Study on fuze-guidance integration technology for improving air target striking capability of fortification storming/heat missiles

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Abstract. In order to realize air-ground integration strike capability of the fortification storming/HEAT missiles, with the study background of addition of a laser proximity fuze to the missile, this paper proposes a fuze-guidance integration design method based on combination of image guidance and laser proximity fuze detection. By utilizing the missile-target encounter images, the gimbal angle of the seeker, the velocity and attitude of the missile, as well as the bearing and distance of the target detected by the laser proximity fuze, our design method establishes the space geometric equations of the relative motion of the missile and target, and of the equivalent conical plane of the dispersion center of the warhead fragments in the coordinate system of the missile body. Meanwhile, by solving the equations, a fully formulaic optimal time delay model of fuze-warhead matching is obtained, and the optimal detonation time of the warhead is given. The results show that this integration design method can effectively improve the damage effect of the missile on the helicopter target under complex encountering conditions, and realize the integrated air-to-ground strike capability of the fortification storming/HEAT missile.

1. Introduction

In order to meet the multi-functional and multi-mission operational requirements for weapon equipment put forwarded by new military revolution, it is an important research direction to improve the missile’s air-ground integration strike capability. The image-guided fortification storming/HEAT missile is mainly used to strike tanks, armored vehicles and reinforced fortifications. Mid-course inertial guidance and terminal image-homing guidance are used. The warhead is multifunctional, including fortification storming/HEAT/killing modes, which is composed of the main stage and the follow-up killing stage. See figure 1 for the structure schematic. The two-stage warhead is equipped with tungsten blocks and safety detonation device, which receive the detonation information respectively and detonate independently. When striking a tank or an armored vehicle, the two-stage warhead simultaneously detonates to form two clusters of fragments to fly away, assisting to kill the instruments outside the tank or armored vehicle while the main warhead penetrates the armor. When striking a fortification target, the follow-up killing projectile enters the fortification through the hole penetrated by main warhead explosion, and detonates in a time delay, forming flying fragments to kill the personnel and equipment inside.
The effective dispersion angle of the fragments of the main stage warhead and the follow-up projectile are all about $4^\circ \sim 6^\circ$. The dispersion distribution density of single cluster of fragments at the maximum miss distance is less than 5 pieces/m², which can be used to strike armed helicopters. The main problem is that the distribution density of single cluster of fragments is small and the dispersion angle of single cluster of fragments is small, not effectively damaging the target. If the two clusters of fragments can hit the same critical part of the target, then the problem of insufficient fragment density can be solved, which puts forward higher requirements for the control accuracy of ammunition initiation.

The fuze-guidance integration design is an effective method to improve ammunition initiation control accuracy. In-depth and systematic research has been carried out in this field both at home and abroad and has been applied practically, but mainly limited to the air defense missile field using the radar homing guidance system. The United States patriot -3 (PAC-3), standard -6 (SM-6) and Russian S-300V air defense missiles have adopted the fuze-guidance integration technology of the radar homing guidance system [1-4]. At present, the research on the fuze-guidance integration guidance technology of image-homing guidance systems is only limited to research on the fuze-warhead matching technology of infrared homing air defense missiles [5-7].

Based on the research background of image-homing guided fortification storming/HEAT missiles, taking the precondition of adding a laser proximity fuze to the missile, this paper puts forward the design method for fuze-warhead matching of the fuze-guidance integration for air target striking of fortification storming/HEAT missiles. The design idea is that, based on the seeker’s image in the missile-target encounter phase, the seeker's missile-target line of sight angle, the missile speed, the target position and distance detected by the laser proximity fuze and other information, the space geometric equation of the equivalent conical plane of the fragmentation dispersion center of the warhead is established in the coordinate system of the missile body. Meanwhile, by solving the equations, a fully formulaic optimal delay time model of fuze-warhead matching is obtained, and the optimal initiation timing is determined accurately and separate explosion of the two-stage warhead is controlled, making the front-back clusters of fragments hit the same critical part of the target. By comparing with the simulation results of the conventional fuze-warhead matching method, it is verified that the method can effectively improve the initiation control accuracy and the fuze-warhead matching efficiency, so as to realize the integrated air-ground strike capability of the fortification storming/HEAT missiles.

