International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 13, Issue 9 [September. 2024] PP: 457-462

Research Into Uav Control Methods Aims To Reduce The Likelihood Of Interception By Air Defense Missile Systems

Minh Tuyen Vu[1]
[1] *Vietnam Air Defense - Air Force Academy,*
Corresponding Author Email: Vuminhtuyen11091979@gmail.com

Abstract: *The article presents the results of studies on the evaluation of methods for reducing the interception probability for unmanned aerial vehicles using the RM-5V27 target missile as an example. A modified trajectory control algorithm is proposed to overcome the kill zones of anti-aircraft missile systems. The results of numerical modeling of interception of target missiles by the S-125M system during their implementation of various trajectories are presented. The system was developed in 1970 and is currently decommissioned. The influence of the target missile motion parameters on the miss of an anti-aircraft guided missile is considered. For the most objective study of this algorithm, an interception model with two S-125M systems located at a distance from each other is used. The conditional interception probability is considered as the main parameter for evaluating the effectiveness of target motion algorithms. This parameter is defined as the ratio of the integral time of the conditional interception on the trajectory to the total flight time along this trajectory..*

Keywords: *Target missile, Kill zone, Proportional guidance method, Anti-missile maneuver, Interception.*

Date of Submission: 14-09-2024 Date of acceptance: 29-09-2024

I. Introduction

Historical experience of recent decades shows that in local military conflicts, the use of air attack weapons by the opposing sides comes to the forefront, largely predetermining the outcome of the entire operation.In this regard, the development of air defense systems (AD) dictates a number of tasks in the creation of guided high-precision weapons and strike unmanned aerial vehicles (UAVs). Here, one of the main tasks is to increase the probability of UAVs overcoming enemy air defense systems.

Based on the analysis of materials carried out in works [1], the solution to this problem is associated with the implementation of technical measures in two main areas:

- The use of false targets and reduction of the signal characteristics of UAVs;
- The formation and implementation of trajectories of a special type of UAV.

The use of false targets and reduction of the signal characteristics of UAVs is aimed at complicating the detection and capture of automatic tracking of UAVs by an air defense radar station. The second direction is of greatest scientific interest to the authors of this work. Formation of UAV trajectories of a special type is aimed at avoiding the UAV from meeting with an anti-aircraft guided missile (SAM) and is performed after its launch (the "snake" maneuver); exclusion (maximum reduction) of a section of the UAV trajectory in the zone of destruction of an anti-aircraft missile system (SAM). This paper presents the results of numerical modeling for the study of these UAV control methods aimed at reducing the probability of their interception by an SAM

II. Content

The problem of intercepting a maneuvering aerial target with the V-601P SAM of the S-125M Neva-M SAM system, which is currently decommissioned, is considered. In accordance with work [2], the RM-5V27 (V-601P) target missile was selected as a UAV (air target simulator). The appearance of the V-601P missile is shown in Fig. 1. The aerodynamic and flight-technical characteristics of the V-601P were obtained based on the materials of the draft design [3]. The missile consists of two stages: a booster that is separated in flight and a cruise stage. When modeling the dynamics of motion, it is conventionally assumed that the target missile (TM) has an onboard command and software device that determines its angular and spatial position, and also generates the necessary control signals. Calculations of the trajectories of the SAM and RM movement are carried out under the following provisions and assumptions:

- The movement of the control objects (CO) is considered in the normal earth (starting) coordinate system (NECS), which is assumed to be inertial;
- The atmospheric parameters correspond to GOST 4401–81 “Standard Atmosphere. Parameters”, there is no wind;
- The rotation of the Earth and its surface curvature are not taken into account;

- The CO moves as a material point;
- There are no cross-links in the pitch and yaw channels;
- Balancing occurs instantly;
- The CO is stabilized by roll;
- The coordinates of the location of the S-125M SAM for the RM are known in advance;
- The influence of the radio horizon when overcoming the S-125M SAM is not considered.

