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Space Projectile Explosion Position Parameters Measurement Method and Target Damage Probability Calculation Analysis

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ABSTRACT Because the random states of the projectile explosion position relative to the intersection target, the dispersion characteristics of warhead fragments are inconsistent, and it is difficult to provide a scientific calculation model of the target damage of warhead fragments formed by projectile proximity explosions. This paper studies a testing method of the projectiles explosive position using a combination of six screen sensors and an area array camera. We set up a calculation model of the projectile proximity explosion position parameters, which establishes the proximity explosion area probability of the projectile hitting the target. The calculation method of the target damage condition probability under the condition of firing multiple projectiles in one test was researched according to the dispersion characteristics of projectile proximity explosion, the damage area of the target, and the intersection condition of the projectile and the target. We also establish a target damage probability calculation model under the condition of an effective projectile proximity explosion hitting the target. The experimental results show that the target damage results of a theoretical simulation calculation and an actual projectile proximity explosion test data calculation were basically consistent. Moreover, the proposed target damage calculation model was verified under the probability of multiple projectile proximity explosions hitting the target.

INDEX TERMS Six screen sensor, area array camera, projectile explosion position, target damage probability.

I. INTRODUCTION

The hit probability of a projectile fired by artillery is an important indicator for evaluating the development level and combat capability of a weapon system [1], [2]. The hit probability of the weapon system depends on the precision of the weapon system and the density of artillery [3], [4]. The actual target damage effectiveness is obtained by the density degree of the projectile hitting probability [5], specifically, the damage effectiveness of the air defense interception warhead, which is an important parameter for assessing the power of the projectile proximity explosion [6], [7]. The damage of the air defense interception warhead is that the projectile fuse detonates under the condition of the projectile and target intersection (projectile explosion position and target position) when the projectile approaches the target and then forms warhead fragments to damage the target [8]. Because of the uncertainty of the projectile's flight states and the diversity of the target's flight attitude, the intersection of the projectile and the target are random, and different amounts of damage are produced. From the perspective of the damage target, it is closely related to the projectile explosion position and the warhead fragment dispersion generated by the projectile proximity explosion. At present, there are two modes of warhead fragments by a projectile proximity explosion. One is prefabricated warhead fragments. In this mode, the

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quality and quantity of the warhead fragments produced by the projectile proximity explosion are basically determined. The difference is that the dispersion angle, velocity, and flight vector parameters of warhead fragments caused by the projectile proximity explosion are uncertain [9]. The second mode is non-prefabricated warhead fragments. In this mode, the mass, size, and quantity of the warhead fragments formed by the projectile proximity explosion are uncertain [10]. No matter which type of projectile proximity explosion damage, it is necessary to analyze the correlation of the projectile explosion position and target position and then establish the appropriate damage model at the intersection states of the warhead fragments and the target. Because the parameters of warhead fragments are difficult to obtain in air defense interception projectiles, especially in the condition of a projectile proximity explosion at a high altitude, it is more difficult to obtain the parameters of the warhead fragments [11]. Based on the existing test system, it is difficult to comprehensively obtain the relevant damage calculation parameters; for the current damage assessment calculation methods, and modeling and analysis are used for near-Earth target damage. Prior work [12]–[14] has mainly studied target damage on ground artillery strike cluster equipment and established damage calculation methods based on known and determined target vulnerable conditions.

With the development of weapons, the damage of the target in space is an important part of testing. Because of the uncertainty of the projectile proximity, it is necessary to establish a damage calculation method of a spatial target in the projectile hitting area. The target damage at a projectile and target intersection with an uncertain state do not have a relatively perfect mathematical model. This paper establishes a target damage calculation method of the projectiles proximity explosion hit probability at the projectile and target intersection, and the purpose is to effectively and scientifically evaluate the damage effectiveness of warhead fragments formed by projectile proximity explosions on the target.

II. BASIC PRINCIPLES OF A PROJECTILE PROXIMITY EXPLOSION UNDER THE CONDITION OF PROJECTILE AND TARGET INTERSECTION

A projectile proximity explosion under the condition of the projectile and target intersection mainly means that when the projectile fired by the artillery is close to the target in space, the fuse device of the projectile receives the echo energy emitted by the target; when the echo energy is greater than a certain set detonation threshold, the interior of the projectile fuse turns on the detonation device; once the distance of the projectile and the target is less than a certain distance, the projectile explodes and forms the warhead fragments group and the shock wave; and then the kinetic energy and shock wave presented by the warhead fragments dispersion hit and damage the target [15], [16]. A schematic diagram of damage effect caused by the projectile proximity explosion under the condition of the projectile and target intersection is shown in Figure 1, where φ is the intersection angle of projectile and target.