2. Integration working principle of the fortification storming/HEAT missile

The integrated design of the fortification storming/HEAT missile is based on information integration. In terms of hardware composition, the fuze and components of the guidance system exist independently. This approach has the advantage of making minimal changes to the missile's hardware. The fuze information processing unit comprehensively processes the information provided by the
guidance system and the fuze target detector, calculates the optimal delay time of the two-stage warheads respectively, and outputs the detonation signal to detonate the warhead at the right time. Figure 2 shows the composition and information flow relationship of the fuze-guidance integration system of the fortification storming/HEAT missile, and figure 3 shows the working principle of the system.

After the missile turns into the image homing guidance phase, the seeker begins to determine whether starting conditions of the laser proximity fuze are satisfied. When the target identified through the image is an aircraft target and the target image pixels reach more than 30% of the image pixels of the seeker detector, the seeker outputs the starting signal of the laser detection device and the arming command, which is forwarded to the laser proximity fuse by the onboard computer. After the laser proximity fuze receives the information, the laser proximity detection device turns on the target detection function, and the safety detonating device is armed. The information processing unit begins to query the target detection information. At this moment, the onboard computer begins to send the guidance information to the information processing unit, including the missile-target relative velocity vector information, the missile-target line-of-sight angle guidance information, etc. When the target enters the laser detection beam and the laser proximity detection device confirms that it has detected the target, according to the target detection information and guidance information, the information processing unit solves the optimal fuze-warhead matching delay time, and safety detonation device detonates the two-stage warheads in delay time to complete damage to the target.

3. Fuze-warhead matching model

3.1. Transformation matrix from missile body coordinate system to missile-target relative velocity coordinate system

Because the missile adopts proportional guidance, and tilt stability control is employed during the whole flight, the direction of missile-target line of sight is the relative velocity direction of the missile during the missile-target encountering. According to the information of the seeker’s pitching & yaw line-of-sight angles, the transformation matrix E from the missile body coordinate system [1] to the relative velocity coordinate system [1] can be obtained.
\[
E = M_x(M_y M_z) \\
E = \begin{bmatrix}
\cos \varepsilon_x \cos \beta_x & \sin \varepsilon_x & -\cos \varepsilon_x \sin \beta_x \\
-\sin \varepsilon_x \cos \beta_x & \cos \varepsilon_x & \sin \varepsilon_x \sin \beta_x \\
\sin \beta_x & 0 & \cos \beta_x
\end{bmatrix}
\]

where \( \varepsilon_x \) is the pitching gimbal angle of the seeker, and \( \beta_x \) is the yaw gimbal angle of the seeker.

### 3.2. Missile-target relative velocity

The target velocity can be obtained by real-time difference of the target position. The missile velocity can be obtained from the inertial navigation unit. The relative velocity of the missile and the target is calculated as follows:

\[
V_r = \sqrt{\frac{R_t(i-1) - R_t(i)}{\Delta T}} - V_{m1}^2 + \frac{\frac{R_t(i-1) - R_t(i)}{\Delta T}}{\frac{\Delta T}{\Delta T}} - \frac{V_{m2}^2}{\Delta T}
\]

where, \( R_t, R_t, R_t \) are the X, Y and Z components of the real-time position of the target obtained by the missile via a data link in the launch coordinate, \( V_{m1}, V_{m1}, V_{m1} \) are the X, Y and Z components of the missile's flight velocity output by the inertial navigation unit in the launch coordinate.

### 3.3. Miss distance and miss azimuth

The laser proximity fuze confirms the instant of target detection, and the target is located at point T. At this time, the missile-target relative motion relationship at terminal phase of encounter is shown in figure 4. The target position T in the missile body coordinate system \( o_x, y, z \) is expressed as:

\[
\begin{bmatrix}
T_{mx} \\
T_{my} \\
T_{mz}
\end{bmatrix} = \begin{bmatrix}
R_f \cos \Omega_f + d_i \\
R_f \sin \Omega_f \cos \omega_f \\
R_f \sin \Omega_f \sin \omega_f
\end{bmatrix}
\]

where \( R_f \) is target distance detected by the fuze, \( \Omega_f \) is the central inclination of the beam detected by the fuze, \( \omega_f \) is the target azimuth detected by the fuze, \( d_i \) is the distance between the fuze center and the main-stage warhead center projected on the missile axis.

