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Methodology for the Development of Radar Control Systems for Flying Targets with an Artificially Reduced RCS

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***Abstract*—The article explores methods for detecting and tracking air targets in radar with an artificially reduced radar cross-section (RCS). A technique for control the radar antenna system using an adaptive method is presented, which is based on adapting the system to the conditions of information uncertainty due to fluctuations in the excitation signal of the radar target's radar-absorbing coating. Known methods of radar aircraft (active and passive, which do not take into account the structure of the coating of the aircraft) do not allow obtaining information about an air target with an artificially reduced RCS. The main contribution of this article is the development of radar and control methods based on the resonant frequency-phase interaction of the microwave electromagnetic field with the crystal structure of the radar absorbing coating of the aircraft. The stages of antenna system control based on the "frequency-phase detection method", "passive-active" tracking method, and "adaptive method" of antenna control have been studied. To test the proposed methods, an experiment was conducted to determine the transient process in the control system under conditions of information uncertainty. As a result of the experiment, the probability of tracking the target is increased by 14-19%. The findings will be useful for developers of radar and control systems for modern air facilities with an artificially reduced RCS.**

Keywords—Control; Unmanned Aerial Vehicles; Radar Cross-Section; Fuzzy Control; Adaptive Control

I. INTRODUCTION

The capabilities of the radar to obtain direction finding information about aircraft with ultra-low Radar Cross-Section (RCS) are limited due to small geometric dimensions and equivalent surface scattering, high flight speeds, and difficulties in detection active radar data and tracking [1], [2]. These are the global trends in the impact of the development of technology for the creation and use of composite materials. According to the analysis in [3] of the prospects for the development of aviation, the most urgent tasks for radar facilities are the identification of aircraft with an artificially reduced RCS and small objects that make up the main arsenal of manned, unmanned aerial vehicles (UAV) [4], [5].

The paper [6] presents the results of the direction-finding technique and the determination of RCS based on the determination of the echo power, but the control techniques are not considered in detail. In [7], the methods for reducing in-band RCS for automotive radars were considered; the features of the frequency-phase method were not covered in detail. Article [8] proposes a new radar technique based on monitoring the phase-frequency instability of signals, circuitry, a mathematical description is given, but the features of radar absorbing materials were not described. A description of new trends in the design of millimeter-wave radars is presented in [9], and a performance metric for RCS estimation based on random models is introduced. However, the circuitry of automatic and intelligent radar control has not been studied. Mathematical description of control systems for phased antenna arrays is given in [10], [11]. An analysis of the main characteristics of the quality of control systems is presented. However, no emphasis was placed on the types of radar-absorbing materials of modern aircraft [12], [13].

That is, a problematic situation has been created, the main difficulty of which lies in the insufficient compliance of the capabilities of existing radars with the conditions for detecting and taking aircraft for escort [14]. The use of aviation is characterized by a high level of sudden change in the situation, speed and dynamism, forecasting difficulties and a wide change in the scale of flights [15]. This provision gives rise to the specifics of obtaining radar information about aerodynamic objects with an artificially reduced RCS, necessitates the development of new radar systems (RS) for target localization in distributed hybrid non-coherent active-passive radar networks [16], [17] and effective control [18] - [20]. Given the above, it can be argued that it is necessary to radically increase the efficiency of RS in the face of the need to obtain information about aircraft with an artificially reduced RCS.

To do this, the radar system in the process of its improvement should be considered as a set of interconnected systems for detecting and tracking aircraft, control algorithms for multirotor aerial systems [21] - [23]. From such an initial concept, the methodology of radar system synthesis acquires full specificity - ensuring an increase in the efficiency of functioning of both each subsystem of the station and the entire control system [24] - [26]. The existing radar synthesis methodology in the world assumes a consistent connection between such subsystems as detection, tracking of objects [27] - [29]. Existing control systems are not focused on obtaining radar information about aircraft with an artificially low RCS and do not have theoretically substantiated methods by which subsystems would function for each stage [30] - [32]. The patterns of links between tracking errors and their sources necessitate a joint analysis of errors in measuring coordinates and their sources and the influence of error components on the results of radar operation in detecting aircraft with an artificially reduced RCS. It is these topical issues that are considered in the article. To improve the efficiency of radar for air targets, the article proposes an adaptive method for controlling the antenna system, and presents a mathematical description of the control system. The article provides a rationale for the recommendations for improving the control system of the radar for tracking radar targets with an artificially reduced RCS.

