Multiple projectile power situation model: Damage assessment method for terminal sensitive projectile with laser detection sensors

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ABSTRACT To effectively evaluate the damage efficiency of the terminal-sensitive projectile to the ground target under the power of multiple projectiles, this paper proposes a new method to calculate the damaging effect of the ground target by dividing the falling multiple sensitive projectiles into a multi-layer plane, uses the superposition principle to set up the multiple projectile power situation and analyzes the distribution of projectiles falling near the ground. The paper researches the detection method of the terminal-sensitive projectile with laser and infrared composite detection and establishes the calculation model of laser reflection echo power and thermal radiated power of the target. From the aspects of detection, attack and electronic jamming abilities, this paper set up the calculation model for multiple projectile power situation. Based on the distribution of the terminal sensitive projectile group established, the fuzzy relationship between each evaluation index of the ground target and the distribution state of the terminal sensitive missile group is used to establish the power evaluation function of the terminal sensitive projectile. The analysis results demonstrate that the power of terminal-sensitive projectiles is related to the distance of the intersection of projectile and target, and when the intersection distance is small, the damaging effect of terminal-sensitive projectiles on the ground targets is better.

INDEX TERMS Terminal-sensitive projectile, Dispersion characteristics, Laser detection, Projectile power situation, Damage assessment.

I. INTRODUCTION

In the field of weapon guidance, multiple projectiles attacking ground targets form explosive power fields. The power field is an important evaluation content of the weapon’s performance, and also an important evaluation source of terminal-sensitive projectile formation damage [1]. The projectile is equipped with a guided laser detection sensor that uses its own emitted laser to irradiate the ground target. The ground target forms the reflected echo energy. Then the photoelectric detector of the guided laser detection sensor obtains the echo reflected by the ground target. When the reflected echo energy reaches a certain amplitude, the laser detection sensor controls the detonating device of the projectile, and achieves the effect of the projectile explosion that form multiple-warhead fragments. The warhead fragments attack the ground target and cause ground target damage. To better evaluate the damage performance of terminal sensing ammunition, a Monte-Carlo method has been utilized in [2] to simulate the hitting point of terminal sensing ammunition. In [3], the principle and the method of quantitatively characterizing and evaluating the comprehensive power of warhead using the damaged area have been proposed, and the calculation model of the damaged area combined with the target damage model has been deduced.

The explosive power field of the terminal-sensitive projectile is an important indicator for evaluating the damage effectiveness of ground targets. Various studies have been conducted on terminal-sensitive projectiles [4-5]. The carrier projectile throws multiple terminal-sensitive projectiles in the air and then forms a power situation with a certain array to achieve effective damage to the ground targets. After the carrier projectile is launched, it has a certain distance from the ground in the process of landing. Since the terminal-sensitive projectile has sensors with different detection performances, once the distance meets the requirements for opening positions, multiple projectiles with sensors are thrown out by implementing the opening
mechanism of the carrier projectile. Multiple terminal-sensitive projectiles form a random array in the air and control the detonating device using the sensors in order to form a warhead with certain lethality that can attack the ground targets effectively [6]. The dispersion process of the terminal-sensitive projectile is the most complex stage in the whole flight process and directly determines the ground dispersion of projectiles. Yun et al. [7] considered the application background of the terminal sensitive missile-loaded linear array laser radar and researched the integrated cross-scan line method and the ground-distance image point of the gradient connected domain to enhance the detection and recognition performance of the terminal sensitive missile on the ground armor target in different scenarios. In the field of carrier projectile, considerable research has been conducted on the trajectory modeling of the terminal-sensitive projectile, opening control and dispersion of carrier projectile shrapnel. Ma et al. [8] researched the submunition ground dispersion of aviation terminal-sensitive cluster warhead (ATSCW), and established the 6-DOF mathematics model of ATSCW at the flight stage based on the Euler method. In [9], for reducing the large searching blind area phenomenon of terminal sensitive projectile intinterval sampling mode, this phenomenon is analyzed through establishing a scanning point distribution model in interval sampling mode and example demonstrating, which is caused by the periodic repetition or small increment of discrete normalized polar angle. Based on this rule, the geometric features and the forming conditions of large blind area phenomena of parachute and wing and terminal sensitive projectile with parachute terminal sensitive projectile have been studied. The three-dimensional unsteady compressible N-S fluid control formulas and six freedom rigid body motion formulas described by arbitrary Lagrange Euler have been solved by coupling and the three-dimensional unsteady flow field of projectile separated in different compartments under the time-series dispersion mode has been numerically simulated in [10] to obtain the interference characteristics of the separated flow field of carrier projectile in different compartments and the variation curves of aerodynamic parameters of the projectile. For the problem of ground dispersion of airborne terminal-sensitive projectile, a fast estimation method of the impact point dispersion of projectile based on the upper and lower bounds has been proposed in [11]. The ground dispersion law of airborne terminal-sensitive projectile has been analyzed under different dispersion conditions in [12]. Based on the adaptive cabin opening method of the error value of the ballistic data of the carrier projectile, the whole trajectory model of the projectile has been established in [13] through the dynamic analysis of the flight process of the spinning stabilized carrier projectile. The model was used to simulate and analyze the impact point dispersion of the father projectile, and an adaptive opening method of the carrier projectile with a modified opening point was proposed [13]. In [14], the most favorable fire distribution method of carrier projectile with uniform distribution projectile has been studied. The calculation method of firing efficiency of gun launched carrier projectile against uniformly distributed cluster targets is studied. The ellipse region of uniform distribution of projectiles is equivalently transformed into a rectangular region of uniform distribution. Under the condition of suitable firing direction, the mathematical model of firing efficiency calculation of carrier projectile against uniformly distributed cluster targets in a rectangular section has been derived in [15] through the analysis of the conditional damage probability of a single target. The above-mentioned studies have great significance in the development of terminal-sensitive projectiles. The purpose of the sensor of the terminal-sensitive projectile is mainly to control the detonating mechanism of the terminal-sensitive projectile, and then form a killing warhead group to damage the ground targets [16].