The motion of the control unit is described by a system of differential equations

$$
\begin{aligned}
&m\frac{dV}{dt} = P\cos\alpha\cos\beta - C_{xa}S\frac{\rho V^2}{2} - mg\sin\Theta;\\
&mV\frac{d\Theta}{dt} = P\sin\alpha + C_{ya}S\frac{\rho V^2}{2} - mg\cos\Theta;\\
&-mV\cos\Theta\frac{d\Psi}{dt} = -P\cos\alpha\ \sin\beta + C_{za}S\frac{\rho V^2}{2};\\
&\frac{dx_g}{dt} = V\cos\Theta\cos\Psi;\\
&\frac{dy_g}{dt} = V\sin\Theta;\\
&\frac{dz_g}{dt} = -V\cos\Theta\sin\Psi;\\
&\frac{dm}{dt} = f(t\ )
\end{aligned}
$$

Here and below the following notations are used:
V- ground speed of the CO (in the considered formulation of the problem, the air and ground speeds coincide);
P- thrust;
Θ, Ψ — angles of inclination of the trajectory and path;
x_g, y_g, z_g — coordinates of the center of mass in the NZSK;
α, β — angles of attack and slip of the CO;
m — mass of the CO;
Cx_a, Cy_a, Cz_a — aerodynamic coefficients of drag, lift and lateral forces;
S- characteristic area of the CO;
P- air density;
g - acceleration of gravity.

The CO is controlled by changing the angles α and β with a corresponding deflection of its control surfaces. The two-stage engine of the V-601P rocket has the following characteristics:

- The starting stage (booster): operating time t1 = 3.2 s, thrust force P = 16,000 kgf, total mass of the booster m01 = 525 kg, mass of fuel m1 = 281 kg, dm/dt = fr = 87.81 kg/s;
- The cruise stage: operating time t1 = 18.3 s, thrust force P = 1,100 kgf, total mass of the cruise stage m02 = 413 kg, mass of fuel m2 = 165 kg, dm/dt = fr = 7.67 kg/s; The total mass of the rocket m0 = 938 kg, the characteristic area of the booster S1 = 0.239 m2, the characteristic area of the cruise stage S2 = 0.110 m2.

The dependences of the aerodynamic coefficients of the drag force, lift and lateral forces of the first and second stages of the V-601P rocket in the active phase of flight, obtained from the materials of the draft design [3], are shown in Fig. 2. The characteristics are given in dependence on the Mach number for different angles of attack in the velocity coordinate system [4]. At the stage of the booster operation, the CO movement occurs without control along a ballistic trajectory, the lift force is absent

III. Interception model scenario.

Let us consider two S-125M SAM systems, designated r_1 and r_2, and the RM flight trajectories (Fig. 1). The target missilesare launched in turn from five launch positions (points O1–O5) located at distances of 47, 51, 57, 65, and 70 km from the target (the defending SAM system, point r1). Fig. 3 shows three RM flight trajectories from point O_5. The flight trajectories from points O_1-O_4 have a similar profile, so they are not shown here. Three RMs are launched from each launch position at an elevation angle of 64◦ (the maximum launch angle of the SAM system). All RMs move in a straight line throughout the entire active flight segment. Upon completion of the second stage cruise engine operation (during the passive flight segment), all RMs are detected by the SAM radar stations (at points A_1-A_5). The target missiles perform a programmed turn in the vertical plane to an elevation angle of 0◦ (point B5). From this moment, the r1 and r2 SAMs launch SAMs at moving RMs every second.