II. Method for Improving the Radar for Detecting and Tracking Air Targets

A. *The Structure of the Resonant Radar Feed*

The method is based on radiation in a packet of probing signal pulses. The carrier frequency is a multiple of the frequency of natural oscillations of the atoms of the crystal structure of the radar-absorbing radar coverage of the target with an artificially reduced RCS (Fig. 1). Reception of a carrier frequency signal information about the target is carried out in the frequency band of the occurrence of the overtone, that is, the excitation signal. The target track is tied and the coarse coordinates are measured using the measured and estimated coordinates. The implementation of the frequency-phase method is proposed with the help of a resonant feed of the radar for detecting and tracking radar targets, the structure of which is similar [5].

A feature of this device is that a sample of the base substance of the radar absorbing material is placed in the radar waveguide line. During the channeling of the probing signal from the transmitter to the opening of the antenna, the sample is excited and the signal is emitted with sufficient parameters to excite such a radar-absorbing material for the coating of the aircraft [33].

The main element of such a radar is a resonant irradiator, which, due to the multichannel structure, will provide the necessary resonant radiation power to achieve resonant excitation of the air target coating. Tracking and control of radar targets is carried out on the basis of a passively active method. The passive-active method of tracking radar targets makes it possible to carry out direction-finding of targets using a resonant excitation signal from a radar-absorbing coating in a passive mode at an overtone frequency due to irradiation of the radar active channel by a probing signal. This method is based on the joint functioning of passive and active means (Fig. 1).

The joint functioning of active passive tracking channels presupposes their subsequent use. The passive channel receives the excitation signal and carries out tracking of an air target with an artificially reduced RCS or searching for a target in a responsible sector using an active channel that emits a resonant signal and locking on target tracking with a passive channel. In this case, two modes of operation are possible: when the time of viewing the space by the active channel is equal to the time of viewing by the passive channel of the tracking radar - that is, synchronous mode, and when the time of viewing the airspace by the corresponding channels does not match - non-synchronous mode. A feature of the passively active method of tracking air targets with an artificially reduced RCS [34] is that passive means cannot measure the range to the target, but only measure the angular coordinates. Therefore, range tracking is offered by listing estimates, since the range to the target is a function of the angular coordinates and a rough measure of the range to the target of the detection radar.

B. *Development of a Frequency-Phase Method for Monitoring Radar Targets with an Artificially Reduced RCS*

At the first stage of location, it is proposed to use a frequency-phase method for detecting radar targets with an artificially reduced RCS. Passive means inspect the controlled space and detect air targets. The active channel of the radar is switched on with radiation at separate time intervals. In this case, the joint filtering of measurements of

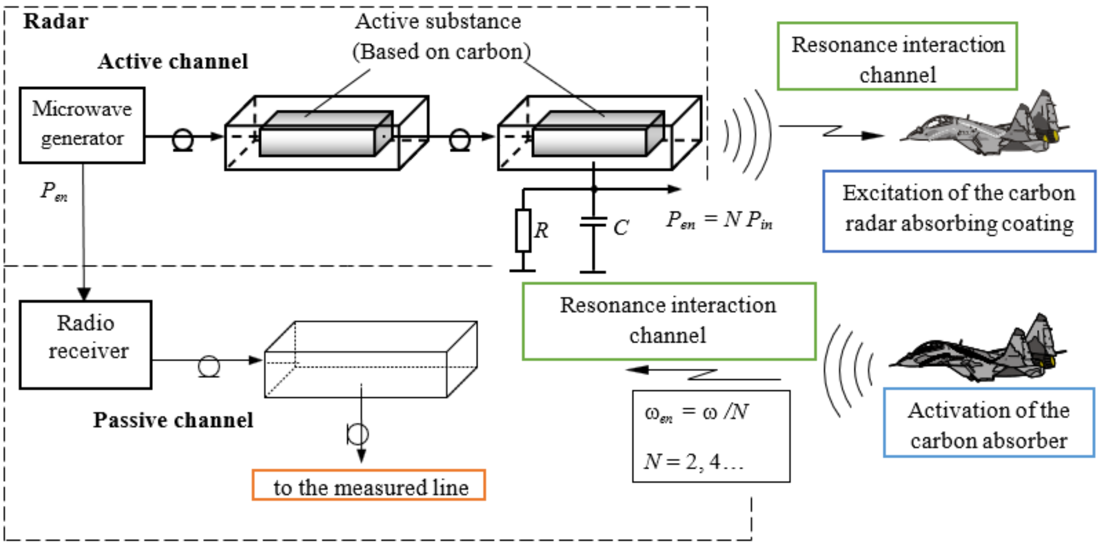

Fig. 1. The structure of the resonant feed radar detection and tracking of air targets

