Research Article

Monte Carlo-Based Analysis and Experimental Validation of the Interception-Damage Probability of the New Active Interception Net

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Received 23 March 2022; Revised 15 June 2022; Accepted 1 July 2022; Published 8 August 2022

Academic Editor: Ali Ramazani

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This study aims to prove the intercepting effectiveness of the new active interception net. According to the timing sequence of intercepting the incoming missile body by the new interception net, the external ballistic equations of the incoming missile body and the interception net are established, respectively, and then the mathematical probability model conforming to the physical characteristics of the interception process is constructed. The process of intercepting the incoming missile by interception net is simulated 1000 times by Monte Carlo method on the basis of considering the random parameters such as route shortcut, dive angle, and incoming velocity of the incoming missile. The simulation results under different intercept conditions, including the optimal intercept angle, the power of the payload warhead, and the probability of intercept damage, are analyzed. Through analysis, it is found that with the cooperation of multiple interception nets, the probability of interception and damage to the incoming target can be significantly improved. When the velocity of the incoming missile body is up to 900 m/s, the probability of damage is over 65%. The research content theoretically verifies the effectiveness of ultra-short-range interception of the new active interception net. In order to further verify the reliability of interception, a new interception net was carried out to verify the interception of the incoming missile body. Through the analysis of the test results, it is found that the new interception net can intercept the incoming missile body effectively after launch, which well verifies the Monte Carlo simulation results and further proves the intercepting effectiveness of the new interception net.

1. Introduction

In recent years, with the improvement of information technology and the development of military science and technology, the offensive ends of weapons systems and equipment used by various countries are constantly being updated and replaced. The current international situation is volatile, and local conflicts occur from time to time. The threat of strikes against essential targets such as government agencies, covert aircraft depots, island facilities, large water conservancies, and hydropower projects is increasing daily. Although most countries now have a relatively complete long, medium, and near-range ladder air defense system, new offensive weapons are emerging. In existing interception-based defense systems, there may be missed or late intercepts, leading to vulnerabilities in hyper-proximity protection [1] against high-value targets of high-value targets. As the last line of defense (in the ladder defense paradigm), Ultra-close-range active interception technology plays the gatekeeper role. It is of great significance in ensuring protected targets’ security.

Focusing on the interception efficiency study of short-range active interception net, Lei and Zhang [2] adopted the traction body with a flexible attitude to launch mesh ammunition, forming a point-facing “net” to intercept the incoming target. The interception efficiency parameter design problems are simulated and analyzed by the Monte Carlo shooting experiment method, which provides
technical support for other optimization designs of the new active protection system. Lu et al. [3] designed an active protection system based on distributed MEFP and verified the feasibility of intercepting incoming targets through scheme design, parameter analysis, numerical simulation, and experimental study. In addition, in terms of the research on the probability of intercept damage of other types of short-range protection means, Liu and Zhu [4] studied the interception of incoming projectiles by high-speed clustered combatants. They assessed the damage probability concerning arithmetic as applied to various real-life cases. Wu et al. [5] focused on the EML parameters and the interception probability of the EML two ATIs salvo with the Monte Carlo method. Wei et al. [6] discussed the vulnerability and damage destruction mechanism of typical cruise missiles and established a Monte Carlo simulation analysis algorithm based on experimental error data to estimate the damage probability of antimissile rockets. Yan [7] carried out the simulation calculation of damage probability. They performed a Monte Carlo analysis of the interception probability of an interception hit by an ultra-close-range naval gun weapon system around the interception process of intercepting late-maneuvering antiship missiles to provide a basis for the determination of the firing regime. Zhang et al. [8] established a probabilistic model for rocket weapon interception of cruise missiles based on simulation calculations to provide theoretical support for evaluating the effectiveness of air defenses and antimissile weapon systems. According to the current research, the existing means of proximity protection are mainly in proximity. However, less involved in ultra-proximity [9], and the protective measures are mostly point-to-point interception of a “bullet-to-bullet” nature, which has a relatively low cost-efficiency ratio. Monte Carlo, as a common probabilistic analysis tool, is widely used in various fields such as risk assessment, validity evaluation, and targeting probability analysis [10–17].

Based on the previous research, this paper takes the new type of ultra-short-range active interception technology as the research object. It uses the Monte Carlo method to analyze the interception probability of the new active interception net. The corresponding dynamic interception test preliminarily verifies the feasibility of this technique. This research is expected to provide a reference for developing and demonstrating new ultra-close-range defence weapons.