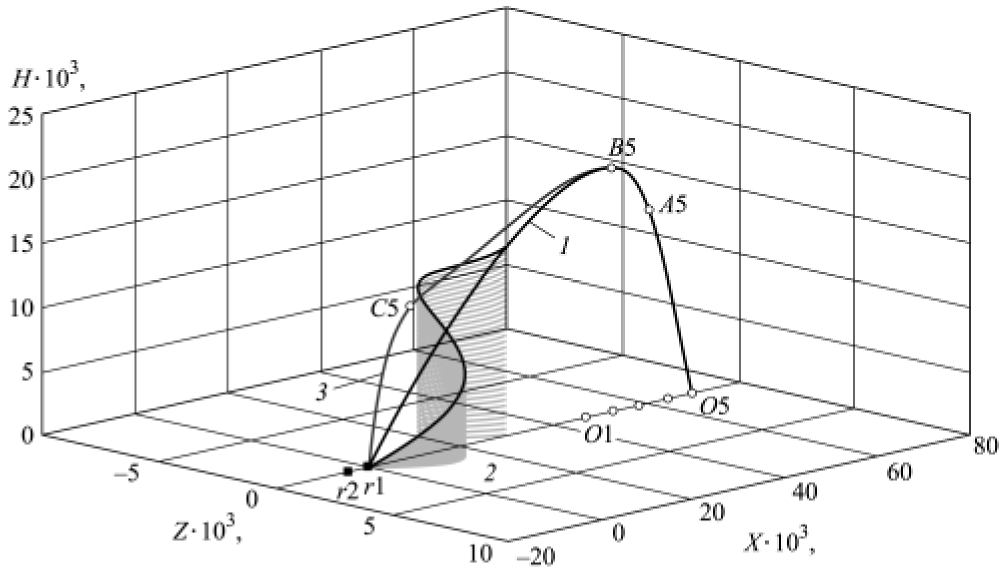

Figure 1. The PM flight trajectory is obtained by the proportional guidance method (1), during the "snake" maneuver (2) and by the method of reducing the probability of interception (3)

The target missiles implement individual programmed flight trajectories in order to reduce the probability of their defeat by SAMs. For the most objective assessment of the effectiveness of the programmed RM trajectories, their interception by two SAMs is considered. Moreover, the second SAM r2 defends the r1 SAM and is located 5 km behind it. Thus, the r1 SAM being covered is completely inside the defeat zone of the r2 SAM. In the absence of data on the parameters of the air target's movement, finding the coordinates of the SAM's meeting point with it is a separate and very labor-intensive task that requires detailed study. In this work, the azimuth and inclination angles of the SAM launchers were determined for the current meeting point, assuming a constant speed and direction of the RM's movement starting from the moment of the SAM's launch. The SAM speed is assumed to be constant and equal to 600 m/s when calculating the meeting point. The SAM is guided to the RM using the proportional guidance method (PGM) with a proportionality coefficient of N = 7 [6]. The maximum required SAM overloads for two control channels are limited to 10 units. The calculation of the SAM and RM trajectories when integrating the system of differential equations (1) is performed with a step of 1 ms. Interception of the RM in the rear hemisphere (in pursuit) is not considered in this formulation. Trajectory of RM #1. When forming the control law of RM #1 in the guidance section (section B5–r1) to determine the values of the required overloads, the MPN with the proportionality coefficient N = 3 is used. Trajectory of RM #2. The trajectory is implemented with a horizontal maneuver in the kill zone. Guidance to the target (r1) in the vertical channel is carried out by the MPN with the proportionality coefficient N = 3. The anti-missile maneuver "snake" in the horizontal flight plane is performed with a maximum acceleration of 8 units according to the relay law. According to work [7], when maneuvering an air target with the law of change in overload in the form of alternating rectangular pulses, the SAM miss is significantly (by ≈ 60%) greater than with a maneuver with a sinusoidal law. This is explained by the increase in the amplitude of lateral oscillations in the trajectory of the air target and a sharper change in the parameters of its motion. In the altitude range of the RM flight of 13,500. . . 15,000 m, the lateral overload of 8 units was programmatically set, and in the altitude range of 12,500…10,000 m, the RM flew with a lateral overload of - 8 units. In all other altitude ranges, the required lateral overloads of the RM were determined by the MPN. According to the authors, the "snake" maneuver in the vertical plane on the passive section of the RM flight is energetically inefficient. Therefore, it was not considered in this paper. Trajectory of the missile launcher No. 3. The trajectory is implemented using the method of reducing the probability of interception (MRPI). During pre-flight preparation, the trajectory of the missile launcher is determined and calculated using the available mathematical model of the missile launcher, initial conditions, target coordinates, SAM destruction zones, and maneuverability of the missile launcher. Reference points are entered into the memory of the onboard computer of the missile launcher, including the coordinates of the control start point (point B5), the dive point (point C 5), and the coordinates of the target point (point r1), through which the reference trajectory of the missile launcher passes. The authors selected the MPN as a guidance method for flying from one reference point to another. This modified guidance method is described in detail in [8]. The coordinates of the reference points are taken as the guidance points, thereby the movement of the missile launcher is carried out along a trajectory with a minimum length in the SAM destruction zone.