active-passive means and estimation of the parameters of the trajectories of radar targets with an artificially reduced RCS is relevant. Let us consider the possibility of estimating the trajectory parameters in the process of filtering measurements of active passive means of detecting and tracking an air target. Features of measurements of active and passive means determine the need to obtain estimates in the process of filtering the parameters of the trajectory of radar targets in the Cartesian coordinate system, and residuals in the spherical one.

The filtering equations of such a filter have the form

$$\hat{a}_k = \hat{a}_{k/k-1} + M_k\big(\theta_k - \hat{\theta}_{k/k-1}\big) \quad (1)$$

accuracy matrix

$$C_{\hat{a}_k} = (B_{k-1}C_{\hat{a}-1}^{-1}B_{k-1}^T)^{-1} + H_k^T C_{\theta_k} H_k \quad (2)$$

where $\hat{a}_k = \left\|\hat{a}_k^{(j)}\right\| = \begin{vmatrix} x \\ y \\ H \\ \dot{x} \\ \dot{y} \\ \dot{H} \end{vmatrix}$ is the vector of estimated parameters in a rectangular coordinate system with the origin at the active-passive system standing point; x, y, z, H is the current values of estimates the coordinates of the parameters the target trajectory and the rate of their change; $M_k = C_{\hat{a}_k}^{-1} H_k^T C_{\theta_k}$ is the filter gain; $C_{\hat{a}_k}^{-1}$ is the vector estimation error correlation matrix $\hat{a}_k$; C_{θ_k} is the vector precision matrix θ_k; $H_k = \left\| {\partial h_k^{(i)}}\Big/{\partial a_k^{(j)}} \right\|_{a_k=\hat{a}_{k/k-1}}$ is the recalculation matrix of the estimated vector $\hat{a}_k$ into the vector sample space θ_k; B_{k-1} is the forecast matrix; $\hat{a}_{k/k-1} = B_{k-1}\hat{a}_{k-1}$ is the extrapolated at t_k the moment of time the value the vector $\hat{a}_{k-1}$ of parameters the target trajectory, which is determined, into the space of vector parameters θ_k [35].

Using a filter of this type makes it possible to obtain an estimate of the parameters of the target's trajectory along the radar measurement vector. In the mode of operation of only the active radar - when receiving two measurements $(k = 1,2)$. In this case, the evaluation vector $\hat{a}_k$ at the time of obtaining the second measurement is in accordance with the expression

$$\hat{a}_2 = \begin{Bmatrix} x_2 = cos\,\varepsilon_2 \cos\beta_2 \\ y_2 = cos\,\varepsilon_2\, sin\,\beta_2 \\ H_2 = sin\,\varepsilon_2 \\ \dot{x}_2 = \dfrac{x_2 - x_1}{\Delta t} \\ \dot{y}_2 = \dfrac{y_2 - y_1}{\Delta t} \\ \dot{H}_2 = \dfrac{x_2 - x_1}{\Delta t} \end{Bmatrix} \quad (3)$$

where β_2 is the azimuth; ε_2 is the elevation angle.

In the mode of synchronous operation active-passive means, the filter is loaded as in the case of radar detection. In this case, both when loading the filter and when filtering measurements, the angular coordinates are refined in accordance with the maximum likelihood criterion. The maximum plausible value of the angular coordinates is determined according to the expression

- refined measurement vector

$$\theta_k^{'} = \frac{\theta_{k\text{rad}} C_{\theta_{k\text{rad}}}^{-1} + \theta_{k\text{pas}} C_{\theta_{k\text{pas}}}^{-1}}{C_{\theta_k^{'}}^{1}} \quad (4)$$

where are the active radar measurements at discrete times (t_k) are represented by a 3-D vector of measurements $\theta_{k\text{rad}} = \left\|\theta^{(i)}\right\|$; measurements of the passive agent at discrete times (t_n) are represented by a 2-D vector $\theta_{n\text{pas}}$.