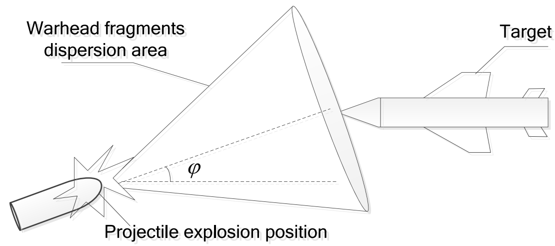

FIGURE 1. Schematic diagram of damage effect caused by projectile proximity explosion under the condition of the projectile and target intersection.

As shown in Figure 1, there are two main factors for the damage caused by projectile fuse detonation: one is the damage capability of warhead fragments, and the other is the damage capability of the shock wave formed by the projectile proximity explosion. Both factors are related to the projectile hitting the target, and the number of warhead fragments in a limited dispersion range and the effective shock wave coverage area can cause a certain amount of target damage. The damage capability of warhead fragments represents the damage caused by a warhead fragment to the target, which is mainly related to the distribution state of the vulnerable area of the target itself. When the projectile explodes, warhead fragments form a cone, and the cross-section of the cone intersection the target is the warhead fragments dispersion group with a radius of R. The density of the warhead fragments can be calculated under this condition, and the damage capability of the warhead fragments can be obtained. The damage effect of the shock wave is mainly reflected in the impact pressure on the target formed when the projectile explodes. This paper ignores the impact of the shock wave and focuses on discussing the damage effectiveness of warhead fragments formed by the projectile proximity explosion hitting the target.

III. THE TEST METHOD OF PROJECTILE EXPLOSION POSITION COORDINATES

According to Figure 1, we can find that there is a certain intersection angle between the projectile and the target, the intersection angle is different, and the energy obtained by the echo receiving device of the projectile fuse is also different. Therefore, the dynamic parameters of the projectile explosion are uncertain. To study the damage effect of warhead fragments formed by a projectile explosion on the target, it is necessary to obtain the dynamic parameters of the projectile explosion. This paper introduces the six screen testing system, which is mainly composed of six unit photoelectric detection sensors, a data acquisition module, and a computer processing module. In the six screen testing system, the unit photoelectric detection sensor is composed of an optical lens, a photoelectric detection receiver, and a slit diaphragm. The working principle of this sensor is referred to in prior work [17]. The photoelectric detection sensor has a slit diaphragm, and the slit diaphragm is projected to the sky through the optical lens to form the detection screen. Figure 2 shows the test method of dynamic projectile explosion position parameters by the detection screen of the six unit photoelectric detection sensors and area array camera.

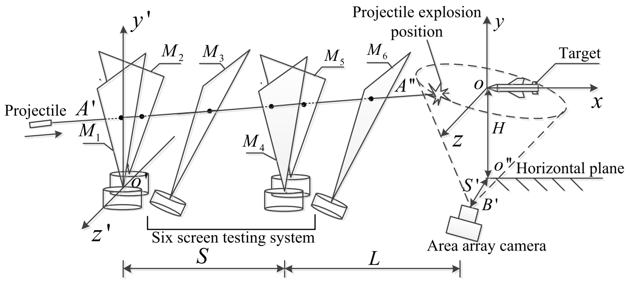

FIGURE 2. The test method of dynamic projectile explosion position parameters by the detection screen of the six unit photoelectric detection sensors and area array camera.

In Figure 2, where $M_1 - M_6$ are six unit photoelectric detection screens; M_1 and M_4 are the vertical-horizontal plane and are parallel to each other; S is the distance between M_1 and M_4; the intersection angle between both M_1 and M_3 and M_4 and M_6 are α; the intersection angle between M_1 and M_2 and M_4 and M_5 are both β; and the detection screens M_2 and M_5 are perpendicular to the plane xoz. By collecting the output signal of the six unit detection screens of $M_1 - M_6$, signal recognition, time information extraction of target passing through the detection screen, and so on, the time values of $t_1 - t_6$ that the target passes through at the six unit detection screens intervals can be obtained [18]. Through the six time values, according to the geometric structure relationship of the six detection screens, the calculation model of projectile flight parameters is established. The main parameters are the flight velocity of the projectile, the dispersion coordinate in the yoz plane of the coordinate system, and the flight azimuth at the moment of the projectile explosion. The six-screen test system is placed on the horizontal trajectory, and $y'o'z'$ is the coordinate system of the six-screen testing system. In the test, the six-screen testing system is placed in the firing direction of the gun and the target ballistic. The distance between the projection point o'' and detection screen M_4 is L, and the distance from the target to the ground is H. The coordinates obtained by this test system are the relative position of o with the target center as the origin, and the dispersion is in the plane yoz. Suppose the flight path of the projectile is $A'A''$, then the intersection angle between $A'A''$ and the horizontal plane xoz is γ, which is called the pitch angle. The intersection angle between $A'A''$ and the horizontal plane xoy is θ, which is called the azimuth angle. According to the spatial geometric model of the testing system, the dispersion of the projectile in the yoz plane can be obtained, and the dispersion parameters of flight projectile can be obtained from Equation (1).