IV. Simulation Results

Here and below, by miss h we mean the absolute value of the minimum distance between the centers of mass of the SAM and the RM. The dependence of the SAM miss on time h(t) is shown in Fig. 2. RM No. 1–3 are launched from point O5. The time in the figure is counted from the start of the SAM launches (the moment the RM is at point B5). The dashed line in Fig. 2 indicates the SAM miss of 60 m.

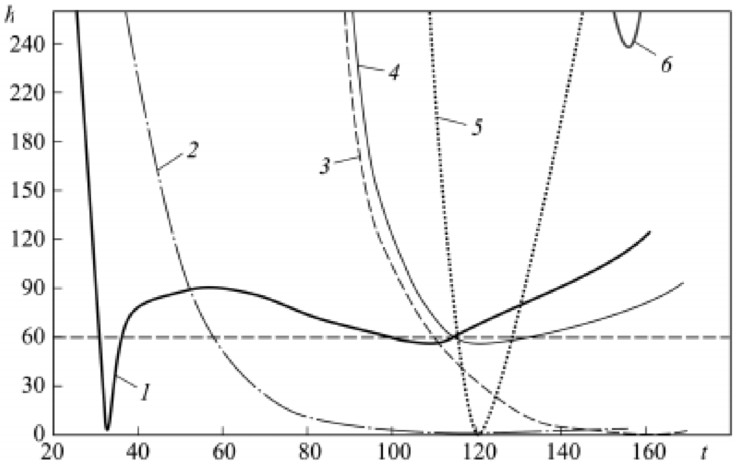

Figure 2. Dependence of missile glide on launch time for PM trajectory, obtained MPN for air defense missile system r2 (1), MPN for air defense missile system r1 (2), during “solid” maneuver for air defense system r1 (3), during “solid” maneuver for air defense system r2 (4), MSVP for air defense system r2 (5), MSVP for air defense missile system r1 (6)

According to the draft design [6], the specified value is the threshold for the operation of the pulse radio fuse located on board the SAM. In the presented interception model, it is conditionally assumed that if the distance between the SAM and the RM is less than the specified value, the RM will be destroyed, regardless of their mutual angular position. The values of the interception parameters for the trajectories of RM No. 1–3, launched from point O5, 120 s after the RM was at point B5 are given in the table. The following designations are introduced in the table: VZUR-SAM flight speed; VRM-RM flight speed; V_{sbl} -SAM and RM approach speed; D- distance between SAM and RM at the moment the SAM reaches the maximum available overload; ε - angular velocity of the SAM–RM sighting line at the moment the SAM reaches the maximum available overload.