**Figure 4.** Missile-target relative motion relationship at the terminal phase of encounter.

At the encountering instant, the relative motion track of the target can be equivalent to a spatial linear model, with the starting point being T and the direction being the target moving velocity direction \( \vec{V}_f \), relative to the missile. In the relative velocity coordinate system \( o_x, y, z \), the missile-target relative motion track is a line parallel to the axis \( o_x \), and the coordinate of the starting point T in the relative velocity coordinate system is:
The target's miss distance $\rho$ relative to the missile in the relative velocity coordinate system is:

$$\rho = \sqrt{T_{\rho \rho}^2 + T_{\rho z}^2}$$  \hspace{1cm} (6)$$

The target's miss azimuth relative to the missile $\theta$ is:

$$\tan \theta = \frac{T_{\rho z}}{T_{\rho \rho}}$$  \hspace{1cm} (7)$$

3.4. Warhead dispersion model

The warhead dispersion model is established in the missile body coordinate system, and the origin of coordinates is set at the center of the main-stage warhead. The fragment dispersion center of the warhead tilts forward relative to the missile axis (the inclination angle of the fragment dispersion center is less than 90°), the fragments at the dispersion center of is equivalent to a conical plane model with an included angle of $\psi$ to the missile body axis $x_w$. The fragment dispersion center of the follow-up projectile is perpendicular to the missile axis (the inclination angle of the fragment dispersion center is 90°), the fragments at the dispersion center are equivalent to a plane model perpendicular to the missile body axis $x_w$.

**Figure 5.** The warhead dispersion model.

The equation for the dispersion conical plane of fragments of the main-stage warhead is:

$$\frac{x_m^2}{\tan^2 \psi} + \frac{z_m^2}{\tan^2 \psi} = x_w^2$$  \hspace{1cm} (8)$$

where $\psi$ is the inclination angle of the fragment dispersion center.

The equation for the fragment dispersion plane of the follow-up projectile is

$$x_w = -d_z$$  \hspace{1cm} (9)$$

where $d_z$ is the distance between the main-stage warhead center and the follow-up killing projectile center projected on the missile axis.

3.5. Optimal fuze-warhead matching delay time model

The best time-delay criterion is that the fragment dispersion centers of two clusters of fragments (direction of maximum fragmentation density) all hit the detection point T on the target detected by the laser fuze. In order to facilitate modeling and equation solving, the solving model for optimal fuze-warhead matching delay time is established in the relative velocity coordinate system.
According to the transformation matrix $E$ from the missile body coordinate system to the relative velocity coordinate system and equation (8), the equation for the conical plane of fragment dispersion of the main-stage warhead in the relative velocity coordinate system is

\[
\left( \sin \beta_a x_a + \cos \beta_a y_a \right)^2 + \left( -\sin \beta_a \cos \beta_a x_a + \sin \beta_a \cos \beta_a y_a + \cos \beta_a z_a \right)^2 \tan^2 \psi = \left( \cos \beta_a \cos \beta_a x_a - \cos \beta_a \sin \beta_a y_a + \sin \beta_a z_a \right)^2 \tag{10}
\]

According to the transformation matrix $E$ from the missile body coordinate system to the relative velocity coordinate system and equation (9), the equation for the fragment dispersion plane of the follow-up killing projectile in the relative velocity coordinate system is

\[
\cos \beta_a \cos \epsilon_a (x_a + d_2 \cos \beta_a \cos \epsilon_a) - \cos \beta_a \sin \epsilon_a (y_a - d_2 \cos \beta_a \sin \epsilon_a) + \sin \beta_a (z_a + d_3 \sin \beta_a) = 0 \tag{11}
\]