$$
\begin{cases}
v = \dfrac{S}{t_4 - t_1} \cdot \cos\gamma \cdot \cos\theta \\
z = [S + L - x - v \cdot (t_2 - t_1)] \cdot \tan\theta \\
\quad +v \cdot (t_2 - t_1) \cdot \cot\beta \\
y = H - \{v \cdot (t_3 - t_1) \cdot \cot\alpha \\
\quad +[S + L - x - v \cdot (t_3 - t_1)] \cdot \tan\gamma\} \\
\gamma = \arctan \dfrac{[(t_6 - t_4) - (t_3 - t_1)] \cdot \cot\alpha}{t_6 - t_3} \\
\theta = \arctan \dfrac{[(t_5 - t_4) - (t_2 - t_1)] \cdot \cot\beta}{t_5 - t_2}
\end{cases}
\tag{1}
$$

Here, v is the velocity of the projectile. By collecting the signal of the projectile passing through the detection screen of the six-screen testing system and by signal processing, the time value of each detection screen can be obtained and the explosive position parameters can be calculated.

From Figure 2 and Formula (1), the six screen testing system only obtained the coordinates (y, z) in yoz, but it could not obtain the three-dimensional coordinates (x, y, z) of the projectile's explosive point relative to the damaged target. If we want to scientifically evaluate the damage effect of the exploding position of the projectile on the damaged target, we need to test the three-dimensional coordinates of the actual explosion of the projectile. Based on the principle of Figure 2, an area array camera was arranged in the direction of the ballistic ox and on one side of the projection point o''. As shown in Figure 3, point B' is the position of the area array camera, and the vertical distance from point B' to $o'x'$ is S'. During the test, the imaging optical axis of the area array camera was perpendicular to ox.

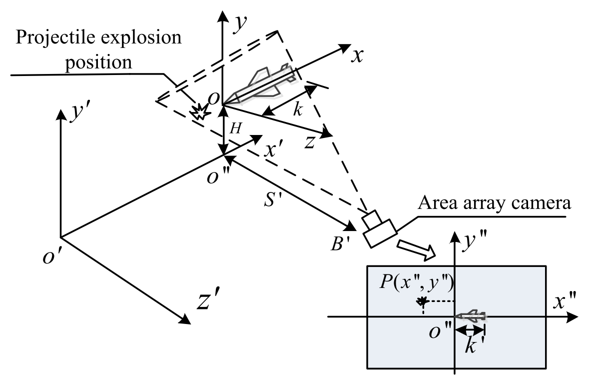

FIGURE 3. Schematic diagram of the layout and test principle of the ballistic side area array camera.

Suppose that $P(x'', y'')$ is the image position of the area array camera on the image sensor, $x''o''y''$ is their coordinate system, and o'' is the origin of the relative coordinates of the target head imaging on the area array camera. If the real length of the target is k, then the image pixel length is k' in the area array camera. Then,

$$
x = x'' \frac{k}{k'}. \tag{2}
$$

From the test principle and model, it can be seen that the damage effect of the projectile proximity on the target mainly depends on the dispersion position of the warhead fragments formed by the projectile explosion in the target. According to the basic principle of projectile and target intersection, the position of the projectile explosion is random and uncertain, but it needs the warhead fragment group formed under the condition of a certain area to damage the target. Therefore, it is necessary to master the probability distribution of projectiles explosion dispersion in the hit area of the space coordinate *xoy*.

IV. PROBABILITY CALCULATION METHOD OF PROJECTILE HIT TARGET PROXIMITY EXPLOSION AREA

A. PROXIMITY EXPLOSION AREA PROBABILITY OF THE PROJECTILE HITTING TARGET

As shown in Figure 1, in the projectile explosion position measurement of the proximity fuse, it is mainly evaluated that the projectile fuse explodes in a certain area of the simulated target (damaged target) area and plays the role of damaging the target. In the weapon firing area, the designated target is taken as the center, and it is fired at a certain area. A schematic diagram of the artillery aiming center is shown in Figure 4, where o is the center of the simulated target. Suppose that the designated target is taken as the center and the weapon is fired within the area of $2l_y \times 2l_z$, then the projectile fuse can work in such a situation, and thus the projectile hits the target and plays the role of damaging the target. Meanwhile, the area of $2l_y \times 2l_z$ is generally within the theoretical miss target range.