2. Materials and Methods

2.1. New Active Interception Net Model. The newly developed ultra-close range active interception technology includes radar detection, a control solver, tracking fire, and an active interception net. When the attack target is approaching, the parameters are solved according to the attack speed and direction by detecting and tracking the threat target within 1000 m. Launch the new active interception net and detonate the EFP warhead on the interception net within 100 m of the protected object. The short-range active interception technology can explode the incoming missile body in advance and change the damage of direct penetration into indirect air shock waves and explosive debris. It can provide a practical, reliable, and cost-effective interception means for aircraft bunkers, command protection projects, and other important military and economic targets. The composition of ultra-short-range active interception technology and its sequence diagram is shown in Figure 1.

2.1.1. Analysis Modeling of the Active Interception Net. The interception range of the new active interception net is within 3 kilometres of the ultra-short range airspace, the interception of aircraft bombs, cruise missiles, and other incoming missile bodies. When the incoming targets enter the interception range, they are in the glide section at the end of the trajectory and no longer manoeuvre. Therefore, a rigid body ballistic model with six degrees of freedom [18] can be used to represent the actual trajectory of the incoming threat projectile. The active interception net mainly relies on the EFP warhead loaded on the net to intercept the incoming missile body. The net rope only plays a bearing role and does not participate in the final interception process. Combined with the above characteristics, the active interception net can be represented by a particle trajectory model with three degrees of freedom. According to the existing external ballistic theory [19], after considering the effects of Earth curvature, gravitational acceleration, and air resistance, the ballistic centroid equation of the active interception net under nonstandard conditions was derived.

Before deducing and analyzing the ballistic equation, it is assumed that the shape and mass distribution of the active interception net is axisymmetric, and the angle between the symmetry axis and the velocity vector of the centre of mass is always 0. Under the assumption, as shown in Figure 2, the force of the active interception net can be obtained according to Newton’s second law:

$$\frac{d^2\vec{r}}{dt^2} = \vec{F}_i + \vec{R}_x + m\vec{g} - \vec{R}_C,$$

(1)

where $\vec{F}_i$ represents thrust during flight, $\vec{R}_x$ represents air resistance, and $\vec{R}_C$ represents Coriolis inertia force.

It can be obtained from (1):

$$\frac{d^2\vec{v}}{dt} = \vec{a}_x + \vec{a}_c + \vec{g} - \vec{a}_c.$$

(2)

In (2), different $\vec{a}$’s represent the acceleration of force in (1). For active interception net, there is no thrust after launch, let $\vec{F}_i = 0$, then:

$$\frac{d^2\vec{v}}{dt} = \vec{a}_x + \vec{g} - \vec{a}_c.$$

(3)

In the ground Cartesian coordinate system, it is assumed that the components of velocity $v$ in the $x$- axis and $y$-axis directions are:

$$\begin{cases} v_x = v\cos\theta, \\ v_y = v\sin\theta. \end{cases}$$

(4)

The scalar equation of motion is obtained by projecting (3) above onto the $x$-axis and $y$-axis:
According to $a_x = cH(y)G(v, c_y)v$, it can be obtained:

$$\frac{dv_x}{dt} = -a_x \cos \theta,$$

$$\frac{dv_y}{dt} = -a_x \sin \theta - g.$$  

According to $a_x = cH(y)G(v, c_x)v$, it can be obtained:

$$\frac{dv_x}{dt} = -cH(y)G(v, c_x)v_x,$$

$$\frac{dv_y}{dt} = -cH(y)G(v, c_y)v_y - g,$$

where ballistic coefficient $c = id^2 \times 10^9/m$ and $H(y)$ is the air density function.

For the pressure,

$$\frac{dp}{dr} = \frac{dp}{dy} \frac{dy}{dr} = -\rho g v_y,$$

where $\rho$ is the atmospheric density.