According to the terminal guidance killing power, when the projectiles and the ground target have an intersection, the power formed by a single terminal-sensitive projectile is limited. If the projectiles do not intersect with the ground target in a certain range, the explosion of the terminal-sensitive projectile cannot produce a killing effect. Effective damage can only be formed in a certain range of intersections. To improve the impact of the terminal-sensitive projectile to effectively damage the ground targets, it is necessary to rely on the joint action of multiple projectiles thrown by the terminal-sensitive projectile. At the same time, it is also necessary to consider the attack effectiveness of multiple terminal-sensitive projectiles under the condition of space formation. Therefore, this paper studies the detection efficiency of terminal-sensitive projectile and the damage assessment effect of the target based on laser detection sensor and multiple projectile power situation. The main contributions of this work are as follows:

1) A new calculation method of the damaging effect of the ground target is proposed by dividing the falling multiple sensitive projectiles into a multi-layer plane. The superposition principle is used to set up the power situation of multiple projectiles and analyzes the distribution of projectiles falling near the ground.

2) The detection method of laser detection sensor loaded on the projectile and the explosive principle that the projectile forms under the intersection between projectile and the ground target are researched and the calculation models of target reflection echo power and target thermal radiated power are established.

3) From the aspects of detection, attack and electronic jamming abilities, this paper set up the calculation model of the power situation of multiple projectiles. Based on the distribution of the terminal sensitive projectile group established, the fuzzy relationship between each evaluation index of the ground target and the distribution state of the terminal sensitive missile group is used to establish the
power evaluation function of the terminal sensitive projectile.

The remainder of this paper is organized as follows. Section II states the motion characteristics and the formation model analysis of multiple terminal-sensitive projectiles. Section III describes the detection mechanism of the terminal-sensitive projectile and the target’s laser reflected power calculation model. Section IV presents the power situations model of the terminal-sensitive projectile. Section V provides the damage assessment under the power situation. Section VI presents the calculation and analysis of the theoretical model. Finally, Section VI concludes this paper.

II. DISTRIBUTION CHARACTERISTICS OF MULTIPLE TERMINAL-SENSITIVE PROJECTILES ATTACKING GROUND TARGETS

In the field of weapon development, the changing dynamic parameters of a projectile, such as the falling velocity of the projectile and the location where the projectile explodes in terminal trajectories, restrict the performance of the weapon. These parameters are mainly related to the velocities and dispersion coordinates at initial, middle, and terminal trajectories. Due to the gun barrel vibration and the projectile friction in the gun bore during the process of projectile firing, uncertainty exists at the moment when the projectile leaves the gun bore that leads to uncertainty in the coordinate distribution of the projectile at the terminal trajectory. The multi-barreled weapons can fire multiple projectiles in a short time. These projectiles have laser detection sensors, so they all have the function of detecting and controlling the explosions when the projectile falls close to the ground target. The laser detection sensor is equipped with an emitting laser module and a laser energy processing module that receives the reflected energy from the ground target. The projectile uses the laser detection sensor of the device to sense the amount of energy reflected by the ground target to control the position of the projectile explosion in space. The projectile with execution and control is called a terminal-sensitive projectile. For a weapon that continuously fires multiple terminal-sensitive projectiles, the multiple terminal-sensitive projectiles form an uncertain explosion position distribution at terminal trajectories due to the inconsistent sensitivity of the laser detection sensor of the projectile and the difference in the flight velocity of the projectile. Therefore, the damage of multiple terminal-sensitive projectiles to the ground target also presents different power distribution. The damage caused by multiple terminal-sensitive projectiles attacking the ground targets is one of the important researches at present.

A terminal-sensitive projectile has the function of laser detection that can detect and recognize the ground target. By recognizing the useful information on the ground targets, the control actuator of the projectile ignites the internal detonating device to form the warhead to effectively hit and damage the ground targets. When multiple terminal-sensitive projectiles explode, the lethality of warhead fragments produced by the explosion of the projectile is the main factor that constitutes the formation power and situation distribution of the projectile. The power field at any point is caused by the superposition of the kinetic energy of all warhead fragments of the projectiles. Therefore, it is important to understand the relationship between the distribution of explosion positions of multiple terminal-sensitive projectiles and ground targets. Figure 1 shows the schematic diagram of the distribution of multiple terminal-sensitive projectiles explosion positions and the ground targets.

In Figure 1, taking the center of the ground target as the center coordinates denoted as \( o(0,0,0) \), \( \alpha \)xyz is the coordinate system. \( P(x_i, y_i, z_i) \) is the position where any terminal-sensitive projectile explodes. In this paper, the warhead fragments generated by the explosion of each terminal-sensitive projectile are set to be the same size and distribution direction.

According to the dispersion characteristics of multiple terminal-sensitive projectiles in terminal ballistics, the falling process of multiple terminal-sensitive projectiles is a random distribution. The multiple terminal-sensitive projectiles form a certain queue by mapping from the ground to the air, thus causing a certain power attack situation to the ground targets. Therefore, to study the effective damage ability of multiple terminal-sensitive projectiles to the ground target, it is necessary to analyze the power situation of multiple terminal-sensitive projectiles. Suppose \( N \) terminal-sensitive projectiles are attacking the ground target as shown in Figure 2.
In Figure 2, the falling projectiles can be layered according to the time sequence of falling. The number of projectiles in each layer is $n_i$, and there are total $n_S$ layers. Then the terminal-sensitive projectile group is determined by $n_i \times n_S \times N = n_i \times n_S$.