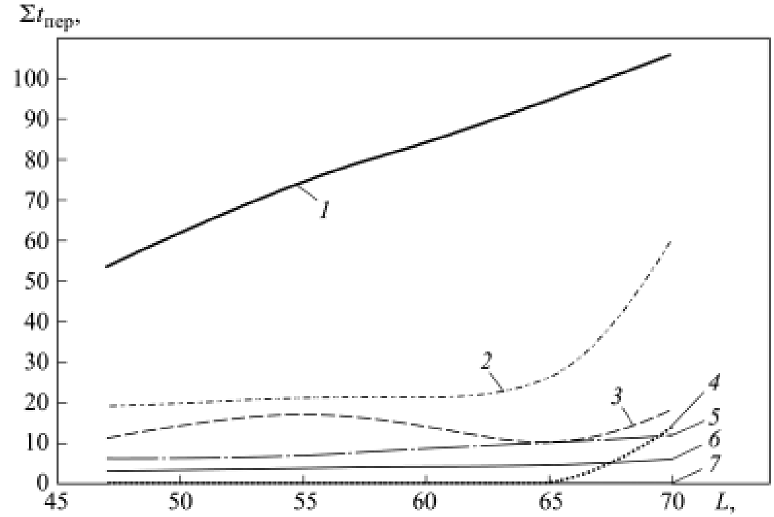

Figure 3. Dependence of the integral time of the conditional interception of the missile launcher on its launch range for the trajectory of the missile launcher obtained by MPN for the air defense missile system r1 (1), during the “solid” maneuver for SAM r1 (2), MPN for SAM r2 (3), during the “solid” maneuver for SAMr2(4), MSVP for the air defense missile system r2 (5), MSVP and “solid” maneuver for the air defense system r2 (6), MSVP for the air defense missile system r1 (7)

The dependence of the integral time of the conventional interception $P_{tper}M$ on its launch range is shown in Fig. 3. The integral time of the conventional interception is the sum of the time intervals during which the RM is hit by the SAM.

V. Determination of the conditional probability of interception of RM.

In this work, to assess the effectiveness of the presented methods of RM flight control, the probability of their interception is considered as the main indicator. In general, the probability of RM interception is a chain of sequential events Si, which can be described as follows: S_1 - RM detection by SAM electronic means; S_2 - SAM launch; S_3 - SAM reaching the required distance (between the SAM and RM) for the radio fuse to operate; S_4 - detonation of the SAM warhead; S_5 - destruction of the RM by high-explosive fragmentation impact (for the V-601P) of the SAM warhead. Each of the listed events corresponds to a probability. Thus, the probability of RM interception is determined by the formula $Pper = P_1P_2P_3P_4P_5$. In view of the previously adopted assumptions, considering the worst case for the RM, we assume that events S_1, S_2, S_4, S_5 are certainly fulfilled and probabilities P_1, P_2, P_4, P_5 are equal to one. In this case, the probability of RM interception is found by the formula $Pper = P_3$.

The value of the conditional probability of RM interception for the entire RM flight trajectory is found by the formula Pper = P3. The value of the current probability P3(t) on the RM flight path is determined from the conditions:

$$\begin{cases} P_3(t) = 1 \ \text{при} \ h < 60\,\text{м}; \\ P_3(t) = 0 \ \text{при} \ h \geq 60\,\text{м}. \end{cases}$$

The dependence of the conditional probability of intercepting a missile for all calculated trajectories on their launch range is shown in Fig. 3.

VI. Discussion of the obtained results.

During the simulation of overcoming the kill zones of two S-125M RM SAM systems along various flight trajectory profiles (according to the MPN, with a horizontal “snake” maneuver and according to the MSVP), the following results were obtained. The flight trajectory of RM No. 1, obtained by the MPN, is quite typical for a UAV and is taken as a standard when assessing the effectiveness of the other two movement algorithms of RM No. 2 and No.3. Target missile No.1 is intercepted at all launch ranges, while the integral interception time for SAM r1 is 54…106s, for SAM r2 -10…18 s. Accordingly, the conditional interception probability of RM No.1 at all launch ranges is equal to 0.58…0.63 for SAM r1 and 0.07. . . 0.15 for SAM r2. According to the dependencies shown in Fig. 3, the flight trajectory of RM #2 with a horizontal "snake" maneuver ensures a decrease in the conditional probability of its interception by 2-3 times (depending on the launch range) compared to the conditional probability obtained by the MPN (RM #1) for SAM r1. Target missile #2 is almost invulnerable to SAM r2, its interception is possible only within 14 s at a launch range of 70 km (point O5). The conditional probability of interception of RM #2 at all launch ranges is 0.15…0.35 for SAM r1 and 0… 0.08 for SAM r2.