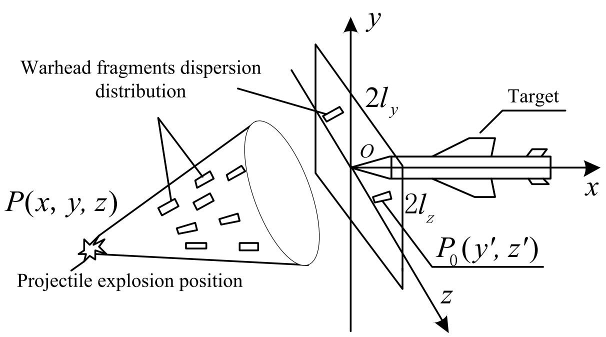

FIGURE 4. Schematic diagram of the artillery aiming center.

Suppose that $\Phi(y) = 2\int_0^y e^{-t^2/2}/\sqrt{2\pi}dt$, $P_0(y', z')$ is the aiming point, $(E_{\bar{y}}, E_{\bar{z}})$ is the accuracy of the starting elements, and (E_y, E_z) is the density, then the first projectile hit probability is

$$P_f = \{\Phi[(y' + l_y)/E_Y] - \Phi[(y' - l_y)/E_Y]\} \times\{\Phi[(z' + l_z)/E_Z] - \Phi[(z' - l_z)/E_Z]\}/4 \quad (3)$$

Here, $E_Y^2 = E_{\bar{y}}^2 + E_y^2$ and $E_Z^2 = E_{\bar{z}}^2 + E_z^2$.

If N is fire number of projectiles in the test, then the conditional probability of at least a projectile hitting the target under the error of (y, z) is

$$P'(y, z) = 1 - [1 - P(y, z)]^N. \quad (4)$$

Here,

$$P(y, z) = \{\Phi[(y' + l_y + y)/E_Y] - \Phi[(y' - l_y + y)/E_Y]\} \times \{\Phi[(z' + z + l_z)/E_Z] - \Phi[(z' + z - l_z)/E_Z]\}/4$$

The full probability that at least a projectile when the shooting projectile number is N hitting the target is

$$\overline{P} = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f(y, z)P_N(y, z)dydz = 1 - \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f(y, z)[1 - P(y, z)]^N dydz \quad (5)$$

Here, $f(y, z)$ is the distribution density of the element errors (y, z), and the expression of $f(y, z)$ is

$$f(y, z) = -\exp(-y^2/2E_{\bar{y}}^2 - z^2/2E_{\bar{z}}^2)/2\pi E_y - E_z \quad (6)$$

From the above calculation and reasoning analysis, the probability of at least a projectile of the N projectiles fired by artillery hitting the target can be calculated.

B. CALCULATION OF THE RELATIONSHIP BETWEEN THE PROJECTILE EXPLOSION POSITION DENSITY AND THE PROBABILITY OF HITTING TARGET

The projectile explosion position density of artillery is mainly expressed in two ways, the high-low direction error E_y and the left-right direction error E_z in the plane *yoz* [19], that is:

$$E_y = 0.6746\sqrt{\frac{\sum_{i=1}^{N}(\bar{y} - y_i)^2}{N - 1}} \quad (7)$$

and

$$E_z = 0.6746\sqrt{\frac{\sum_{i=1}^{N}(\bar{z} - z_i)^2}{N - 1}} \quad (8)$$

Here, y_i and z_i are the coordinates of the $i - th$ projectile hitting the target in the plane *yoz*, $\bar{y}$ and $\bar{z}$ are respectively the average value of the coordinates of a group of projectiles hitting the target in the two directions, and $i = 1, 2, \cdots, N$.

$$\bar{y} = \frac{1}{N}\sum_{i=1}^{N} y_i \quad (9)$$

$$\bar{z} = \frac{1}{N}\sum_{i=1}^{N} z_i \quad (10)$$

According to the probability of the projectile hitting the target at the proximity area and the relationship between the projectile explosion position density and the projectile hitting the target probability, the target damage effect can be calculated.

V. CALCULATION MODEL OF THE DAMAGE PROBABILITY OF PROJECTILE PROXIMITY EXPLOSION WARHEAD FRAGMENTS

The damage probability of the projectile proximity explosion warhead fragments is related to the relative coordinates $P(x, y, z)$ between the projectile explosion position and target; the volume, velocity, and the mass of warhead fragments; the effective damage area of warhead fragments group and target intersection; and the vulnerable characteristic parameters of the target. The damage probability is a relatively complicated calculation mechanism. To simplify the calculation, this paper analyzes projectile hitting probability and projectile explosion position density by introducing the explosion position of the projectile hitting the target, the target projection area, and the warhead fragments dispersion damage area. The calculation model of the target damage probability is established under the condition of the projectile proximity hitting the target.