According to theoretical mechanical analysis, Coriolis acceleration is equal to the product of interception net velocity vector $\vec{v}$ and Earth rotation velocity vector $\vec{\Omega}$, which can be expressed as follows:

$$\vec{a}_c = 2 \vec{v} \times \vec{\Omega}.$$  

In the ground Cartesian coordinate system, the projection components of $\vec{\Omega}$ along the $X$, $Y$, and $Z$ directions are $\Omega_x$, $\Omega_y$, and $\Omega_z$, respectively. It is assumed that the unit vectors of $X$, $Y$, and $Z$ directions in the ground Cartesian coordinate system are $\vec{n}_1$, $\vec{n}_2$, and $\vec{n}_3$, respectively. Coriolis acceleration can be obtained from the above parameters as follows:

$$\vec{a}_c = 2 \vec{v} \times \vec{\Omega}$$

$$= 2 \begin{vmatrix} n_1 & n_2 & n_3 \\ \Omega_x & \Omega_y & \Omega_z \end{vmatrix}$$

$$= 2 \begin{vmatrix} v_x & v_y & v_z \\ \Omega_x & \Omega_y & \Omega_z \end{vmatrix}$$

$$+ 2 \begin{vmatrix} v_x & v_y & v_z \\ \Omega_x & \Omega_y & \Omega_z \end{vmatrix}$$

In the above equation, the values of $\Omega_x$, $\Omega_y$, and $\Omega_z$ are determined by the direction and latitude of the launching point of the interception net. Assuming that in the ground coordinate system, the launch direction is $a$ and positive in the clockwise direction, and the other $\Lambda$ represents latitude, the following (10) can be obtained:

$$\begin{cases} 
\Omega_x = \Omega \cos \Lambda \cos \alpha, \\
\Omega_y = \Omega \sin \Lambda, \\
\Omega_z = -\Omega \cos \Lambda \sin \alpha.
\end{cases}$$
Based on the above equation, when the curvature of the Earth and the acceleration of gravity change with altitude, the trajectory equation is as follows:

\[
\frac{dv}{dt} = -cH(y)G(v_r,c_r)(v_r - w_r) + \frac{(v_r - w_r)(v_r - w_r)}{R} (1 - \frac{y}{R})^{-1},
\]

\[
-2\Omega \left[ (v_r - w_r) \sin \Lambda + (v_r - w_r) \cos \Lambda \sin \alpha \right].
\]

\[
\frac{dv}{dt} = -cH(y)G(v_r,c_r)(v_r - w_r) - g_0 \left( 1 + \frac{y}{R} \right)^2 + \frac{(v_r - w_r)}{R} (1 - \frac{y}{R})^{-1},
\]

\[
-2\Omega \cos \Lambda \left[ (v_r - w_r) \cos \alpha + (v_r - w_r) \sin \alpha \right].
\]

\[
\frac{dv}{dt} = -cH(y)G(v_r,c_r)(v_r - w_r) - 2\Omega \left[ (v_r - w_r) \cos \Lambda \cos \alpha - (v_r - w_r) \sin \alpha \right],
\]

\[
\frac{dx}{dt} = v_r \left( 1 + \frac{y}{R} \right)^{-1}.
\]

\[
\frac{dy}{dt} = v_y,
\]

\[
\frac{dz}{dt} = v_z.
\]

\[
\frac{dp}{dt} = -\rho v_r v_y.
\]

(11)

where sound velocity \(c_s = \sqrt{k_s R \rho \tau}\), air density function \(H(y) = \rho / \rho_{\text{an}}\), and air density \(\rho = \rho_{R\tau} \tau\).

Rotational speed of the Earth \(\Omega = 7.292 \times 10^{-5} \text{rad/s}\), Resistance function \(G(v_r,c_r) = \pi/8000 \rho_{\text{an}} C_{\text{son}}(v_r/c_r)v_r\), Speed of summation \(v_r = \sqrt{(v_x - w_x)^2 + (v_y - w_y)^2 + (v_z - w_z)^2}\), Resistance factor \(C_{\text{son}}(v_r/c_r) = C_{\text{son}}(Ma)\), Projectile-shaped coefficient \(i = C_{\text{sd}}(Ma)/C_{\text{son}}(Ma)\), and ballistic coefficient \(c = id^2/m \times 10^4\). The virtual temperature \(\tau\), the velocity of sound \(c_s\), and air density \(\rho\) in the formula are calculated according to the standard meteorological conditions for artillery.

2.1.2. Calculation of Model Parameters. In the analysis, the basic shape of the ideal explosively formed projectile (EFP) is assumed to be shown schematically in Figure 3.