The trajectory of the RM #3 flight obtained by the MSVP is practically invulnerable to the r1 SAM system, the minimum SAM miss is 239 m when launching the RM #3 from point O5. For the r2 SAM, its conditional interception probability is 1.1–2 times lower (depending on the launch range) compared to the conditional probability determined by the MPN (RM #1). The conditional interception probability of the RM #3 at all launch ranges is 0 for the r1 SAM system and 0.05…0.07 for the r2 SAM system. A combination of two methods- the horizontal “snake” maneuver and the MSVP - is the most difficult SAM interception. At the same time, the RM is practically invulnerable to the r1 SAM system, and its interception by the r2 SAM system is 2 times lower than that of the MSVP. Conditional probability of intercepting a missile at all its ranges: 0 for SAM r1 and 0.025… 0.035 for SAM r2. The data presented in the table correlate with the formula [10], which connects the instantaneous miss of the SAM and the speed of its approach to the RM. The general tendency for the conditional interception probabilities to increase for all missiles with increasing launch range is explained, first of all, by the decrease in the missile flight speed at the time of their interception (increase in the length of the passive flight segment of the missile). According to formula (2), on collision courses ($-\pi/2 < VZUR \wedge VRM < \pi/2$) the approach speed Vsbl increases with decreasing missile flight speed. In this case, an increase in the approach speed, all other things being equal, leads to a decrease in the miss, and therefore to an increase in the probability of interception of the missile.

VII. Conclusion

In this paper, we develop a mathematical model for intercepting the RM SAM of the S-125M complex. The target missiles follow various programmed trajectories (MPN), including a horizontal "snake" maneuver and MSVP. To assess the effectiveness of these evasion methods, we propose a conditional probability of interception. According to our calculations, the MSVP maneuver is recognized as the most effective strategy against two S-125M complexes. Furthermore, the combination of MSVP and the horizontal "snake" maneuver results in the lowest conditional probability of interception. Considering this, this combination proves to be the most effective for overcoming the engagement zones of SAMs, regardless of their location. Our findings align with previously established relationships between SAM misses and the movement parameters of aerial targets. This problem can also be explored further with more modern missile interception and evasion systems.

References

[1]. Talanov B.P. Sposob Control method for high-speed air objects within beaten danger zone. Patent RF, no. 2158697, 2000.

[2]. Golovin A.I., Kurdin G.V., Maklashov V.A., Sadkov V.D. Method of counteracting means of air defense (AD) and device for its implementation. Patent RF, no. 2226278, 2001.

[3]. Shchepetil'nikov S.R., Ovchinnikov M.V. Method of forming spiral motion of gliding flying vehicle relative to reference trajectory. Patent RF, no. 2306593, 2007.

[4]. Timokhin E.L, Zharyy O.N. Rocket-target "Pishchal" is cheap, effcient and easy to operate. Voennyy parad [Military Parade], 1998, no. 4, pp. 56–57.

[5]. Personal site on the history of Air Defense Anti-Aircraft Missile "PVOZRK S-125 "Neva" ("Pechora").

[6]. State Standard of the Russian Federation: GOST 20058-80. Aircraft dynamics in atmosphere. Terms, defnitions and symbols. Moscow, USSR State Committee on Standards, 1981. 54 p.

[7]. Arapov O.L., Zuev Yu.S. Increasing the probability of overcoming means of air defense by air vehicle. Vestn. Kontserna PVO "Almaz-Antey"

[8]. Neupokoev F.K. Anti-aircraft missiles fring. Moscow, Voenizdat Publ., 1980. 296 p.