When the projectile is fired, the error of the projectile proximity explosion position from the effective proximity explosion area range is described by three-dimensional coordinates in the system of *oxyz*, the firing error is

$$e(t) = \left[e_x(t), e_z(t), e_y(t)\right]^T. \tag{11}$$

Here, $e_x(t)$ is the *ox* direction deviation of the projectile explosion position, $e_z(t)$ is the left-right deviation of the projectile explosion position, and $e_y(t)$ is the high-low deviation of the projectile explosion position. According to the correlation analysis, the firing error of $e(t)$ is decomposed into

$$e(t) = e_a(t) + e_b(t) + e_c(t) + e_d(t) \tag{12}$$

Here, $e_a(t)$ are the uncorrelated errors, $e_b(t)$ are the weakly correlated errors, $e_c(t)$ are the strongly correlated errors, and $e_d(t)$ are the systematic errors. Each error is a covariance matrix, which is a constrained factor in whether the projectile proximity explosion can be in the effective control detonation range. Within the allowable range of satisfying the error, the projectile fuse plays a part in the explosion and produces the damage effectiveness on the target. From Equations (5) and (6), it can be known that the offset of projectile explosion position coordinates $P(x, y, z)$ restricts the damage effectiveness of warhead fragments on the target after the projectile explosion. From this point of view, the effective hit probability of each projectile proximity explosion is a prerequisite for the damage target of projectile proximity explosion. Therefore, it is necessary to find an effective area where the projectile proximity hitting the target produces warhead fragments group damage the target within the theoretical error range.

Assume that warhead fragments group formed by projectile proximity explosion is cones, each warhead fragment is spherical, and its radius is r_i, then when the warhead fragment hits the target at an angle ϕ_i, the damage area to the target's surface is

$$S_i = \pi r_i^2 \cos\phi_i \tag{13}$$

The damage area caused by the entire warhead fragments group hitting the target's surface is the sum of the damage area caused by effective warhead fragments. If n warhead fragments hit the target's surface, then the total damage area of the target is calculated as

$$S_e = \sum_{i=1}^{n} \pi r_i^2 \cos\phi_i. \tag{14}$$

Suppose that N projectiles are fired in the test, the target damage probability is P_N, that event A represents the event of target damage, and event B represents the effective one projectile proximity hitting the target, then

$$P_N = P(A)P(B|A) + P(\overline{A})P(B|\overline{A}) \tag{15}$$

In the test, if the effective damage area of the target is not zero, then event A is a full probability event, if the effective damage area of the target is zero, then event $\overline{A}$ is a full probability event [20], and then

$$\begin{cases} P(A) = 1, & (S_e \neq 0) \\ P(\overline{A}) = 1, & (S_e = 0) \end{cases} \tag{16}$$

Suppose that the warhead fragments are distributed uniformly, and then the probability of the warhead fragment formed by a projectile hitting the target is

$$P_s = S_e/S_t \tag{17}$$

Here, S_t is the area formed by the total warhead fragments of the projectile proximity in the plane *yoz*. The required average number of warhead fragments damaging the target is m, and thus the probability of one projectile damages the target is expressed as follows:

$$P(B|A) = 1 - (1 - \frac{P_s}{N})^m \tag{18}$$

From Equations (13)–(17), the target damage probability of one projectile in the test is

$$\begin{cases} P_N = 1 - (1 - \frac{S_e}{N \cdot S_t})^m, & (S_e \neq 0) \\ P_N = 0, & (S_e = 0) \end{cases} \tag{19}$$

VI. CALCULATION AND EXPERIMENTAL ANALYSIS

A. CALCULATION ANALYSIS

Based on the probability of projectiles hitting the target and considering the distribution characteristics of the projectile proximity warhead fragments, we calculate and analyze the target damage probability of a certain number of warhead fragments under the condition of a certain projectile hitting probability. According to the theoretical calculation given in part II, if the center coordinate of artillery aiming is on the plane *yoz* and the center coordinate is $(0, 0)$, then the firing floating variation of l_y and l_z in the plane *yoz* are about the average values of 5 m, that is, o is the firing center, and the aiming area range is (−2.5 m, 2.5 m) in the *oz*-direction, (−2.5 m, 2.5 m) in the *oy*-direction. Thus, $l_z \in (-2.5m, 2.5m)$, $l_y \in (-2.5m, 2.5m)$, and the area of hitting the target is about 25 m^2. When the projectile intersects the plane *yoz* within the effective range of the center of *o* point, it is regarded as the previous condition that the projectile hits and explodes. From the theoretical calculation model, the warhead fragments formed by projectile proximity explosion can damage the target, which depends on the *x*-coordinate value of the projectile explosion position $P(x, y, z)$. Assuming that the target is a cylinder with a diameter of 0.6 m and a length of 4 m, then according to the calculation method of the target parameters, $S_0 = \pi r_t^2$, r_t is the radius of target, the target area in the plane *yoz* is about 0.28 m^2.S_1 is the target side area, which is about 2.4 m^2, and it is calculated by its diameter and length. According to the given parameters and the established calculation model, under the effective projectile explosion conditions, it is assumed that the projectile explosion position is the same. The warhead fragments dispersion characteristics formed by the projectile proximity explosion are the same, that is, the same warhead fragments cross-section. The number, velocity, and dispersion radius of the warhead fragments are the same. φ expresses the intersection angle of the warhead fragment and the target. The different intersection angles are calculated when the projectile intersects with the target, and φ is the effective intersection angle only when the warhead fragments dispersion intersects with the target's surface. Otherwise, when the warhead fragments do not intersect with the target's surface, the damage probability is zero regardless of the value of φ. When the projectile explosion position is $(x, 0, 0)$, and $x < 0$, Figure 5 shows the change curves of the target damage probability at different values of x under the condition of effective warhead fragments intersection.