The effective initiation area $S_i$ of each terminal-sensitive projectile to the ground target is determined by the height of the projectile explosion and the dispersion angle of the warhead fragments. This paper mainly considers the area that the falling terminal-sensitive projectile can turn over and the area of a single target on the ground. According to the intersection of the two factors, whether the terminal-sensitive projectile group can effectively damage the ground target is determined. If the coverage area formed by $n_i \times n_S$ terminal-sensitive projectile is $S_i$, $S_i = \sum_{i=1}^{N} S_i$, and the area of a single ground target is $S_2$. When the condition $S_2 \in S_i$ is satisfied, the ground targets may be damaged. From the power situation of multi-layer formation in Figure 2, each terminal-sensitive projectile has its communication, detection and anti-interference abilities, which form the power situation under certain formation conditions. At the same time, for the coverage area formed by $n_i \times n_S$ terminal-sensitive projectiles, some of them intersect with the ground target, while others do not. In this mode, it can be defined as gain or loss by using whether the terminal-sensitive projectile group intersects with the ground target. Gain is when the two intersect and loss when they do not intersect. Based on the gain and loss, the power situation of terminal array formation of multiple terminal-sensitive projectiles evaluation model is established.

III. LASER DETECTION MECHANISM AND ECHO POWER CALCULATION MODEL OF TERMINAL-SENSITIVE PROJECTILE IN TERMINAL TRAJECTORY

A. LASER AND INFRARED DETECTION MECHANISM

Before evaluating the power situation of the random array of multiple terminal-sensitive projectiles, it is necessary to establish the laser echo power calculation model and infrared radiated power of ground targets according to the scanning detection mechanism of the terminal-sensitive projectile. The array terminal-sensitive projectile can form an effective attack target and achieve a damaging effect. Each terminal-sensitive projectile must produce effective damage warhead fragments, which means that the terminal-sensitive projectile needs to reach the explosion purpose under the condition of the effective intersection distance between the terminal-sensitive projectile and the ground target. In this paper, the laser detection sensor of the terminal-sensitive projectile uses a pulse laser and corresponding wavelength photoelectric receiving module. According to the wavelength of the photoelectric detector, the laser detection sensor can be divided into laser wavelength and infrared wavelength. Figure 3 shows the schematic diagram of the laser detection sensor of the terminal-sensitive projectile.

The laser photoelectric receiving module comprises a weak detection amplifying circuit, a signal conversion circuit and a trigger detonation device actuator. In the detection and control of the terminal-sensitive projectile, the infrared photoelectric module mainly senses the thermal radiation generated by the ground target to perform detonation control.

If $R$ is the distance between the terminal-sensitive projectile and the ground target, according to the rotating scanning mechanism of the terminal-sensitive projectile, there is always a laser emission coverage area that can detect the ground target and form a reflection echo, here, $R = \sqrt{x_i^2 + y_i^2 + z_i^2}$, $i = 1, 2, \ldots, n$, where $i$ is the $i$-th projectile and $n$ is the number of projectiles. Because of the fast rotation speed of the terminal-sensitive projectile, the reflected laser echo energy is a continuous signal with a certain time interval. The peak of the signal energy is determined by the emitting power of the laser and the position where the projectile is relative to the ground target.

It is necessary to consider the parameters of the laser emitting and receiving light path to effectively estimate the detection ability of the laser detection sensor of the terminal-sensitive projectile. The distance between the laser emission lens and the receiver lens of the photoelectric receiving module is $a$. It is not difficult to find that the distance between the projectile and the ground target is much greater than that of $a$. In this paper, the effect of $a$ on the received echo energy in the photoelectric receiving module is ignored. When the emitting laser scans a ground target, the ground target’s surface reflects laser energy, and then, the reflected laser energy incident the window of the photoelectric detection module. This reflected laser energy is amplified in amplifying circuit, the amplified signal passes through the signal conversion circuit and form a control instruction to control the detonator of the terminal-sensitive projectile. The principle of an infrared sensor that detects the ground targets is the same. The difference is that the infrared detection module mainly receives the thermal radiation of the ground targets, and forms the detonation control of the terminal-sensitive projectile through the size of the radiated power.
For the detonation control of the terminal-sensitive projectile, the signals output by the laser waveband and the infrared waveband of the laser detection sensors are determined together. Thus, the terminal-sensitive projectile has detection, attack and electronic jamming abilities.

B. ECHO POWER AND RADIATED POWER CALCULATION MODELS

Since the terminal-sensitive projectile is affected by air resistance and gravity in the process of falling at the terminal ballistics, it has a certain angle when attacking the ground target. This angle is also the intersection angle between the terminal-sensitive projectile and the ground target. Suppose the vertical height between the terminal-sensitive projectile and the ground target is \( H \), the intersection angle of terminal-sensitive projectile and ground target is \( \theta \). For the principle of laser detection sensor of the terminal-sensitive projectile, the pulse of the emitting laser is a Gaussian pulse, and the emitting power of the pulse laser is related to the time that the emitting laser irradiates the ground target and then returns to the laser emission lens of photoelectric detection module. The emitting power of the pulse laser can be expressed by formula (1).

\[
P_i(t) = P_0 \exp\left[-t^2 \ln 2 / \tau^2 \right]
\]

(1)

In formula (1), \( P_0 \) is the peak power of the pulse laser; \( \tau \) represents the half-width of the emitted laser output pulse [17-18] and \( t = 2R / c \), where \( c \) is the velocity of light. When \( R \) is different, \( t \) is also different.