An EFP combat part mass is supposed to be \(m\), and the cylindrical part diameter is \(d\), measured by test-EFP flight distance as \(x_1\) and \(x_2\), at speeds \(v_1\) and \(v_2\), respectively, so according to the speed drop, the flight drag coefficient is given by

\[
c_{x_0} = \frac{4m}{\sqrt{\pi d^2}} \ln \left( \frac{v_2}{v_1} \right). \tag{12}
\]

The drag coefficient of EFP can also be obtained by numerical simulation, and according to the numerical calculation of EFP [20], the drag coefficient is taken as its average value \(c_{x_0} = 0.6\).

2.1.3. Initial Parameters of the EFP Combatant. The initial parameters of the EFP trajectory are determined by the initial parameters of the active interception net trajectory at the launching point and the state of the EFP after launching (such as position, attitude, and velocity). The ballistic parameters are calculated from the flight trajectory of the active interception net and the launching state of the EFP is calculated from the launching trajectory.

The whole active interception net is simplified in analyzing the problem, so the attitude of each EFP and its randomly varying angle of attack cannot be obtained. Assume an ideal distribution of all EFP warheads (solid red circles) as shown in Figure 4.

The position parameters of each EFP relative to the overall new active interception net centre point within the new active interception net path coordinate system are assumed to be \((x_{E_{ij}}, y_{E_{ij}}, z_{E_{ij}})\), and the initial ballistic parameters of each EFP are as follows:

- \(x\)-axis coordinates \(x_{E_{ij}} = x_{E_{ij}} + x_{E_{i}}\), \(y\)-axis coordinates \(y_{E_{ij}} = y_{E_{ij}} + y_{E_{i}}\), \(z\)-axis coordinates \(z_{E_{ij}} = z_{E_{ij}} + z_{E_{i}}\), velocity in \(X\) direction \(v_{x_{E_{ij}}} = v_{x_{E_{ij}}}\), velocity in \(y\) direction \(v_{y_{E_{ij}}} = v_{y_{E_{ij}}}\), velocity in \(z\) direction \(v_{z_{E_{ij}}} = v_{z_{E_{ij}}}\), directional angle \(\theta_{E_{ij}} = \theta_{E_{ij}}\), and pitch angle \(\phi_{E_{ij}} = \phi_{E_{ij}}\).

The EFP self-destructs occur at \(t_{f_{ij}} = 0.5s\) after the active interception net fuse is activated, so the calculation terminates at
\[
t = t_0 + t_m + t_n + t_k + t_h.
\] (13)

In \( t \in [0, t_{th}] \) time, the detection radar on monitoring after \( t_m \) time to find the incoming projectile and in \( t_0 + t_m \) moment to launch the active interception net, the active interception net is propelled by the launch charge to accelerate \( t_n \) time (internal ballistic motion process), in \( t_0 + t_m + t_n \) time, the active interception net leaves the launcher, gradually unfolds, and takes shape in the air and flies for \( t_k \) time, and at \( t_0 + t_m + t_n + t_k \) time, the EFP combat section on the interception net is detonated, and the EFP meets the target after \( t_h \) time and intercepts the target.

In the subsequent numerical simulation of the solution hit process, the flight of the EFP is relatively short, so after detonation, it undergoes very little change in velocity along its central axis. The active interception net by the interception point inverse initial firing parameters and movement time will be deterministic values. The time can be divided into two stages (before and after detonation), the detonation time depends on the designed multi-EFP time of interception, the size distribution requirements, and the EFP distance of action. During the flight and multi-EFP detonation of the new active interception net, the attitude and position of the EFP will change due to the tractive effect of the tractor bomb, which in turn affects the hit probability (this is temporarily ignored in the analysis).

2.2. New Active Interception Net Hit and Damage Probability Solution. The simulation by the Monte Carlo method can statistically acquire the hit probability of the new active interception net, which can reduce the number of complicated, expensive live-fire target tests to a certain extent and can provide a reference for the demonstration and development of new weapons.

The steps to simulate target shooting by applying the Monte Carlo method with the help of a computer are as follows:

1. Determine the various random perturbation factors and distribution in the new active interception net flight.
2. Establish the corresponding probability analysis model from the distribution of each random disturbance variable to generate the sampling values of each variable.
3. Establishing a mathematical model of the motion of the relatively accurate new active interception net.
4. Input sampling values from (2) into the mathematical model established in (3) and run the ballistic solution of the simulated interception to obtain the randomly perturbed ballistic parameters.
5. Repeat (4) multiple times to obtain a subsample of the random ballistic parameters.
6. Process the interception results obtained after running steps (1) to (5) to obtain the statistical eigenvalues of ballistic parameters.