As shown from the target damage probability curve in Figure 5, when the offset of the projectile explosion position in the *x*-direction is far away from 0, the damage probability is significantly attenuated. The main reason for this is that the value of x is too large and the number of the warhead fragments hitting the target is reduced. When the x value is fixed, the intersection angle is larger and there is a lower target damage probability, which is also the main reason for the decrease in the number of the warhead fragments hitting the target.

When the projectile explosion position is changed, the y and z in $P(x, y, z)$ do not equal zero, x is a fixed constant, and $x < 0$ within the effective range of projectile and target intersection, and the intersection angle is zero. Figure 6 shows the change of the target damage probability at different y and z.

As shown in Figure 6, when y and z exceed (−0.3 m, 0.3 m), as the y and z increase, the target damage probability becomes smaller. The main reason for this is that when the intersection angle is zero and x is a certain value, the target damage probability of the warhead fragments formed by the projectile proximity explosion on the plane *yoz* decreases

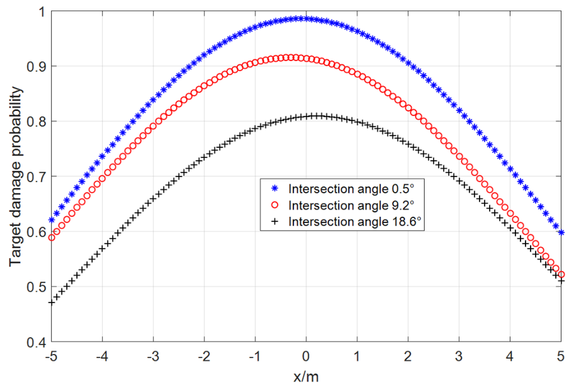

FIGURE 5. **The change curves of target damage probability at different values of *x*.**

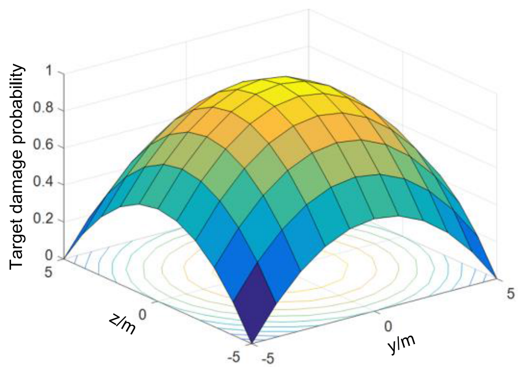

FIGURE 6. **Change curve of the target damage probability at different *y* and *z*.**

as y and z increase. Through an analysis of Figs. 4 and 5, the projectile hitting probability determines the effect of target damage. Under the same mass, velocity, and volume conditions of the warhead fragments, the target damage effect is closely related to the number of warhead fragments hitting the target.

In the effective range of projectile proximity explosion position, Figure 7 shows the change curve of the target damage probability and warhead fragments spatial distribution density at different hit probabilities. From the change curve of target damage probability, it can be seen that in the same number of firing projectiles, the higher the hit probability, the better the target damage effect, and the higher the warhead fragments spatial distribution density, the greater the target damage probability.

B. EXPERIMENTAL ANALYSIS

In the ballistic terminal area, a damaged target was placed in the air at more than 29.4 m from the ground. A six-screen sensor test system was arranged in the ballistic trajectory, the distance of the detection screens M_1 and M_4 was about 9.27 m, and the distance from the projection point of the target to M_4 was 16.5 m. According to the geometric structure of the test system and the arrangement of the test site and other parameters, the target surface formed by the test system

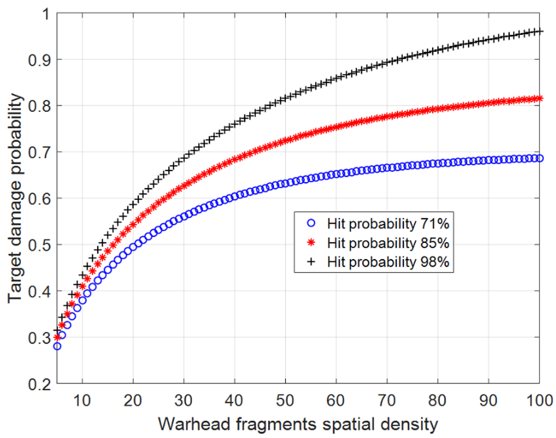

FIGURE 7. Change curve of the warhead fragments spatial density and target damage probability.

in the plane yoz was about $6m \times 6m$. According to the principle of Fig. 3, the vertical distance from point B' to $o'x'$ was $11.2m$, the imaging optical axis of the area array camera was perpendicular to the ox, and the damaged target was a cylinder, the diameter was $0.45m$, the length was $4.6m$.