- total correlation matrix of vector measurement errors $\theta_k^{'}$

$$C_{\theta_k^{'}}^{-1} = C_{\theta_{k\text{rad}}}^{-1} + C_{\theta_{k\text{pas}}}^{-1} \quad (5)$$

In the active-passive mode, with the synchronous operation of the active and passive channels of the detection radar, according to equations (4), (5), an updated vector with a correlation error matrix is formed. Next, the parameters of the measurement vector are filtered in accordance with equations (1), (2). The variance of the estimated range value is formed by linearizing the errors in the estimate of the extrapolated target coordinates (6).

The calculated value of the range r_{pas} and dispersion $\sigma_{r_{\text{pas}}}^2$ are found according to the expression of the form

$$r_{pas} = \sqrt{r^{e2} - d^2} \quad (6)$$

$$\sigma_{r_{pas}}^2 = \left(\frac{\partial r_{pas}}{\partial r^e}\right)^2 \sigma_{r^e}^2 + \left(\frac{\partial r_{pas}}{\partial d}\right)^2 \sigma_d^2 \quad (7)$$

where d is the distance from the point specified by the parameters of the extrapolated measurement vector to the beam directed at the target, specified by the measurement vector of the passive means

$$d = [(xm - yl)^2 + (yn - Hm)^2 + (Hl - xn)^2]^{1/2} \quad (8)$$

where x, y, H is the coordinates of the point specified by the extrapolated measurement $\hat{\theta}^e$ vector in a rectangular coordinate system; l, m, n is the direction cosines of the beam directed at the target, given by the vector of measurements θ_{pas}.

$$\begin{aligned} l &= cos\,\varepsilon_{pas}\, cos\,\beta_{pas} \\ m &= cos\,\varepsilon_{pas}\, sin\,\beta_{pas}; \\ n &= sin\,\varepsilon_{pas} \end{aligned} \quad (9)$$

$$\sigma_d^2 = \left(\frac{\partial d}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial d}{\partial y}\right)^2 \sigma_y^2 + \left(\frac{\partial d}{\partial H}\right)^2 \sigma_H^2 + \left(\frac{\partial d}{\partial l}\right)^2 \sigma_l^2 + \left(\frac{\partial d}{\partial m}\right)^2 \sigma_m^2 + \left(\frac{\partial d}{\partial n}\right)^2 \sigma_n^2 \quad (10)$$

where σ_d^2 is the distance dispersion.

III. Results and Discussion

A. Models of Control Systems

The conducted studies of the control system of the antenna-waveguide system indicated a decrease in the quality of the functioning of the control system. This was especially felt during the tracking of highly maneuverable targets (UAVs) with an artificially RCS in conditions of information uncertainty about the movement parameters. It is proposed to minimize the information uncertainty about the parameters of the target's movement on the basis of the implementation of functioning algorithms created using the mathematical apparatus of fuzzy sets [36]. The quality of functioning the antenna system control can be assessed by the probability of taking on target tracking, which depends on target designation errors.

On Fig. 2 and Fig. 3 shows the proposed radar control schemes. Fig. 2. structural diagram of the radar control, which implements the adaptive method of tracking an air target. On Fig. 3 a block diagram of control with a fuzzy logic controller is presented.

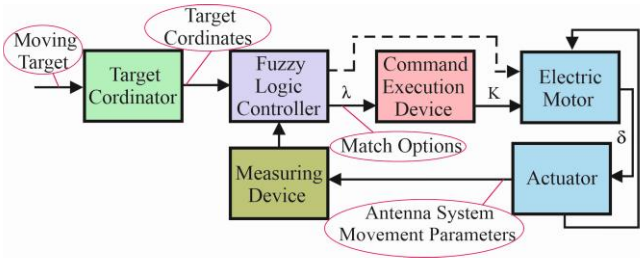

Fig. 2. Structural diagram of the radar control system that implements the adaptive tracking method

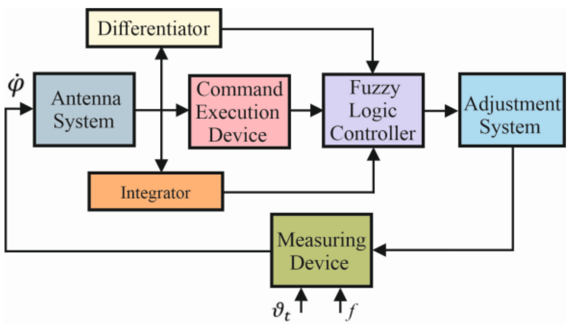

Fig. 3. Structural diagram of antenna control with a fuzzy logic controller

Capture for tracking radar targets with an artificially reduced RCS is proposed to be carried out based on the use of energy that is radiated from the target to the radar. Resonant excitation of the internal structure of the radio absorber is used. When the target is irradiated, the substance of the fuselage of the aircraft in the excited state emits the following types of energy: radar; thermal (infrared).