2.2.1. Hit Random Mathematical Model and Solution. The simulation analysis of a new active interception net’s hit probability can be realized by writing a program driven by the above set of equations for the active interception net.

The detection of the ground Cartesian coordinate system is used in the simulation analysis. The X-axis points east, the Z-axis points south, and the Y-axis is in the lead plane perpendicular to the X and Z axes according to the right-hand rule.

(1) In the detection of the ground Cartesian coordinate system, starting from \( t = t_0 + t_m + \delta_n \), the set of interception net equations with random variables is calculated, and the end time of the calculation is set as the flight time of the interception net \( t_h \), so as to obtain the interception net parameters at point of detonation.

(2) Calculate the parameters of each EFP in the probe right-angle coordinate system and calculate the ballistic trajectory of each EFP combat section from time \( t = t_0 + t_m + \delta_n + t_k \). The termination time when EFP self-destruction is assumed to be \( t_h \) is calculated.

(3) Solve the system of equations for the incoming projectile from time \( t = t_0 + t_m \) in detecting the right-angle coordinate system to obtain its position and velocity on the future trajectory as a function of time.

(4) Count the number \( N_{hi} \) of EFPs entering the target area in the target ballistic axis coordinate system and consider the new interception net hit when \( N_{hi} > 1 \).

(5) Repeat steps (1) to (4) for multiple hit solution analyses until the total number of simulations \( N_s \) is satisfied.

(6) Count the number of hits of the new interception net \( N_h \) and divide by \( N_s \) to get the interception net hit probability \( P_r \).

\[
P_r = \frac{N_h}{N_s}.
\] (14)

In addition, the average number of EFP hits per hit is counted as \( N_{rhit} \).
2.2.2. Combined Damage Probability Model. When a combatant on a new type of interception net, vertically strikes a cylindrical threat projectile (shell outer radius $R_1$, inner charge radius $R_2$), when the radial position at the hit is $r$, the relationship between the effective penetration depth $l$ of the combatant on the shell and the hit position is assumed to be as shown in Figure 5.

\[
l = \sqrt{R_1^2 - r^2} - \sqrt{R_2^2 - r^2} \quad (-R_2 < r < R_2).
\]

When the threat projectile hits the target and makes an angle $\theta$ with the vertical section of the target, the actual depth of penetration in the casing is as follows:

\[
L = \frac{\sqrt{R_2^2 - r^2} - \sqrt{R_1^2 - r^2}}{\cos \theta} \quad \text{(17)}
\]

After analyzing the conditions under which the formula holds, the range of values of the radial position $r$ at the hit is $r \in (-R_2, R_2)$, when the combatant power $L_{\text{max}}$ (the actual penetration depth of the detonated target charge) is certain, for any radial position $r$, there is a combatant that can penetrate the outer layer of the incoming projectile with the maximum incidence interception angle $\chi$, which is described by the following equation (21):

\[
\chi = \arccos \left( \min \left( \frac{\sqrt{R_1^2 - r^2} - \sqrt{R_2^2 - r^2}}{L_{\text{max}}} \right) \right) (-R_2 < r < R_2).
\]

The formula for the incoming projectile destruction probability $P(v_r)$ can be derived from the Weibull function [22]:

\[
\begin{align*}
P(v_r) &= 1 - \exp \left[ -B_5 (v_r - B_6)^{B_7} \right], \quad v_r \geq B_6, \\
P(v_r) &= 0, \quad v_r < B_6.
\end{align*}
\]

(19) where $P(v_r)$ is the probability of destruction of an explosively formed projectile with $v_r$ on impact with an incoming projectile; where the three constants $B_5$, $B_6$, and $B_7$ can be found by use of the Jacobs-Roslund equation [23, 24]

\[
\begin{align*}
B_5 &= \frac{-4.61}{(v_{\text{max}} - v_{\text{min}})^{B_7}}, \\
B_6 &= v_{\text{min}}, \\
B_7 &= \frac{-1.9}{\ln v_{\text{mid}} - v_{\text{min}} / (v_{\text{max}} - v_{\text{min}})}.
\end{align*}
\]

where $V_{\text{max}}$ is obtained by the EFP impacting the incoming projectile at the optimal attitude, $V_{\text{min}}$ is deduced by the EFP impacting the incoming projectile at the worst attitude, and $V_{\text{mid}}$ is intermediate to these extremes. For combatant damage studies, a commonly used technique relies on the empirical Jacobs-Roslund equations (19)–(21) that can be used to calculate the velocity threshold when an explosively formed projectile destroys an incoming projectile.