After the projectile was fired by the artillery, it exploded at the projectile proximity explosion position to destroy the damaged target. The projectile proximity explosion position at the test site is shown in Figure 8.

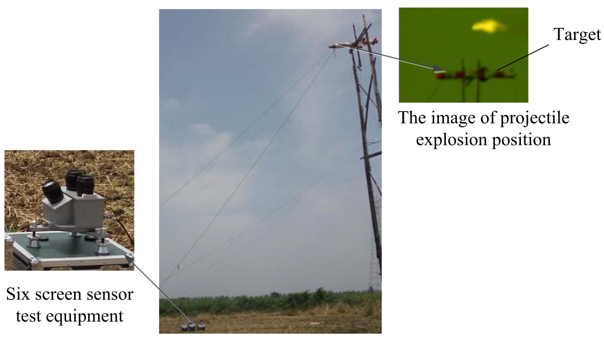

FIGURE 8. Arrangement and projectile proximity explosion diagram at the test site.

According to the probability theory that the projectile hits the target, it was assumed that the center coordinate of the artillery aiming area was (−0.5 m, 0.5 m), the unit was in meters, and the average values l_y and l_z were about 5 m. The principle of the multi-screen test system has been described in prior work [18]. This measurement method can obtain the three-dimensional coordinates of the projectile explosion position relative to the target's head, the velocity of the projectile explosion instant, and the deflection angle of the projectile explosion instant. θ is the high-low pitch angle of projectile flight in the nearby projectile explosion position, and γ is the left-right azimuth angle of projectile flight in the nearby projectile explosion position. The projectile explosion parameters are obtained by the six screen testing system, and then the established probability function of projectile hitting the target is utilized to calculate the first and total probability of projectiles hitting the target. Table 1 and Table 2 are the two sets of experimental data, and each group tested 11 projectiles.

TABLE 1. Experimental data of the first group of projectile explosion positions.

No.	$\theta(^o)$	$\gamma(^o)$	$x(m)$	$y(m)$	$z(m)$	$v(m/s)$
1	0.71	0.92	-2.55	3.09	-1.77	688.1
2	1.08	0.34	-1.99	4.16	-0.99	675.2
3	0.82	0.39	0.23	4.08	-1.72	680.4
4	1.37	1.85	-3.02	3.84	1.33	685.7
5	0.86	0.64	1.43	3.85	-0.74	681.2
6	1.44	-2.56	-3.16	3.23	3.56	691.3
7	-1.76	2.01	-2.67	2.34	2.11	689.6
8	-0.95	-2.16	-0.05	3.04	1.88	687.3
9	1.46	2.37	-1.98	3.68	1.87	684.2
10	2.68	-0.81	1.38	3.65	2.05	679.6
11	0.92	1.85	1.13	3.94	2.58	688.7

TABLE 2. Experimental data of the second group of projectile explosion positions.

No.	$\theta(^o)$	$\gamma(^o)$	$x(m)$	$y(m)$	$z(m)$	$v(m/s)$
1	1.64	0.47	2.78	3.45	-3.86	677.4
2	0.56	1.15	2.46	3.18	1.98	673.5
3	0.87	-1.21	3.24	3.56	-2.63	682.1
4	0.18	2.75	-3.53	2.39	-3.44	675.7
5	3.04	-0.48	-2.21	3.73	-1.71	676.9
6	2.17	1.56	2.15	3.82	-3.26	679.3
7	2.87	1.12	2.69	4.12	2.19	677.5
8	1.83	1.55	-1.79	3.07	-1.36	673.8
9	2.06	1.67	1.88	3.11	-0.85	681.1
10	0.82	-1.53	-1.65	4.21	-2.47	676.4
11	1.43	1.89	2.18	3.88	-1.66	681.3

According to the data in Table 1, the density was $(0.372, 1.262)$, $E_{\overline{y}} = 1.207$, $E_y = 0.372$, $E_Y = 1.263$, $y = 3.536$, $E_{\overline{z}} = 2.016$, $E_z = 1.262$, $E_Z = 2.378$, $z = 0.924$, and the first projectile hitting probability was about 25.2%. In the test, 11 projectiles were fired, and the errors of elements were 3.536 in the y-direction, and was 0.924 in the z-direction. The conditional probability of at least one projectile hitting the target area was about 55.6%. Similarly, from the data in Table 2, it can be calculated that the first projectile hitting probability was about 24.5%, and the conditional probability of at least one projectile hitting the target area was about 87.9%.