When the terminal-sensitive projectile gradually approaches the target, the echo energy reflected from the surface of the target increases and the peak value of the echo analog signal formed by it also gradually increases. The echo analog signal is similar to a sine wave. The cosine distribution of reflection intensity instead of the uniform distribution of reflection intensity is closer to the actual situation, that is, the reflection intensity in the incident direction is considered to be twice the average intensity. Regarding the surface of the ground target as an extended plane, the photoelectric detection module can receive the reflected laser power from the ground target that can be obtained by formula (2).

\[
P_{\text{LI}}(t) = \frac{P_i A_{\text{ROI}} \rho \tau_i \cos \theta}{2\pi R^2} \exp\left(-t^2 \ln 2 / \tau^2 - 2\mu R \right)
\]

(2)

In formula (2), \( \tau_i \) and \( \tau_0 \) are the transmittances of the laser transmitting system and the photoelectric detection module, respectively; \( \mu \) is the attenuation coefficient of the laser energy through the atmosphere; \( A_{\text{ROI}} \) is the receiving area of the photoelectric detector and \( \rho \) is the diffuse reflection coefficient of the ground target [19-20].

For the detection of the infrared waveband, the thermal emissivity of the gray body is determined by the absolute temperature of the ground target and the emissivity of the ground target in the infrared waveband. According to Planck’s law, the radiant exitance of the ground target is obtained by formula (3).

\[
M(\lambda, T) = \frac{2\pi h c^2 \lambda^{-5}}{e^{h c / \lambda k T} - 1}
\]

(3)

In formula (3), \( \lambda \) is the wavelength of radiation; \( T \) is the absolute temperature of the ground target; \( K \) is the Boltzmann constant; \( h \) is the Planck constant and \( c \) is the velocity of light.

For the ground targets with a heat source such as tanks, infrared radiation is emitted to space in the hemispherical form. The infrared detection module can obtain the radiated power from the ground target that can be calculated by formula (4).

\[
P_{\text{IR}} = \eta \int \lambda^2 e M(\lambda, T) d\lambda / 8(\pi R)^2
\]

(4)

In formula (4), \( B \) is a constant of responsivity for the instantaneous field of view [21]; \( \epsilon \) is the average emissivity of the surface of the ground target; \( \eta \) is the atmospheric transmittance of thermal radiation; \( t' \) is the duration time when the radiated power reaches the highest level and \( \lambda_1 - \lambda_2 \) is the responsive waveband range of the infrared sensor.

IV. POWER SITUATION MODEL OF MULTIPLE TERMINAL-SENSITIVE PROJECTILE WITH LASER AND INFRARED COMPOSITE

A. POWER SITUATION MODEL OF TERMINAL-SENSITIVE PROJECTILE

From the detection principle of the terminal-sensitive projectile and its reflected laser power calculation function, the terminal-sensitive projectile can meet the explosion condition if the photoelectric detection module receives a certain laser reflection energy from the ground target. Therefore, the explosion position of each terminal-sensitive projectile presents a different distribution state [22].

It can be seen from Figure 2 that the multiple terminal-sensitive projectiles form a multi-layer and multiple projectiles distribution. Assuming that at time \( t \), \( (x_i, y_i, z_i) \) is the spatial position of the \( i \)-th terminal-sensitive projectile, the power situation of the \( i \)-th terminal-sensitive projectile can be expressed by formula (5).

\[
E_i(t) = E_i(x_i, y_i, z_i, y_{T1}, y_{T2}, z_{T1}, t) = E_{\text{IR}}(t)(\omega_{1i} E_{\text{IR}}(t) + \omega_{2} E_{\text{IR}}(t))
\]

(5)

In formula (5), \( E_{\text{IR}}(t), E_{\text{IR}}(t) \) and \( E_{\text{IR}}(t) \) are detection, attack and electronic jamming abilities, respectively, while \( \omega_{ij} \) is the weight of the \( j \)-th index at time \( t \), and satisfies

\[
\sum_{j=1}^{2} \omega_{ij}(t) = 1[23].
\]

Assuming that there are \( n_1 \times n_2 \) terminal-sensitive projectiles, if multiple terminal-sensitive projectiles are
independent of each other, there may be multiple terminal-sensitive projectiles in the same position \( P(x_i, y_i, z_i) \) within the range of \( S_1 \). Then the power situation at this position will be acted by multiple terminal-sensitive projectiles and can be expressed using formula (6).

\[
E(t) = \sum_{k=1}^{m_1} \sum_{l=1}^{m_2} E_{0(k,l)}(t) + \alpha E_{2(k,l)}(t) + \lambda E_{3(k,l)}(t)
\]

(6)

In formula (6), \( m_1 \) is the number of terminal-sensitive projectiles of \( n_1 \), \( m_2 \) is the number of terminal-sensitive projectiles of \( n_2 \), and \( E(t) \) is the general power situation of all terminal-sensitive projectiles.

**B. DETECTION ABILITY OF TERMINAL-SENSITIVE PROJECTILE**

In terminal-sensitive projectile with laser detection sensor, the detection ability of terminal-sensitive projectile is a key to forming an effective damage situation. Assuming that the terminal-sensitive projectile is detected by laser and infrared modes, the detection ability model of the terminal-sensitive projectile can be expressed by formula (7).

\[
E_n(t) = \sum_{k=1}^{m_1} \sum_{l=1}^{m_2} \ln(1 + \sigma_{0(k,l)}(t) + \sigma_{2(k,l)}(t))
\]

(7)

In formula (7), \( \sigma_{0(k,l)}(t) \) and \( \sigma_{2(k,l)}(t) \) are the laser detection and the infrared detection ability factors of the terminal-sensitive projectile, respectively [24].