\[
v_k = \frac{A}{\sqrt{D \cos \theta}} \left( 1 + \frac{B}{T} \right)
\]

$\chi$-the velocity threshold for the destruction of incoming projectiles by explosively formed projectiles (km/s), $A$-explosive sensitisation factor (mm/$\mu$E), $B$-fragmentation shape factor, $C$-cover plate protection factor, $T$-thickness of the cover plate (mm), $D$-the main size of the fragment (mm), $\theta$-angle of incidence of impact ($\cdot$).

2.2.3. Combined Destructive Model of Multiple New Active Interception Nets. If the newly developed interception net ultra-close-range active interception technology is a defence system composed of multiple new active interception nets, it will enlarge the interception area and increase the number of interceptor screens, and can improve the hit and damage probability of incoming projectiles.

With $P_R$ interception net units, the combined interception and damage probability of multiple interception net are calculated as follows:

\[
P_p = 1 - (1 - \lambda_R P(v_r))^{P_R},
\]

where $\lambda_R$ is the fire overlap factor (greater than 1) of each EFP unit.

2.2.4. Characterisation of Incoming Projectiles and Interceptor System Components

(1) Incoming Projectile Characteristics. Using an existing type of cruise missile as a hypothetical threat projectile, the relevant characteristic parameters are listed in Table 1.

(2) Characteristics of Each Part of the Interception System. According to the protection context of the new active interception net and the characteristics of the threat targets, the configuration overview of each subsystem such as defence position, radar, and interception net units of the interceptor protection system is shown in Figure 6.

Here, $\lambda_R$ is the fire overlap factor (greater than 1) of each EFP unit.

2.2.5. The Selection Strategy of Intercepting Position of the Barrage Interception. If the target is hit head-on, the EFP warhead’s speed increases, increasing the adequate penetration depth. However, the target is generally a long cylinder and its projectile face is the smallest in this case, which is not conducive to hitting. Suppose the counterattack is in the vertical axis direction of the projectile. In that case, the area of the projectile surface is the largest, but the projectile is not an ideal oblique penetration state. Especially when the target velocity is high, the projectile impact angle is too small, making the equivalent wall thickness of the target huge.
The actual problem is not only the optimization of the area and relative penetration velocity. The distribution of EFP warheads is assumed to be an ideal barrage plane. In studying space problems, the ideal rendezvous (hit) in the interception process is not completed instantaneously but successively. The schematic diagram of the ideal rendezvous is shown in Figure 7. Suppose it is considered that the barrage is large and the target has no angle of attack moves. In that case, a space intersection volume is determined by the velocity of the barrage, the target, and the angle of the intersection. The larger the volume is, the more conducive to the hit and damage of the barrage.

Considering the mathematical expression of the intersection volume (the dimension of flow) in unit time-space, we discuss the physical meaning of the reflection of the intersection volume in this space. The mathematical model is shown in Figure 8, and the formula is as follows:

\[ V_q = S_0 \cos \theta (V_1 + V_2 \sin \theta) , \]

where \( S_0 \) is the area of the axial symmetry plane of the incoming target; \( V_1 \) is the velocity of the counterattack projectile (EFP); \( V_2 \) is the velocity of the incoming projectile body; and \( \theta \) is the angle between the target and the barrage. The space intersection volume described by this formula has the following characteristics.

1. If \( V_2 = 0 \), the target is stationary. The volume \( V_q = S_0 V_2 \cos \theta \sin \theta \) is the largest when \( \theta = 0^\circ \).
2. If \( V_1 = 0 \), the barrage is stationary. The volume \( V_q = S_0 V_2 \cos \theta \sin \theta \) is the maximum when \( \theta = 45^\circ \).
3. When \( V_1 \) and \( V_2 \) are assumed to be nonzero constants, the maximum value of the continuous function corresponds to the position where the first derivative is zero, that is, \( 2V_2 (\sin \theta)^2 + V_1 \sin \theta - V_2 = 0 \), the negative value is ignored, and the solution is \( \sin \theta = -V_1 + \sqrt{V_1^2 + 8V_1V_2/4V_2} \). The value of \( \theta \) can be determined by taking the inverse sine function.

