Simulation study of smoke screen jamming laser terminal guidance projectile

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Abstract: With the large-scale application of precision guided weapons, it has realized the transition from conventional ammunition cluster attack mode to guided munition precision strike mode, thus achieving the best combat cost performance. Its laser weapons are widely used in the military field to effectively combat laser weapons. Smoke screen bombs are favored by all countries due to their high cost-effective advantages. In this study, taking the smoke screen interferes with laser terminal guided projectiles as an example, the guidance principle of laser terminal guided projectiles, and the principle of smoke screen interference with laser terminal guided projectiles were studied. The shielding effect of the smoke screen on the laser seeker was introduced into the simulation process of external ballistic. Taking miss distance as an indicator, the jamming system simulation model was established, and the simulation research of smoke screen against laser terminal guided projectiles was realized. The research results show that the simulation system can provide the best jamming strategy for smoke screens against laser terminal guided projectiles, and can provide auxiliary decision-making for combat training and effectiveness evaluation of typical smoke munitions.

Key words: laser terminal guidance projectile; smoke screen; laser seeker; simulation research; jamming strategy

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烟幕干扰激光末制导炮弹的仿真研究

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摘　要：随着精确制导武器的大量应用，实现了常规弹药集群攻击模式向制导弹药精确打击模式的转变，从而达到了最优的作战性价比，其激光武器被广泛应用于军事领域，为有效对抗激光武器，烟幕弹以性价比高等优势受到各国的青睐。以烟幕干扰激光末制导炮弹为例，研究了激光末制导炮弹的制导原理，烟幕干扰激光末制导炮弹的原理，将烟幕对激光导引头的遮蔽效果引入到外弹道仿真过程，以脱靶量为指标，建立了干扰系统仿真模型，实现了烟幕对抗激光末制导炮弹的干扰仿真研究。研究结果表明，该仿真系统可以为烟幕弹对付激光末制导炮弹提供最佳干扰策略，为典型烟幕弹药的作战训练和效能评估提供辅助决策。

关键词：激光末制导炮弹； 烟幕； 激光导引头； 仿真研究； 干扰策略

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0 Introduction

As a typical precision guided weapon, laser terminal guided projectile is most famous for the "copperhead" of the United States [1] and the "red earth" of Russia [2]. Its laser terminal guidance has high precision, strong anti-jamming performance, simple structure and low cost [3]. The basic principle is to use the laser beam emitted by the laser target indicator to irradiate on the target. The laser seeker of the laser terminal guidance projectile uses the laser reflected by the target to control and track the target, so that the laser terminal guidance projectile flies to the target [4]. At present, in the laser terminal guided projectile, the proportional guidance method is the most commonly used [5]. In the whole process of laser terminal guided projectile attacking the target, the main guiding devices are target indicator and laser seeker. However, cloud, fog and rain will seriously affect the laser transmission, smoke and dust will attenuate the laser energy and affect the guidance performance of laser terminal guided projectile [6]. In addition, the laser terminal guidance weapon is a kind of "point to point" precision guidance weapon, which is difficult to carry out large-scale operations. The size of smoke screen formed by smoke bomb is also limited, which makes it possible for smoke screen to interfere with laser terminal guided projectile. Smoke screen scatters and absorbs energy from the incident laser signal to reduce the energy received by the seeker of the enemy's laser terminal guided projectile [7−10], and smoke bomb is just in line with this mode of operation. At present, our army has a relatively large number of smoke bombs distributed on all kinds of combat vehicles, but there are some problems in the process of smoke bombs jamming laser terminal guidance shells, such as inaccurate smoke casting. How to use the simulation system to estimate the time of smoke casting, and then form the jamming strategy of smoke bombs against laser terminal guidance shells. Based on the study of the working principle of laser terminal guided projectile and the smoke interference with laser terminal guided projectile, six degrees of freedom interference model of smoke interference with laser terminal guided projectile is established. By controlling the formation time of smoke and comparing the miss distance after interference, the interference strategy of smoke is proposed, It provides assistant decision-making for combat training and effectiveness evaluation of typical smoke bomb.

1 Working principle of laser terminal guidance projectile

The signal transmission system of the laser terminally guided projectile is the center of the laser terminally guided weapon. The signal of the laser terminally guided projectile has undergone the following transmission process: the laser signal emitted by the illuminator is transmitted in the atmosphere and received by the target's reflective surface. The reflecting surface reflects the laser signal according to a certain rule, and the reflected laser signal is transmitted through the atmosphere and finally reaches the seeker of the laser guided artillery projectile. Taking into account the influence of background noise, the signal finally reaching the seeker has background noise signals in addition to the laser signal. All input signals are photoelectrically converted and processed by the laser seeker system to form a guided output signal, which is the driving signal of the laser terminal guidance projectile [11]. The following is a detailed description of the seeker's received signal power model, 1.06 μm laser atmospheric transmittance model, and target indicator launch laser power model.

1.1 The target indicator emits a laser power model

The pulse repetition frequency of the laser target indicator used is usually 10-20 ps. In order to meet the requirements of laser pulse encoding, the repetition frequency may be higher. The laser target indicator generally requires the divergence of the laser beam to be reduced as much as possible. The beam divergence of an ordinary stable laser is 35 mrad [12]; the seeker of the "red earth" laser terminal guided projectile selects the amplitude and difference single pulse. For the laser seeker, the corresponding field of view of the relay area is ±15°, and the main function is to capture the field of view. The linear area corresponds to a small field of view of ±3°, which is used to track the field of view [13], its laser target indication calculation model is shown in formula (1).

$$P_d = E_d/\tau_d \cdot T_d \tag{1}$$

Where, P_d is the pulse transmitting power of the laser target indicator; E_d is the laser pulse energy of the laser target indicator; τ_d is the laser pulse width of the laser target indicator; T_d is the transmittance of laser target indicator optical system.