The laser detection ability factor of the terminal-sensitive projectile can be calculated by formula (8).

\[
\sigma_{0(k,l)}(t) = \alpha \frac{R_{\text{max}}^2}{4R} \theta_{R(k,l)}(t) P_{k_2} \cdot (k' \times I')^{0.05}
\]

(8)

In formula (8), \( R_{\text{max}} \) is the maximum detection distance of laser, \( R \) is the actual detection distance, \( \theta_{R(k,l)}(t) \) is the total azimuth of the searched target in the laser mode of the terminal-sensitive projectile, \( P_{k_2} \) is the target detection probability in the laser mode of the terminal-sensitive projectile, \( \alpha \) is the measurement coefficient of laser mode, \( k' \) is the number of targets detected simultaneously in laser mode, and \( I' \) is the number of ground targets allowed to attack simultaneously in laser mode [25].

The infrared detection ability factor of the terminal-sensitive projectile can be calculated using formula (9).

\[
\sigma_{2(k,l)}(t) = \beta \frac{R_{\text{max}}^2}{4R} \theta_{R(k,l)}(t) P_{k_3} \cdot (k' \times I')^{0.05}
\]

(9)

In formula (9), \( R_{\text{max}} \) is the maximum detection distance in infrared mode; \( \theta_{R(k,l)}(t) \) is the total azimuth of infrared searching target of the terminal-sensitive projectile; \( P_{k_3} \) is the target detection probability in infrared mode of the terminal-sensitive projectile; \( \beta \) is the measurement coefficient of laser mode; \( k' \) is the number of targets detected simultaneously in infrared mode; \( I' \) is the number of targets allowed to attack simultaneously in infrared mode.

**C. ATTACK ABILITY OF TERMINAL-SENSITIVE PROJECTILE**

According to formula (5), multiple effective terminal-sensitive projectiles combine to form attack ability. The model can be expressed by formula (10).

\[
E_I(t) = \sum_{k=1}^{m_1} \sum_{l=1}^{m_2} \ln(1 + \sigma_{0(k,l)}(t))
\]

(10)

In formula (10), \( \sigma_I(t) \) is the attack ability factor [13], and its model is as follows:

\[
\sigma_{0(k,l)}(t) = k \times l \times R \times P_{k_1} \times \frac{\varphi_{(k,l)}(t)}{2\pi} \cdot \frac{e_{\text{max}}}{35} \times \frac{S_{\text{max}}}{20} \times K_{r}
\]

(11)

In formula (11), \( k \times l \) is the number of terminal-sensitive projectiles at the current time \( t \), \( P_{k_1} \) is the kill probability of a single terminal-sensitive projectile, \( \varphi_{(k,l)}(t) \) is the attack angle of the terminal-sensitive projectile, \( e_{\text{max}} \) and \( S_{\text{max}} \) are the maximum available overload and the maximum attack area of the terminal-sensitive projectile, respectively, \( K_r \) is the correction coefficient of the guidance mode of the terminal-sensitive projectile, which is generally 1, and \( R \) is the detection distance [26].

**D. ELECTRONIC JAMMING ABILITY OF TERMINAL-SENSITIVE PROJECTILE**

Assuming that the flight axis of the terminal-sensitive projectile is in the same direction as the ground target axis, the electronic jamming ability model of the terminal-sensitive projectile can be constructed by formula (12).

\[
E_J(t) = \ln(1 + \sigma_{21(k,l)}(t) + \sigma_{22(k,l)}(t) + \sigma_{23(k,l)}(t))
\]

(12)

In formula (12), \( \sigma_{21(k,l)}(t) \) is the active jamming ability factor, \( \sigma_{22(k,l)}(t) \) is the laser jamming ability factor and \( \sigma_{23(k,l)}(t) \) is the infrared jamming ability factor. The active jamming ability factor model is obtained by formula (13).

\[
\sigma_{21(k,l)}(t) = \frac{A_j \cdot \phi \cdot \sigma \cdot e \cdot P_j \cdot G \cdot P_j}{R \cdot \Delta t \cdot (\Delta f + \Delta \phi)}
\]

(13)

In formula (13), \( A_j \) is the jamming gain of the terminal-sensitive projectile, \( P_j \) is the laser jamming transmitting power, \( \phi \) is the beamwidth of the jamming source, \( \sigma \) is the maximum pointing range of the jamming source transmitting wave in space, \( e \) is the multiple laser jamming ability, \( P_j \) is the frequency range coverage ratio of the jamming source to the frequency range of the jammed laser, \( \Delta t \) is the time of the jamming source from receiving the threatening laser signal to transmitting the radio frequency jamming signal, \( \Delta f \) is the time and
frequency error of the signal, $\Delta \phi$ is the azimuth error, and $G$ is the gain coefficient [27].

The model of the laser jamming ability factor can be expressed by formula (14).

$$\sigma_{22(k,j)}(t) = N' \times P' \times S'_v / t_1$$

In formula (14), $N'$ is the number of interferences between laser modes of the terminal-sensitive projectile; $P'$ is the emission probability under laser mode of the terminal-sensitive projectile; $S'_v$ is the area of the ground target that can be effectively reflected by the laser receiving system and $t_1$ is the emission and receiving time under the laser mode [28].

The model of the infrared jamming ability factor can be expressed by formula (15).

$$\sigma_{23(k,j)}(t) = N_v \times P_v \times S_v / t_2$$

In formula (15), $N_v$ is the number of interferences between laser modes of the terminal-sensitive projectile, $P_v$ is the emission probability under laser mode of the terminal-sensitive projectile, $S_v$ is the area of the ground target that can effectively reflect the infrared receiving system and $t_2$ is the radiation receiving time under infrared mode.