Artificial intelligence elements based on a fuzzy logic controller were introduced into the composition of the onboard radar computer to generate a correction signal and compensate for target tracking errors. Fuzzy logic is used here to formalize fuzzy concepts in terms of semantics and provide efficient processing of qualitative information at a level with clear, quantitative data.

The basis for the functioning of the decision-making block of the fuzzy control model "situation-action" is the principle of determining the system of productions necessary for a given incoming situation of control decisions [37]. The production system associates each situation S_i from a certain set of situations S_s, which characterizes all possible states of the control object, with some control decision. The situations included in the set Ss are reference. Unlike the set $S_s = \{S_1, S_2, \ldots S_N\}$ of typical situations, the set $S_s = \{S_1, S_2, \ldots S_n\}$ $(n <= N)$ of reference situations does not have fuzzy equals for a given threshold of equality of situations. This affects the reduction in the dimension of the productive system and does not reduce the effectiveness of the control model at the boundaries of reliability, which is limited by the threshold of equality. The control decision to be made in the incoming situation S_0 is determined by the situation $S_i \in S_s$, in a sense, the closest situation S_0. It is assumed that the set S_s is complete and the situation S_i is valid for any incoming situation S_0.

The operation of the Fuzzy Logic Controller (FLC) is based on the simulation of the operation of the device for generating control commands for the radar, for which the information received from the Target Coordinator (TC) on the parameters of the movement of an air target is used. Therefore, the specified block is included in the control model that simulates the work Command Execution Device (CED) when managing the object. The principal operation CED with elements of artificial intelligence - a logical controller (LR) is adequate to the operation of a nonlinearity operating in a sliding mode. The CED operation algorithm, built on the mathematics of fuzzy sets, makes it possible to continuously issue control commands according to previously defined thresholds according to the nature of the input actions, smoothly bringing antenna system (AS) to the radar boresight with an acceptable error and keeping it in it. This achieves a more stable target tracking process, which reduces the energy consumed in the antenna control loop.

One of the ways to improve the efficiency of radar targets with an artificially reduced RSC is to optimize the tracking process [38]. The solution of this problem is largely hampered by the information uncertainty of the target motion parameters, mainly due to the absorption of the radio signal and the complexity of the technical implementation of the obtained optimal control algorithms [39], [40]. The need to use the apparatus of fuzzy mathematics is due to the fact that under the conditions of information uncertainty of the state of the control object, it becomes impossible to describe the effects in the control system. Identification (determination) of situations is performed by the state evaluation block based on information about the angular velocity of the line of sight of the missile - an air target coming from AS. Comparing this information with the membership function allows you to determine the degree of conformity of the parameters of the estimated state.

The direction-finding characteristic of the radar has a spread due to the technological features of the manufacture of the random, the accuracy of measurements, as well as the difference in the conditions that occur in individual samples. In addition, we took into account errors from the bearing angles of an aerial target (ε, β). Between the nodal points, the ε, β values are interpolated to the current values after operator conversion

$$W_{\varepsilon,\beta} = \frac{p}{(1 + 0{,}063p) \cdot (1 + 0{,}025p)^2} \qquad (11)$$

The equation describes the approximate link of the bearing error at the AS output and the optimal angular velocity of the line of sight at the AS output. The accuracy of setting the error at the nodal points was ±5%. The obtained value of the uncompensated steepness of the direction-finding characteristic AS after the introduction of the compensation function was for the radar tracking ± 0.02 and ± 0.025.

The signal by which the sign of the steepness of the direction-finding characteristic is determined was fed through a filter (W_F) from the radar receiving system

$$W_F = \frac{p^2}{(1 + 0{,}2p) \cdot (1 + 0{,}1p)^2} \qquad (12)$$

On the fuzzy logic controller, if the signs of the signals at the filter input (W_F) coincide, artificial negative feedback is connected, and if there is a divergence, positive feedback is connected.