The relative missile-target motion equation in the relative velocity coordinate system is

\[
\begin{bmatrix}
    x_a \\
    y_a \\
    z_a
\end{bmatrix} = 
\begin{bmatrix}
    T_m + V_r \tau \\
    \rho \cos \theta \\
    \rho \sin \theta
\end{bmatrix} \tag{12}
\]

According to equations and , the time for the point $T$ on the target to reach the conical plane of the main-stage warhead is:

\[
\tau_{r1} = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \frac{T_m}{V_r} \tag{13}
\]

where

\[
a = \sin^2 \epsilon_a + \sin^2 \beta_a \cos^2 \epsilon_a - \tan^2 \psi \cos^2 \beta_a \cos^2 \epsilon_a
\]

\[
b = 2(\rho \sin \epsilon_a \cos \epsilon_a \cos \theta - \rho \sin \epsilon_a \sin \epsilon_a \cos \epsilon_a \cos \theta - \rho \sin \beta_a \cos \beta_a \cos \epsilon_a \sin \theta
\]

\[
+ \rho \tan^2 \psi \cos^2 \beta_a \sin \epsilon_a \cos \epsilon_a \cos \beta_a \cos \epsilon_a \sin \theta
\]

\[
c = \rho^2 \cos^2 \epsilon_a \cos^2 \theta + 2\rho \sin \beta_a \cos \beta_a \sin \epsilon_a \sin \theta \cos \theta + \rho^2 \sin^2 \beta_a \sin^2 \epsilon_a \cos^2 \theta + \rho^2 \cos^2 \beta_a \sin^2 \epsilon_a \cos^2 \theta
\]

\[
+ 2\rho \tan^2 \psi \sin \beta_a \cos \beta_a \sin \epsilon_a \sin \theta \cos \theta - \rho \tan^2 \psi \cos \beta_a \sin \epsilon_a \cos \beta_a \cos \theta - \rho \tan^2 \psi \sin \beta_a \cos \beta_a \cos \epsilon_a \sin \theta
\]

The time for the fragments of the main-stage warhead to reach the target point $T$ is:

\[
\tau_{f1} = \frac{\sqrt{(T_m + V_r \tau_{r1})^2 + \rho^2}}{V_r} \tag{14}
\]

where $V_r$ is the average dispersion velocity of fragments.

The optimal fuze-warhead matching delay time of the main-stage warhead is:

\[
\tau_1 = \tau_{r1} - \tau_{f1} \tag{15}
\]

According to equations (12) and (11), the time for the point $T$ on the target to reach the fragment dispersion plane of the follow-up killing projectile is:
\[
\tau_{r2} = \frac{\cos \beta_{a} \sin e_{a} \rho \cos \theta - \sin \beta_{a} \rho \sin \theta - d_{z}}{\cos \beta_{a} \cos e_{a} V_{r}} T_{n}
\]

The time for the fragments of the follow-up killing projectile to reach the target point T is:
\[
\tau_{f2} = \sqrt{(T_{n} + V_{r} \tau_{r2} + d_{z} \cos e_{a} \cos \beta_{a})^2 + (\rho \cos \theta - d_{z} \sin e_{a} \cos \beta_{a})^2 + (\rho \sin \theta + d_{z} \sin \beta_{a})^2}
\]

The optimal fuze-warhead matching delay time of the follow-up killing projectile is:
\[
\tau_{2} = \tau_{r2} - \tau_{f2}
\]

4. Simulation verification
According to the fuze-guidance integration design scheme in this paper, typical missile-target encountering conditions are selected for simulation verification.

At the same time, this scheme is compared with the conventional fuze-warhead matching method, which uses the missile-target relative speed to realize the fuze-warhead matching delay time, to verify the effectiveness of the fuze-guidance integration design scheme described in this paper.

