:

$$K_{\Delta\omega_{PRK}}(p)=\frac{\Delta\omega_{PR_K}(p)}{\Delta\omega_C(p)}=\frac{a_0p^4+a_1p^3+a_2p^2+a_3p}{b_0p^4+b_1p^3+b_2p^2+b_3p+b_4}. \quad (21)$$

As in the case of determining the RMS of a system with the principle of deviation control [3, 8, 10–15], the spectral density of the disturbing influence $\Delta\omega_C(t)$ is equal to:

$$S_{\Delta\omega_C}(\omega)=\frac{1}{\omega^2+\beta^2},\ \text{where } \beta=1. \quad (22)$$

The spectral density of the error of the combined system:

$$S_{\Delta\omega_{PR}}(\omega)=\left|K_{\Delta\omega_{PR}}(j\omega)\right|^2S_{\Delta\omega_C}(\omega), \quad (23)$$

where $K_{\Delta\omega_{PR}}(j\omega)=K_{\Delta\omega_{PR}}(p)|_{p=j\omega}$ is the complex transfer function of the combined system.

The spectral density of the error of the combined system:

$$S_{\Delta\omega_{PR}}(\omega)= =\left|\frac{a_0(j\omega)^4+a_1(j\omega)^3+a_2(j\omega)^2+a_3(j\omega)}{b_0(j\omega)^4+b_1(j\omega)^3+b_2(j\omega)^2+b_3(j\omega)+b_4}\right|^2\frac{1}{\omega^2+\beta^2}. \quad (24)$$

The average value of the square of the error is equal to:

$$\overline{\Delta\omega_{PR}^2}=\frac{1}{2\pi}\int_{-\infty}^{\infty}S_{\Delta\omega_{PRK}}(\omega)\,d\omega=\frac{1}{2\pi}\times \times\int_{-\infty}^{\infty}\left|\frac{a_0(j\omega)^4+a_1(j\omega)^3+a_2(j\omega)^2+a_3(j\omega)}{b_0(j\omega)^4+b_1(j\omega)^3+b_2(j\omega)^2+b_3(j\omega)+b_4}\right|^2\frac{1}{\omega^2+\beta^2}d\omega, \quad (25)$$

where

$a_0=10^{-9}$; $a_1=0.00000171$;
$a_2=0.00040688$; $a_3=0.020976$;
$b_0=10^{-9}$; $b_1=0.00000171$; $b_2=0.000825$;
$b_3=0.12$; $b_4=5$; $\beta=1$.

Bringing formula (25) to tabular form:

$$\overline{\Delta\omega_{PR}^2}=\frac{1}{2\pi}\times \times\int_{-\infty}^{\infty}\frac{d_0(j\omega)^8+d_1(j\omega)^6+d_2(j\omega)^4+d_3(j\omega)^2}{\left|c_0(j\omega)^5+c_1(j\omega)^4+c_2(j\omega)^3+c_3(j\omega)^2+c_4(j\omega)+c_5\right|^2}d\omega=I_5, \quad (26)$$

where

$d_0=a_0^2=1\cdot10^{-18}$;
$d_1=-(a_1^2-2a_0a_2)=-2.11034\cdot10^{-12}$;
$d_2=a_2^2-2a_1a_3=9.3813414\cdot10^{-8}$;
$d_3=-a_3^2=0.0004399926$; $d_4=0$;
$c_0=b_0=1\cdot10^{-9}$; $c_1=b_0+b_1=1.711\cdot10^{-6}$;
$c_2=b_1+b_2=8.267\cdot10^{-4}$; $c_3=b_3+b_2=0.121$;
$c_4=b_4+b_3=5.12$; $c_5=5$.