We used the adaptive control method AS, when the contour movement is adapted to the conditions of information uncertainty about the parameters of the target movement by adjusting the direction, speed and acceleration of the direction change to the radar target. The principle of generating control commands to the AS radar power drive is that the target is kept within the allowable dynamic tracking error by damping fluctuation emissions when radar information is interrupted.

Analytical interpretation the adaptive method of functioning the AS control system when tracking an air target with an artificially reduced RCS was represented by the equation

$$\varphi_c = K_1\, \varphi_{tar} + (N \pm K_2)\dot{\varphi}_{tar} t + K_3 \ddot{\varphi}_{tar} \frac{t^2}{2} \qquad (13)$$

where φ_c is the bearing angle; φ_{tar} is the air target angular velocity; N is the coefficient of proportionality; t is the tracking time; K_n is the adaptive coefficients.

In the diagram in Fig. 3, the function of determining the bearing and angular acceleration of the air target was performed by the integrating and differential links, respectively.

B. Operation of Control Systems

During the study, the target maneuver was predicted from the measured values of the angular velocity of the radar-target line of sight. In this case, the target maneuver, in fact, a continuous function, was divided into seven levels, due to fluctuating measurement errors. In this system, an unambiguous conclusion is not given on the actual data, but fuzziness is introduced, expressed by the reliability indicator for each level through the corresponding membership function. We have described it above.

After determining the pointers corresponding to the current state of the control object, that is, having a reference fuzzy situation as a truth condition, a fuzzy situation is determined into which the control object passes under the influence of given control decisions. To do this, the composition of the current fuzzy situation and fuzzy relations is performed that describe control decisions in the found pointer and are implemented in the computing unit of the radar. Next, the difference between the quantitative values of the attributes and the current situation is determined, which sets the quantitative changes in the values of the attributes of the current situation necessary for the transition. The model of adaptive control algorithms implemented in the tracking radar control system has the form

R_1: *if* | φ_a = *PB, then P=*<u>$f(K_1,K_2,K_3)$</u> *and F*=3;

R_2: *if* | φ_a = *PM, then P=*<u>$f(K_1,K_2,K_3)$</u> *and F*=2;

R_3: *if* | φ_a = *PN, then P=*<u>$f(K_1,K_2,K_3)$</u> *and F*=1;

R_4: *if* | φ_a= *N, then P=*<u>$f(K_1,K_2,K_3)$</u> *and F*=0;

R_5: *if* | φ_a = *NN, then P=*<u>$f(K_1,K_2,K_3)$</u> *and F*=-1;

R_6: *if* | φ_a = *NM, then P=*<u>$f(K_1,K_2,K_3)$</u> *and F*=-2;

R_7: *if* | φ_a = *NB, then P=*<u>$f(K_1,K_2,K_3)$</u> *and F*=-3;

where $P = f(K1, K2, K3)$ is the flight adaptation function; F is the control system status indicator.

To implement the obtained pointers, control decisions are set, according to the conditions of target tracking. To solve the problems of adapting the AS control system to tracking conditions, we investigated the possibility of changing the initial state of the homing system to achieve the required quality of antenna control. The purpose of the experiment was to form the necessary transient process of the AS control system under conditions of information uncertainty. The research order is as follows. Based on the equations of dynamics of control systems AS [10], a system of differential equations was formed in matrix form

$$\frac{d}{dt}X(t) = -X(t)A(t) - A(t)^T X(t) - Q1 + X(t)B(t)Q2^{-1}B(t)^T X(t)^T \qquad (14)$$

The constants and initial conditions for the study were set.

A matrix of adaptive coefficients (Z) was formed and substituted into the resulting system of differential equations. We found the vector function $X(t)$ and the function U_{opt} of the command to control a complex system. On Fig. 4. presents a graphical representation of the resulting change in the vector function $X(t)$. On Fig. 5 the form of the obtained dependence of the guidance system control commands (U_{opt})

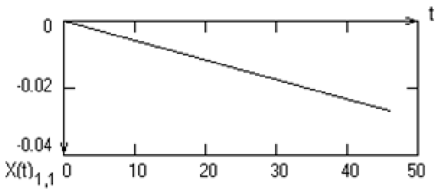

Fig. 4. Distribution dependence of adaptive control coefficients

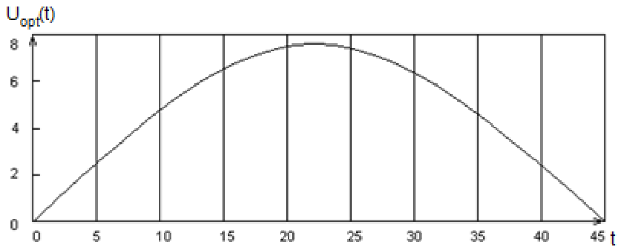

Fig. 5. System control command function graph ($U_{opt}(t)$)

The transient process of the AS control system obtained, necessary under the given conditions, is shown in Fig. 6.