4.1. Simulation conditions
The typical simulation conditions are shown in table 1, which mainly consider four encountering types: heading on (A), chasing (B), lateral attack (C) and dive lateral attack (D).

| Name                        | Encounter Condition |
|-----------------------------|---------------------|
| Relative Speed (m/s)        | A   | B   | C   | D   |
| Pitch line-of-sight angle   | -2  | 1   | -2  | 2   |
| Yaw line-of-sight angle     | 0   | 0   | 6   | 5   |
| Pitch angle of missile      | 6   | 6   | 6   | -30 |
| Yaw angle of missile        | 0   | 0   | 45  | 45  |
| Roll angle of missile       | 1   | 1   | 1   | 1   |
| Yaw angle of target         | 180 | 0   | 145 | 145 |
| Pitch angle of target       | 2   | 2   | 2   | 2   |
| Roll angle of target        | 1   | 1   | 1   | 1   |

4.2. Simulation results and analysis
The simulation results for fuze-warhead matching are shown in table 2. In the table, "Scheme 1" refers to the fuze-guidance integration scheme designed in this paper, and "Scheme 2" refers to the fuze-warhead matching scheme using the missile-target relative speed to realize the fuze-warhead matching delay time.

| Encounter Condition | Miss Distance (m) | Miss Distance (°) | Total Number of Hit Top-Down | Fuze-Warhead Matching Efficiency |
|---------------------|-------------------|-------------------|-----------------------------|---------------------------------|
|                     |                   |                   | Scheme 1 | Scheme 2 | Scheme 1 | Scheme 2 |
| A                   | 2                 | 90                | 23       | 22       | 1.00     | 0.99     |
|                     | 5                 | 90                | 11       | 11       | 0.99     | 0.81     |
|                     | 8                 | 90                | 6        | 6        | 0.85     | 0.43     |
| B                   | 2                 | -90               | 19       | 17       | 1.00     | 0.92     |
|                     | 5                 | -90               | 7        | 6        | 0.89     | 0.42     |
|                     | 8                 | -90               | 5        | 4        | 0.82     | 0.36     |
| C                   | 2                 | 0                 | 106      | 13       | 1.00     | 0.94     |
|                     | 5                 | 45                | 7        | 7        | 1.00     | 0.48     |
|                     | 8                 | 0                 | 31       | 6        | 1.00     | 0.43     |
It can be seen from table 2 that, under the encounter conditions of C and D, Scheme 1 can significantly increase the number of hit fragments, but under the conditions of A and B, the numbers of hit fragments of Scheme 1 and Scheme 2 are almost the same, and Scheme 1 has not obvious advantage. This is because the conditions A and B belong to parallel encounter, while the conditions C and D belong to vertical encounter. It can be seen from figure 7 and figure 8 that, under the conditions of parallel encounter, the effective delay time range of fuze-warhead matching is wide, not requiring
high control accuracy of explosion point. However, the effective delay time range of fuze-warhead matching is narrow under the condition of vertical encounter, which requires high control accuracy of explosion point. The delay time solution results of Scheme 1 are all around the optimal delay time point for each condition, which is more effective for Scheme 1 of complex encounter condition.

It can also be seen from table 2 that, under the encounter conditions of A and B, and in the case that the numbers of hit fragments for the two plans are almost the same, the fuse-warhead matching efficiency of Scheme 1 is higher than that of Scheme 2. This is because the optimal delay time is calculated for the two-stage warheads respectively, so that the two clusters of fragments aim at the same vital part of the target. The fragments of the two-stage warheads cannot aim at the same vital part of the target, so the fragments cannot focus damage on the target.

5. Conclusion
With the requirement of realizing air-ground integration strike capability of the fortification storming/HEAT missile, and with the study background of adding a laser proximity fuze, this paper proposes a fuze-guidance integration design method for the fortification storming/HEAT missile based on the combination of image guidance and laser proximity fuze detection. Through simulation analysis and comparison, the conclusions are as follows:

1) The design method proposed in this paper can significantly improve the number of hit fragments and fuze-warhead matching efficiency for complex encounter conditions such as lateral attack, dive lateral attack and larger miss distance.

2) The design method proposed in this paper can significantly improve the fuze-warhead matching efficiency for the encounter conditions of heading on and chasing under a larger miss distance.

3) The fuze-guidance integration design method proposed in this paper can effectively improve the fuze-warhead matching efficiency of the missile under the complex encounter conditions such as heading on, chasing, lateral attack and larger miss distance, so as to realize the integrated air-ground strike capability of the fortification storming/HEAT missile.

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