V. POWER SITUATION EVALUATION AND DAMAGE ASSESSMENT METHOD OF MULTIPLE TERMINAL-SENSITIVE PROJECTILES

Combined with the power situation model of multiple terminal-sensitive projectiles, the power situation evaluation is related to the terminal-sensitive projectile ability parameters. Different formation forms of the terminal-sensitive projectile are formed at different times when the carrier projectile is opened. Each terminal-sensitive projectile in the formation is regarded as having the ability to effectively attack the ground target. Taking the terminal-sensitive projectile ability parameters as the set of evaluation indexes, the fuzzy evaluation grades and rules of the terminal-sensitive projectile with intersection distribution on ground targets are established.

If $C = \{1, 2, \cdots, h\}$ and $D = \{1, 2, \cdots, g\}$, the evaluation index set with the terminal-sensitive projectile ability parameters as elements is expressed by formula (16).

$$X = \{x_1, x_2, \cdots, x_h\}$$

In formula (16), $x_i (i \in h)$ is the $i$-th index element in $X$. The evaluation grade set is established using formula (17).

$$Y = \{y_1, y_2, \cdots, y_g\}$$

In formula (17), $y_j (j \in g)$ is the membership degree of the $j$-th evaluation grade, and the evaluation grade can be expressed by interval number. Considering the random performance difference between different multiple terminal-sensitive projectiles, their combat effectiveness against ground targets will also be different. The terminal-sensitive projectile is considered as the standard to evaluate various ability indexes, and the scaling method is used to determine the evaluation matrix [29].

$$U = \left[ U_{ij} \right]_{h \times g}$$

In formula (18), $U_{ij}$ is the evaluation scale value of the $i$-th evaluation grade of the $j$-th index of the terminal-sensitive projectile. Fuzzy relation matrix is established by formula (19).

$$F' = \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1g} \\ f_{21} & f_{22} & \cdots & f_{2g} \\ \vdots & \vdots & \ddots & \vdots \\ f_{h1} & f_{h2} & \cdots & f_{hg} \end{bmatrix}$$

where, $f_{ij} = \delta_{ij} / \varphi$. $f_{ij}$ is the membership degree of the index $X_i$ in $X$ corresponding to the evaluation grade $y_j$ in $Y$ and $\delta_{ij} (i \in h, j \in g)$ is the number of times evaluated as $y_j$ of the index $X_i$.

According to formulas (18) and (19), the fuzzy comprehensive evaluation decision matrix formed by the terminal-sensitive projectile group to the ground target is expressed as:

$$F = UF'^T = \left[ o_1, o_2, \cdots, o_h \right]$$

where, $o_i (i \in h)$ is the $i$-th element membership of the damage evaluation grade of the terminal-sensitive projectile to the ground target [30].

According to formulas (16) - (20), the evaluation values of various ability parameters of the terminal-sensitive projectile can be obtained. Then according to formulas (5) - (15), the $j$-th ability of the $i$-th terminal-sensitive projectile can be obtained, and the power evaluation matrix of the terminal-sensitive projectile group against the ground target can be constructed.

$$W = FE = \left[ o_{ij} \right]_{a \times b}$$

where, $o_{ij}$ is the ability function value of the power of the terminal-sensitive projectile group. $a'$ and $b'$ are the ability items of the terminal-sensitive projectile group and the ground target, respectively.

VI. CALCULATION ANALYSIS

A. CALCULATION AND ANALYSIS OF TARGET POWER

The echo power variation law of ground target under different intersection angles and different detection distances is analyzed according to the calculation model of target echo power of the laser sensor system. Assuming that the receiving diameter of the pulse laser sensor system is $0.02m$; the transmittance of the laser transmitting system is...
0.88; the transmittance of the photoelectric detection and receiving system is 0.92; and the diffuse reflection coefficient of the ground target is 0.65, the laser emission power is 75 W. In the process of terminal-sensitive projectile detecting the ground targets, its flight altitude gradually decreases and the flight altitude range decreases from 10 m to 4 m. In addition, assuming that the altitude angle of the terminal-sensitive projectile is 0°, namely, the intersection angle between the axis in the field of view of the laser detection system and the vertical direction is 0°. According to formula (2), the laser echo waveform at different detection distances is shown in Figure 4. It is found that when the detection distance between the projectile and the target is smaller, the echo power reflected by the target is larger, and the output signal of the photoelectric detector is stronger under the same laser emission power condition.

When the laser emission beam irradiates the ground target, because the laser emission beam of the terminal-sensitive projectile is expanded, the laser reflection echo received by the system exists an aliasing effect in the time domain, resulting in the broadening of the pulse width of the laser reflection echo. The larger the detection distance is, the wider the pulse width of the laser reflection echo is. In addition, the pulse peak of laser reflection echo shifts backwards in the time domain due to the aliasing of laser reflection echo. Combined with the shift of laser reflected echo signal in the time domain under different detection distances, the laser echo power waveforms under different detection distances are formed, as shown in Figure 4. It can be seen from Figure 4 that with the increase of detection distance, the laser echo power decreases, and it tends to decrease rapidly first and then slowly. Although the laser echo signal is still similar to the Gaussian distribution in the time domain, the pulse width of the laser echo signal widens with the increase of detection distance.

The altitude of the terminal-sensitive projectile in flight is affected by external factors. The echo characteristics under different intersection angles are calculated and analyzed. Figure 5 shows the laser echo waveforms at different intersection angles when the laser emission power remains unchanged at 75 W and the detection distance is 6m. It is not difficult to find that the larger the intersection angle is, the smaller the echo power is, which fully reflects that the change of intersection angle is also the main parameter that affects the performance of the missile detection target.