The value of the tabular integral [16]:

$$\overline{\Delta\omega_{PR}^2}=I_5=\frac{(-1)^{5-1}M_5}{2\,c_0\,\Delta_5}, \quad (27)$$

where

$$\Delta_5=\begin{vmatrix}c_1 & c_3 & c_5 & 0 & 0\\ c_0 & c_2 & c_4 & 0 & 0\\ 0 & c_1 & c_3 & c_5 & 0\\ 0 & c_0 & c_2 & c_4 & 0\\ 0 & 0 & c_1 & c_3 & c_5\end{vmatrix}=3.591479;$$

$$M_5=\begin{vmatrix}d_0 & d_1 & d_2 & d_3 & d_4\\ c_0 & c_2 & c_4 & 0 & 0\\ 0 & c_1 & c_3 & c_5 & 0\\ 0 & c_0 & c_2 & c_4 & 0\\ 0 & 0 & c_1 & c_3 & c_5\end{vmatrix}=1.575268.$$

The RMS of the combined system is equal to:

$$\varepsilon_K=\sqrt{\Delta\omega_{PRK}^2}=\sqrt{0.002193}=0.04683. \quad (28)$$

According to the formula, the RMS of the existing static system of the AFA with the principle of control with deviation $\varepsilon=0.177$, so thanks to the introduction of an open connection of the disturbing influence, synthesized in accordance with the condition of transformation of a static system into an astatic system with first-order astatism and compensation of a weakly decaying transient error component, it was possible to reduce the RMS by 3.78 times.

3.3. Discussion of the results. The limitations of the mentioned research should be considered the need to have the necessary computing power of the radio-receiving equipment and the initial radio-electronic environment of the operational area.

The advantages of the proposed system of AFA are:
– increased efficiency of frequency adjustment depending on the type of signal, which is accepted not only in the case of changes in the disturbing influence according to deterministic laws, but also in the case of random disturbing influence, compared to the well-known AFA;
– increased dynamic accuracy of the AFA system compared to known ones;
– fixed bug $\Delta\omega_{PR}(t)$ is completely fixed with a gradual change $\Delta\omega_C(t)$;
– the limitation of the final values of the growing root mean square error, with the linear law of change of the disturbing influence by 3.78 times and the time of the transition process is reduced by 3 times.

The direction of further research should be considered the further development of the structural-parametric synthesis of the AFA system in order to reduce the number of shortcomings and limitations of its application.

4. Conclusions

The essence of the obtained result is to obtain new analytical dependencies that form a mathematical model of a combined frequency autotuning system with first-order astatism. Based on the results of the development, a mathematical model of the combined system of automatic frequency tuning with astatism of the first order is proposed.

The differences between the proposed mathematical model are:
– increased efficiency of frequency adjustment depending on the type of signal, which is accepted not only in the case of changes in the disturbing influence according to deterministic laws, but also in the case of random disturbing influence, compared to the well-known AFA;
– increased dynamic accuracy of the AFA system compared to known ones;
– fixed bug $\Delta\omega_{PR}(t)$ is completely fixed with a gradual change $\Delta\omega_C(t)$;
– the limitation of the final values of the growing root mean square error, with the linear law of change of the disturbing influence by 3.78 times and the time of the transition process is reduced by 3 times.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal,

ISSN 2664-9969

authorship or otherwise, that could affect the study and its results presented in this paper.

Financing

The research was conducted without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm they did not use artificial intelligence technologies while creating the presented work.