<table>
<thead>
<tr>
<th>Bullet diameter (m)</th>
<th>Mass of charge (kg)</th>
<th>Length (m)</th>
<th>Wingspan (m)</th>
<th>Velocity (m s(^{-1}))</th>
<th>Interception distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.62</td>
<td>1.26</td>
<td>6.32</td>
<td>3.66</td>
<td>262</td>
<td>20–50</td>
</tr>
</tbody>
</table>

Table 1: Threat projectile characteristics parameters.
When $V_1 = V_2$, $\sin \theta = 0.5$, and $\theta = 30^\circ$, the volume is maximum.

The relationship between intercept angle and projectile velocity and between intercept angle and EFP velocity is reflected through the above research process.

3. Results and Discussion

3.1. Calculation and Analysis of Interception and Damage Using a New Active Interception Net

3.1.1. Best Interception Angles. Based on the established interception analysis model, the optimal angle of incidence interception can be calculated for different incoming projectile velocities and different EFP velocities, as shown in Figure 9.

According to the damage model established under hit conditions, the relationship between the location of the attack point $r$ and the optimum angle of incidence interception $\chi$ for a representative effective penetration depth $L_{\text{MAX}} (30 \text{–} 150 \text{mm})$ for an incoming projectile with an outer diameter of 263.5 mm and an inner diameter of 243.5 mm is illustrated in Figure 10.

3.1.2. Powerful Impact of the Combat Section. The damage probability with the EFP combatant power (effective penetration depth of the EFP jet) is assumed to be as shown in Figure 11.

As can be seen from the above results, as the EFP combatant power (effective penetration depth of the EFP jet) increases, the damage probability increases. However, after the power reaches a certain level, the increase in the interception-damage probability decreases, and further changes with increasing power are no longer apparent.

3.1.3. Interception-Damage Probability by Hit

(1) The Effects of Intercept Route Shortcuts on the Probability of Hitting and Damaging the Target. According to the previously established hit damage model, the incoming target attacks at Mach 0.77 cruising speed at different dive angles under the same 10-m range shortcut. When entering the protection range provided by the new interception net, the probability of interception damage is shown in Table 2.

From Table 2, we can see that the interception-damage probability of the incoming projectile at 45 degrees is the lowest, 83.2%, under several characteristic dive angles (when the value is between 0 degrees and 45 degrees, the interception-damage probability is even lower). Concerning the actual dive angle of the incoming projectile, we take the characteristic dive angle of 45 degrees to study the interception-damage possibility under different route shortcuts.

Similarly, the projectile attacks at a cruising speed of Mach 0.77 and an angle of 45°. When entering the protection scope provided by the new active interception net from

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Table 2: Destruction probability of incoming projectiles attacking with different dive angles.

<table>
<thead>
<tr>
<th>Dive angle of the incoming projectile (°)</th>
<th>45</th>
<th>55</th>
<th>65</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of destruction (%)</td>
<td>81.8</td>
<td>84.1</td>
<td>85.9</td>
<td>87.6</td>
</tr>
</tbody>
</table>

Note. The interception-damage probability is obtained when the number of new interceptor units is 1, and the shortcut of the route is 10 m.

Table 3: Destruction probability of incoming projectiles attacking with different course shortcuts.

<table>
<thead>
<tr>
<th>Shortcut to the voyage (m)</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of destruction (%)</td>
<td>81.8</td>
<td>85.3</td>
<td>87.6</td>
<td>84.7</td>
</tr>
</tbody>
</table>

Note. The probability of destruction is calculated when the number of units of the new interception net is 1 and the dive angle is 45°.
different route shortcuts, the interception and damage probability of the new active interception net is shown in Table 3.

From Tables 2 and 3, it can be seen that:

(a) When other variables are the same, the larger the dive angle of the incoming projectile, the larger its receiving surface and the closer the dive angle is to 90 degrees, and the probability that it intercepts and destroys its target increases.

(b) When other variables remain unchanged, the longer the shortcut taken by the incoming projectile, the greater the probability of hitting and destroying the projectile (albeit this probability decreases). As shown in Table 3, when the dive angle is 45° and the interception distance is between 20 m and 50 m, the best interception shortcut is about 20 m.