According to the calculation model of radiated power of the infrared sensor system, the radiated power variation law under different detection distances is analyzed. The simulation parameters are set as follows: the intersection angle is about 30°; the radiation wavelength is 8 μm; the absolute temperature of the car body is 350 K; the atmospheric transmittance of thermal radiation is 0.8 and the average emissivity of the surface of the ground target is 0.85. According to formula (4), the radiated power with the change of detection distance is calculated, and the results are shown in Figure 6.

It can be seen from Figure 6 that with the decrease of the detection distance of the infrared sensor system, the target thermal radiation received by the infrared sensor system increases and the radiated power increases. However, compared with the trend of the laser echo power of the laser sensor system, the radiated power detected by the infrared sensor system changes more slowly with the detection distance.
distance, which accords with the characteristics of the infrared detection system.

In order to analyze the detection ability of the laser and infrared detection modes to the ground target, the corresponding signal conversion circuit is used to make the two detection modes output voltage signals.

**B. Calculation analysis of situation evaluation**

According to the characteristics of the carrier projectile’s opening cabin to throw the terminal-sensitive projectile and the different falling formation modes of the terminal-sensitive projectile, the ability calculation model of the terminal-sensitive projectile and the power situation evaluation method are established. In this case, five terminal-sensitive projectiles loaded with a carrier projectile are used to attack the ground target (one tank). The calculation method is as follows:

1. Take the relative position of the ground tank as the origin of the system coordinate center. The initial position of the terminal-sensitive projectile is shown in Table 1, and the unit is meter. Based on the initial position of the terminal-sensitive projectile and combined with the signal conversion circuit, the voltage signals output by each terminal-sensitive projectile in laser and infrared detection states are obtained. In Table 1, $V_L$ is the voltage output by the laser sensor system, $V'_L$ is the voltage output by the infrared sensor system, and the unit is millivolt.

| NO. | $P(x, y, z)$ | $V_L$ | $V_p$  |
|-----|-------------|-------|--------|
| 1   | 1.77        | 6.12  | 1.41   | 1605 | 1785  |
| 2   | 2.42        | 5.45  | 1.35   | 1895 | 2032  |
| 3   | 1.37        | 5.52  | 1.31   | 2073 | 2124  |
| 4   | 1.52        | 3.24  | 1.49   | 2706 | 2940  |
| 5   | 1.15        | 4.59  | 1.33   | 2597 | 2556  |

The laser and infrared sensor systems both output voltage signals, and the voltage signal of the terminal-sensitive projectile is greater than the corresponding threshold of each detection system. It is judged that the terminal-sensitive projectile detects the real ground target in the effective detection region.

2. According to formulas (5) - (15), the ability values of the terminal-sensitive projectile are calculated, and then the power matrix is obtained:

$$E = \begin{bmatrix} 6.63 & 4.16 & 5.42 \\ 7.13 & 5.74 & 4.25 \\ 7.32 & 6.41 & 5.01 \\ 7.18 & 6.10 & 3.54 \\ 6.81 & 5.99 & 3.92 \end{bmatrix}$$

3. The terminal-sensitive projectile ability parameters are the evaluation indexes. Taking the detection ability of the terminal-sensitive projectile as an example, according to formula (18), the scaling method is used to obtain the evaluation matrix $U$. According to formula (19), the fuzzy relation matrix of detection ability of each terminal-sensitive projectile is given as $F'_1, F'_2, F'_3, F'_4$ and $F'_5$.

$$U = \begin{bmatrix} 0.65 & 0.12 & 6 & 0.32 & 0.57 \\ 2.11 & 0.19 & 8 & 0.56 & 0.8 \\ 3.08 & 0.43 & 9 & 0.88 & 1.25 \\ 0.45 & 0.15 & 0 & 0.40 & 0.20 \\ 0.35 & 0.50 & 0.65 & 0.55 & 0.80 \\ 0.20 & 0.35 & 0.35 & 0.05 & 0 \end{bmatrix}$$

$$F'_1 = \begin{bmatrix} 0.35 & 0.50 & 0.65 & 0.55 & 0.80 \\ 0.20 & 0.35 & 0.35 & 0.05 & 0 \end{bmatrix}$$

$$F'_2 = \begin{bmatrix} 0.75 & 0.45 & 0.05 & 0.60 & 0.50 \\ 0.10 & 0.15 & 0.40 & 0.05 & 0.20 \end{bmatrix}$$

$$F'_3 = \begin{bmatrix} 0.65 & 0.30 & 0.15 & 0 & 0.30 \\ 0.10 & 0.15 & 0.40 & 0.05 & 0.20 \end{bmatrix}$$

$$F'_4 = \begin{bmatrix} 0.25 & 0.55 & 0.65 & 0.75 & 0.65 \\ 0.10 & 0.15 & 0.20 & 0.25 & 0.05 \end{bmatrix}$$

$$F'_5 = \begin{bmatrix} 0.35 & 0.35 & 0 & 0.10 & 0.15 \\ 0.25 & 0.25 & 0.15 & 0.10 & 0.30 \end{bmatrix}$$

$$F'_1 = \begin{bmatrix} 0.70 & 0.75 & 0.80 & 0.75 & 0.60 \\ 0.05 & 0 & 0.05 & 0.15 & 0.10 \end{bmatrix}$$

The fuzzy comprehensive evaluation decision matrix model can be obtained from formula (20).

$$F'_1 = UF'_1 = \begin{bmatrix} 1.65 & 0.26 & 8.35 & 0.48 & 0.74 \\ 1.12 & 0.19 & 8.30 & 0.43 & 0.74 \end{bmatrix}$$

$$F'_2 = UF'_2 = \begin{bmatrix} 1.26 & 0.21 & 7.90 & 0.64 & 0.73 \\ 0.19 & 0.20 & 8.25 & 0.58 & 0.87 \end{bmatrix}$$

$$F'_3 = UF'_3 = \begin{bmatrix} 1.79 & 0.17 & 7.75 & 0.59 & 0.75 \end{bmatrix}$$

According to formulas (7)-(9), the detection abilities of the five terminal-sensitive projectiles are 6.29, 6.57, 6.42, 6.36 and 6.24.