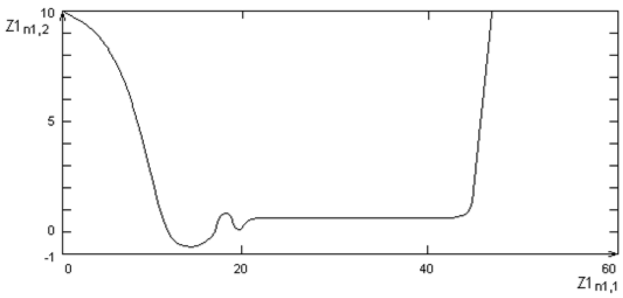

Fig. 6. Calculated transient process of the AS control system

The oscillogram of the detected signal, obtained during the study of an air target with a low RCS, is shown in Fig. 7. It shows the presence of an additional signal in the periodic sequence of radio pulses, which indicates the activation of the radio absorbing material at the resonant frequency.

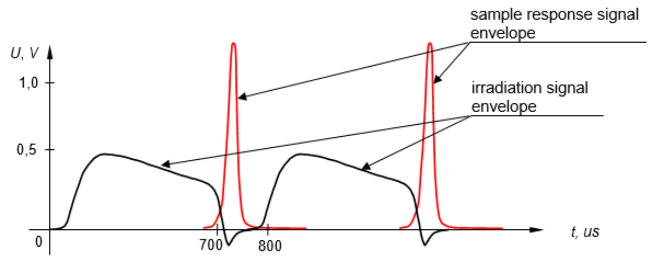

Fig. 7. Oscillogram of the detected signals at the output of the measuring line (see Fig. 1)

C. Discussion

For the first time, the possibility of obtaining radar information about an air target with an artificially reduced RCS has been experimentally established. In contrast to the known methods for improving the efficiency of radar, it is implemented on the basis of the radar frequency-phase detection method, the passive-active tracking method and the adaptive method of functioning of the antenna control system. A new property of radio-absorbing materials of aircraft has been established - the formation of an excitation signal under the action of resonant microwave radiation. The strength of the results is that structural and functional schemes of a radar irradiator for detecting and tracking aircraft with an artificially reduced RCS have been developed, and statistical characteristics of the increase in radar efficiency have been calculated. Research is needed on comparative technical and economic assessments according to the selected criteria and indicators of the developed methods.

Future studies will consider plotting low RCS aircraft detection; distribution of aircraft by losses; determining the probability of detection from a distance to aircraft by RCS; constructing an envelope for the detection zone of aircraft in a vertical plane.

IV. Conclusions

The article substantiates the possibility of technical improvement radar detection, tracking of radar targets in accordance with the proposed methods of radar for air targets with artificially reduced RCS. This will make it possible to obtain radar information due to the resonant excitation signal of the radar-absorbing coating of the radar target.

The article proposes an improved structure of the tracking radar antenna control system, which ensures the implementation of the developed adaptive control method AS. On the basis of FLC, an adaptive method for controlling a radar antenna is implemented to track a radar target with an artificially reduced RCS under conditions of informational uncertainty of its movement parameters.

The method of adapting the AS control system to tracking conditions made it possible to increase the probability of tracking a radar target with an artificially reduced RSC by 14–19% and increase the depth of its search zone to 100 km. The maximum value of the bearing error for the antenna control loop did not exceed 30 arcsec (the slope of the bearing error in the turn plane AS is optimal, if not more than 0.04 rad/s when averaging over a section of 0.01 degrees and in a sector of 2.50 degrees). It is advisable to detect and track air targets with an artificially reduced RCS based on the integrated use of both an active transmitting channel capable of generating a resonant radio signal and a passive radar control channel capable of receiving excitation signals from an absorbent coating in the appropriate frequency range.

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