According to the above test conditions and the flight parameters of the projectile, it is assumed that the projectile was a pre-exploded fuse in the test. Each projectile was preloaded with 100 warhead fragments; the diameter of each warhead fragment was about 10 mm; and the warhead fragment intersected the target in turn according to the four-layer array, among which each layer had about 25 warhead fragments, and the spherical surface of each layer with the center point o of the target's head as the reference origin was distributed in a two-dimensional normal distribution. To more intuitively analyze and calculate the damage effect of the projectile explosion position on the target, the center coordinate system of the projectile explosion position was set to be $y_0o_0z_0$ and it was parallel to the plane yoz. Moreover, the relative offset between o_0 and o is $(d, 0, 0)$, and d is the distance between the two planes of $y_0o_0z_0$ and yoz. When the warhead fragments formed by each projectile exploded with a radius of r_m in the plane yoz, $r_m = 1.5m$ and the warhead fragments density was 80%, that is, the number of warhead fragments passing through in the area was 80% for the total number of warhead fragments, and the warhead fragments were distributed at an equal distance of 0.1 m and damaged the target. From the relative coordinate data of the projectile explosion position, the projectile explosion position of each projectile was not on o_0, and there were deviations. Thus, the linear equation of each warhead fragment passing through the plane yoz after the projectile explosion can be expressed as

$$y_i = 0.1\frac{b}{a}\cos\theta_i \cdot \cos\gamma_i \cdot x_i - d \tag{20}$$

In (20), θ_i is the high-low pitch angle of warhead fragment; γ_i is the left-right azimuth angle of warhead fragment; b is the number of equal intervals of warhead fragment's spread in each layer of the parallel plane yoz; the radius of warhead fragment's spread is r_m; and a is the x coordinate value of projectile explosion position, that is $a = x$, which is obtained by the six screen testing system.

The θ_i and r_i of each warhead fragment was calculated based on the data of Table 1 and Table 2, and $\theta_i \in \theta$, $\gamma_i \in \gamma$ based on the obtained projectile explosion position parameters and given the prefabricated warhead fragment dispersion parameters. The hit probability was calculated according to Formulas (18) and (19). The target damage probability was about 57.812% in Table 1, and the target damage probability was about 50.637% in Table 2.

In Tables 1 and 2, it can be seen that the projectile explosion positions had more warhead fragments distributed in the negative axis of x for the coordinate system $oxyz$, and the data in the coordinates y and z were relatively concentrated and the range was smaller. Both were less than 5 m. Therefore, the number of warhead fragments that the warhead fragment spread and intersected with the target was too large, and the target damage effect is better. The results reflect that the projectile hitting probability was greater, and there was a better target damage effect. At the same time, the target damage effect was related to the number of warhead fragments formed by the projectile proximity explosion penetrating the target and the penetration orientation of warhead fragment. When the number of effective warhead fragments penetrating the target was more, there was a better target damage effect. These experimental calculation results were basically consistent with the theoretical calculation results.

VII. CONCLUSION

According to the principle of projectile and target intersection proximity explosion, in the target aiming area, this paper studied a testing method of the projectiles explosive position by using a combination of six screen sensors and area array cameras. We set up a calculation model of the projectile proximity explosion position parameters, which establishes the probability calculation model of multiple projectiles hitting the target area. We analyzed the relationship between the projectile explosion density and the hit probability and the error of the firing projectile hitting coordinates. According to the warhead fragments distribution characteristics of the projectile proximity explosion, the condition probability of target damage was discussed under the condition of firing multiple projectiles in a test. Based on the number of warhead fragments under the warhead fragments and target intersection and the penetration area of warhead fragments, the target damage probability was established under the event of the effective projectile proximity explosion. Based on the basic conditions of the projectile and target intersection and the characteristics of the target's parameters, quantitative parameter calculation and analysis methods were used to give the target damage probability distribution under the projectile proximity explosion. By using dynamic vision software, according to the effective projectile proximity explosion distribution parameters, the target damage effects were simulated at different projectile explosion positions. Based on the projectile explosion position parameters obtained by the multi-screen testing system, the target damage probability was calculated according to the probability of the projectile hitting the target and the target damage function. The results show that the target damage results of the theoretical simulation calculations and the calculation results of the actual projectile proximity explosion test data were basically the same, which verifies the feasibility of the proposed target damage probability calculation model under the probability of multi-projectile explosion hitting the target. These research achievements provide a reasonable theoretical and engineering practice basis for the calculation and analysis of typical target damage under the conditions of static and dynamic explosions of intelligent ammunition at a weapon range.

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