Similarly, the attack and electronic jamming abilities of the terminal-sensitive projectile group can also be calculated. The weight coefficients that mainly reflect the attack ability are $\omega_1 = 0.75$ and $\omega_2 = 0.25$. Therefore, the power evaluation matrix of the terminal-sensitive projectile group is:

$$W = \begin{bmatrix} 6.29 & 3.61 & 4.58 \\ 6.57 & 4.85 & 3.36 \\ 6.42 & 5.34 & 4.41 \\ 6.36 & 5.28 & 3.03 \\ 6.24 & 4.91 & 2.86 \end{bmatrix}$$

According to the position of the terminal-sensitive projectile in Table 1, the power situation distribution of the terminal-sensitive projectile to the ground target at $t = 0$ and $t = 0.5s$ after the opening time is calculated. For the convenience of analysis, the power potential of the terminal-sensitive projectile is normalized, and the distance
between the terminal-sensitive projectile and the ground tank is recorded as \( R \), and \( R = \sqrt{x_i^2 + y_i^2 + z_i^2} \).

Considering the proportion of the scattered area formed by the explosion of the terminal-sensitive projectile and the area of the upper surface of the ground tank covered, the damage change of the power field formed by the terminal-sensitive projectile to the ground tank is calculated in two time states. The damage probability calculation is adopted, 
\[
P = \frac{\sum S_i}{S},
\]
where \( S \) is the area of the upper surface of the tank, \( S_i \) is the area covered by the terminal-sensitive projectile, and \( \sum S_i \) is the total area of the upper surface of the tank. The vulnerable characteristics of the ground tank are not considered. The calculation results are shown in Figure 7.

![Figure 7](image7.png)

**FIGURE 7.** Damage probability of terminal-sensitive projectile group at \( t = 0s \) and \( t = 0.5s \) after the opening time.

It can be seen from Figure 7 that the dispersion and power of the terminal-sensitive projectile are different at different times after the opening of the carrier projectile. The damage probability of the terminal-sensitive projectile to the ground target is also different at different times. The shorter the relative distance between the terminal-sensitive projectile and the ground target, the greater the power formed after detonation, and the better the damaging effect on the ground target. The power potential damage analysis of each power capability of the terminal-sensitive projectile to the ground target can provide a scientific basis for the next step of situation evaluation of ground multi-target under the random distribution of uncertain terminal-sensitive projectiles.

In order to evaluate the method proposed in this paper, the damage assessment method based on the adaptive Neuro-fuzzy inference system (ANFIS) in Reference [31] is used for comparative analysis. Figure 8 shows the damage probability results of the two calculation methods for the same ground target. M1 and M2 represent the damage probability calculation method proposed in this paper and the method based on ANFIS, respectively.

An ANFIS is also a common method for target damage assessment. However, this method only considers the damage of warhead fragments formed by a single projectile explosion to the target, mainly considering the warhead fragment parameter characteristics, and does not consider the effect of ground damage from the synergy between multiple projectiles, that is, it does not consider the influence factors of power field between terminal-sensitive projectiles. Thus, the calculated damage probability is slightly different. When the distance between the terminal-sensitive projectile and the target is 1 to 3 m, the difference in the target damage probability is not obvious. However, when the distance between the terminal-sensitive projectile and the target is longer, the damage probability based on the ANFIS calculation method is slightly higher. The main reason is that the proposed damage probability calculation method considers more damage factors, and the influence of various factors on the damaging effect cannot reach the ideal value. The damaging effect calculated by the method proposed in this paper is slightly different from that in Reference [31], which also reflects that the proposed method is closer to the damaging effect of the actual test environment.

**VII. CONCLUSION**

According to the condition of the dispersion of the multiple terminal-sensitive projectiles, this paper focuses on the research of the attack power ability of multiple terminal-sensitive projectiles to the ground target and analyzes the characteristics of multiple terminal-sensitive projectiles forming multi-time and multi-layer projectile distributions in the fall. Combining with the effective exposed area of the ground target, the intersection area relationship between the dispersion area of the terminal-sensitive projectile and the ground target is discussed. Combining the compound detection mechanism of the terminal-sensitive projectile with the reflection characteristics of the ground target, the power situation calculation model of the terminal-sensitive projectile is established. From the aspects of detection, attack and electronic jamming abilities, the detection efficiency model of the terminal-sensitive projectile to the ground target is derived considering the fuzzy relationship.
between each evaluation index of the terminal-sensitive projectile.

According to the proportional relationship between the dispersion area formed by the terminal-sensitive projectile explosion and the upper surface area of the ground target, the damage change of the power field formed by the terminal-sensitive projectile to the ground target in two time states is calculated, and the area proportion function is used to calculate the damage probability of the terminal-sensitive projectile to the ground target. The evaluation analysis demonstrates that with the different opening heights of carrier projectile and the different numbers and distribution densities of the terminal-sensitive projectiles, the detection effect of ground targets is different. The obtained results verify the rationality of the model established in this paper.

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