(2) Probability of Hitting and Destroying under Existing Interception Conditions. According to the previously established probabilistic simulation calculation model and parameters, under the current interception conditions, the incoming projectile is assumed to attack randomly from within 360° and enter the protection range afforded by the interception net. The interception process is simulated 1000 times at interception distances of 20 m to 50 m, and the interception-damage probability of the threat target is calculated, as shown in Table 4.

According to Table 4, under the existing combat technology index of the new interception net, the interception-damage probability of the threat projectile can be improved by cooperation between multiple interception net units, and the interception-damage probability in addition to that exceeds 65%, basically meeting interception conditions.

3.2. Interception Verification Test. Based on the important target protection of the new active interception net is dynamic interception protection, so in order to verify the dynamic interception performance of the new active interception net, the verification test of dynamic interception effect was designed and carried out.

The principle prototype of the interception net unit test device is shown in Figure 10, with a coaxial launch and a structure that includes a rope net chamber, an air chamber, a piston, an ejection tube, a support frame, and other accessories.

![Figure 12: The principle prototype of the interception net unit.](image)

The launch prototype uses the energy of burning gunpowder to launch four traction bodies. The rope net and traction bodies used for the experiments in the test system are shown in Figure 12. The warhead of the traction body is a steel ball with a mass of 0.5 kg, and the bullet body comes with a hole for tying the rope. Moreover, the model is 45° steel-shaped material with a specification of Φ76 × 300 mm.

Considering the operability and safety of the validation test conducted, a standard 40 mm rocket was used as the target interceptor, and four traction bodies were used to tow the metal interception net unit, with a new type of interception net unit mesh diameter of 10 mm × 10 mm and a metal wire diameter of 0.9 mm. The field photo of the test is shown in Figure 13.

The interception net launcher was installed in the experiment at a fixed position. The rocket launcher was 30 m away from the interception net launcher and the signal trigger target was presented at the center of both. The target angle was 90° and high-speed photography equipment was installed to observe and record the whole experimental process. The launch of the flexible interception net was controlled by launching a 40-mm rocket against the signal-triggered target. The interception effect of the rocket and the flying flexible interception net was observed and recorded (Figure 14).

Through the analysis of the experimental phenomena of the high-speed photographic video and the verification experiment, it was found that a larger fire appeared in Figure 14 when the incoming rocket was intercepted head-on by the interception net, and combined with the
experimental results, it was found that the rocket was indeed successfully intercepted and exploded by the interception net in flight. The state of the metal interception net after the successful interception and explosion is shown in Figure 15, where the explosion of the armor-breaking projectile has damaged the interception net. The test results show that the new active interception net can effectively intercept incoming munitions during the flight deployment.

4. Conclusion

The following conclusions can be drawn from the new active interception net hit and damage probability model, method, parameters, results, and analysis adopted.

(1) The simulation analysis considers accuracy indicators of each subsystem. The hit and damage probability simulation results show that the accuracy distribution of each system indicator is more reasonable and can meet operational effectiveness requirements of intercepting the incoming projectiles.

(2) In establishing the simulation model and analysis, the object of study is simplified accordingly, and the whole interception process cannot be described in completely realistic terms. This method differs greatly from that underpinning actual interception
operation. Some parameters, such as the aerodynamic parameters of the interceptor, are inaccurate, so there is a certain amount of simplification-induced error, and the interception process needs to be further optimized.

The statistical analysis method is used to analyze the hit-damage problem of the new interception net. Firstly, the mathematical model of the new interception net to intercept the incoming projectile is constructed, and the model conforms to the relevant shooting theory and physical characteristics; the distributions and accuracies of random variables and fuzzy variables in the analysis of the problem are clarified, and the interception process is revealed by Monte Carlo simulation to obtain the best interception angle, EFP combat power, and the interception and damage probability of the new interception net.

The interception probability study carried out the interception verification test of the new type of interception net against incoming projectiles. It was found through the observation test results that the new type of interception net could effectively intercept the incoming projectiles during the flight deployment process. Combining the simulation results with the analysis of test results, the validity of the interception probability simulation model was verified, and the feasibility of the new active interception net applied to the interception protection technology was also initially verified, laying a foundation for future research.

Data Availability

The data used to support the findings of this study are available from the corresponding author on request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

We appreciate the financial support from the National Natural Science Foundation of China’s Major Research Instrument Development Project (grant no. 51527810).

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