References

1. Yahya, A., Sidek, O., Mohamad-Saleh, J. (2008). Performance analyses of fast frequency hopping spread spectrum and jamming systems. *The International Arab Journal of Information Technology, 5,* 115–119.
2. Perez-Solano, J. J., Felici-Castell, S., Rodriguez-Hernandez, M. A. (2008). Narrowband Interference Suppression in Frequency-Hopping Spread Spectrum Using Undecimated Wavelet Packet Transform. *IEEE Transactions on Vehicular Technology, 57 (3),* 1620–1629. https://doi.org/10.1109/tvt.2007.909306
3. Lavaud, C., Gerzaguet, R., Gautier, M., Berder, O., Nogues, E., Molton, S. (2020). Towards Real Time Interception of Frequency Hopping Signals. *2020 IEEE Workshop on Signal Processing Systems (SiPS)*. https://doi.org/10.1109/sips50750.2020.9195246
4. Sârbu, A., Şorecău, M., Şorecău, E., Bechet, P. (2023). Frequency hopping signals tracking and sorting algorithm for military radio networks. *2023 International Symposium on Electromagnetic Compatibility – EMC Europe*. https://doi.org/10.1109/emceurope57790.2023.10274264
5. Artemev, V. M. (1984). *Spravochnoe posobie po metodam issledovaniia radioelektronnykh slediashchikh sistem.* Vyshei, shk., 168.
6. Hokov, O. M. (2022). *Fizychni osnovy tekhnichnykh zasobiv rozvidky.* Kharkiv: KhNEU im. S. Kuznetsia, 255.
7. Zaitcev, G. F. (1989). *Teoriia avtomaticheskogo upravleniia i regulirovaniia.* Kyiv: Vishcha shk., Golovnoe izd-vo, 431.
8. Zaitcev, G. F., Steklov, V. K. (1978). *Kombinirovannye slediashchie sistemy.* Kyiv: Tekhnika, 264.
9. Smirnov, Yu. O. (2009). *Osnovy radioelektronnoi rozvidky. Chastyna 1. Rozviduvalno-informatsiinyi protses, osnovni modeli systemy RER efektyvnist i napriamy yii podalshoho rozvytku.* Kyiv: NDI HUR MO Ukrainy, 155.
10. Levchenko, O. V., Fedotov, B. M. (2006). *Systemy i kompleksy radioelektronnoi rozvidky.* Kyiv: NAOU.
11. Pampukha, I. V., Buryi, S. V., Pusan, V. V. (2017). Analiz suchasnykh avtomatychnykh system monitorynhu radio prostoru na bazi SDR tekhnolohii dlia vedennia zavdan radioelektronnoi rozvidky. *Zbirnyk naukovykh prats Viiskovoho instytutu Kyivskoho natsionalnoho universytetu imeni Tarasa Shevchenka, 56*, 40–46.
12. Okhramovych, M. M., Shevchenko, V. V., Kravchenko, O. I. (2018). Analiz sposobiv vedennia monitorynhu radioprostoru za dopomoho SDR tekhnolohii. *Zbirnyk naukovykh prats Viiskovoho instytutu Kyivskoho natsionalnoho universytetu imeni Tarasa Shevchenka, 59,* 37–45.
13. Rembovskii, A. M., Ashikhmin, A. V., Kozmin, V. A.; Rembovskii, A. M. (Ed.) (2010). *Radiomonitoring – zadachi, metody, sredstva*. Goriachaia lin. – Telekom, 624.
14. Slobodianiuk, P. V., Blahodarnyi, V. H., Stupak, V. S.; Slobodianiuk, P. V. (Ed.) (2008). *Dovidnyk z radiomonitorynhu*. Nizhyn: Aspekt – Polihraf, 588.
15. Stupak, V. S., Dolmatov, S. O.; Oliinyk, V. F. (Ed.) (2004). *Osnovy radiochastotnoho kontroliu.* Kyiv: Feniks, 231.
16. Slobodianiuk, P. V., Narytnyk, T. M., Blahodatnyi, V. H., Saiko, V. H., Bulhach, V. L.; Kryvuts, V. H. (Ed.) (2012). *Teoriia i praktyka upravlinnia vykorystanniam radiochastotnoho resursu.* Kyiv: DUIKT, 586.

✉***Serhiy Hatsenko,*** *PhD, Associate Professor, Deputy Head, Department of Intelligent, The National University of Defense of Ukraine, Kyiv, Ukraine, e-mail: verb288097@proton.me, ORCID: https://orcid.org/0000-0002-0957-6458*

Ivan Vasylyaiko, *PhD Student, The National University of Defense of Ukraine, Kyiv, Ukraine, ORCID: https://orcid.org/0009-0000-2521-4919*

Dmytro Burlak, *Senior Researcher, Research Department, Military Intelligence Research Institute, Kyiv, Ukraine, ORCID: https://orcid.org/0009-0006-7522-1539*

✉*Corresponding author*