Assuming that the average pulse energy of the laser target indicator in each irradiation period is ⩾ 35 mJ (40 mJ in this paper), the pulse width is 10-22 ns (5 ns in this paper), and the transmittance of the optical system of the laser target indicator is 0.8, then the pulse transmitting power of the laser target indicator can be calculated as: P_d=2.133×10^6 W.

1.2 Seeker receives signal power model

When the target diffusely reflected laser pulse is imaged in the relay area, after the signal processing of the electronic cabin, the precession angular velocity of 11 (°)/s is used to reduce the tendency of the misalignment angle, and the target is introduced from the large field of view to the small field of view. So that the reflected laser pulse of the target is diffusely imaged on the central area of the photodetector, so as to automatically track the target. It includes two processes: the target reflecting surface receives the laser model and the target reflecting surface reflects the laser model. The laser energy received by the target reflecting surface is not only related to the transmittance of the atmosphere, but also related to the area of the receiving surface. Suppose the laser emission power of the laser target indicator is P_d, the atmospheric transmittance is τ_t, the target reflecting surface is a circular surface with a radius of r_l, and the distance between the laser target indicator and the target reflecting surface is r_{ld}, and divergence angle of the laser target indicator laser is θ, and the various effects of the atmosphere on the laser beam are the same everywhere, then the energy distribution of the laser spot on the reflecting surface should also conform to the Gaussian distribution, then when the area of the laser scattering spot is smaller than that of the reflecting surface. In terms of area, the laser power P_t received by the target reflecting surface is [14−15]:

$$P_t = P_d \cdot \tau_t(R_{td}) \tag{2}$$

When the area of the laser scattering spot is larger than the area of the reflecting surface, the laser power P_t received by the target reflecting surface is:

$$P_t = P_d \frac{\int_0^r \exp\left(-\frac{2r^2}{w^2}\right) \mathrm{d}r}{\int_0^\infty \exp\left(-\frac{2r^2}{w^2}\right) \mathrm{d}r} \cdot \tau_t(R_{td}) \tag{3}$$

Where, ω is the laser spot radius at the target reflecting surface, $\omega = \theta R_{td}/2$.

The reflecting surface of the target surface reflects the laser model, and it is assumed that the reflecting surface of the target is a rough plane with a certain area, and the direction of the incident light coincides with the normal of the reflecting surface. The incident light is diffusely reflected on the rough surface and conforms to Lambert's law of cosine reflection, then the distribution of light power reaching the seeker after passing through the target reflecting surface is[14]:

$$I_r = \rho_t \frac{P_t}{\pi R_{ts}^2} \cos\theta_L \cdot \tau_t(R_{rs}) \tag{4}$$

Where, R_{ts} is the distance between the shell and the target; I_r is the laser density received at the seeker; ρ_t is the diffuse reflection coefficient of the target reflecting surface; P_t is the laser power received on the target reflecting surface; θ_L is the angle between the eye line of sight and the reflector normal. It is determined by the target reflector normal azimuth (θ_d, φ_d) and the eye line of sight azimuth (θ_s, φ_s).

$$\cos\theta_L = |\sin\theta_d \sin\theta_s + \cos\theta_d \cos\theta_s \cos(\varphi_d - \varphi_s)| \tag{5}$$

2 Working principle of the smoke screen interfering with the laser terminal guided projectile

It can be seen from the foregoing that there are mainly two types of factors that affect laser detection: system inherent parameters and external influence parameters. The inherent parameters of the system are determined by the physical properties of the laser and receiver and cannot be changed. The external influence parameters include the attenuation of the atmosphere to the laser, the working distance, and the double-layer transmittance of the smoke screen. This research focuses on the range of action, the attenuation of the laser light by the atmosphere, and the double-layer transmittance of the smoke screen. The operating distance is given by the guidance model, and the double-layer transmittance of the smoke screen is affected by the thickness of the smoke screen and the type of smoke screen.

2.1 Smoke diffusion model

Smoke screen is a variable fluid, and the atmosphere is its transmission medium. When studying the properties of smoke screens, it is inseparable from the study of atmospheric diffusion. In the smoke screen diffusion model, there are mainly two types of continuous point source and instantaneous body source concentration distribution modes, since the explosion of the smoke screen shell is instantaneous explosion, the Gaussian mode of instantaneous body source concentration distribution is selected in this paper, and the lead direct to the smoke screen density distribution equation in the instantaneous point source smoke screen density distribution model is as follows[16]:

$$C_Z = \frac{Q}{\sqrt{\pi/2}u\sigma_y}\exp\left(-\frac{y^2}{2\sigma_y^2}\right) \tag{6}$$

Where, C_Z is the smoke concentration at height Z (g/m^3); Q is the smoke velocity of the smoke screen (g/s): u is the average velocity during the release period (m/s); σ_y is the atmospheric dispersion variance in the y direction (m).

In the Gaussian diffusion model, the smoke screen speed and average wind speed can be obtained by related instruments and methods; the smoke screen speed in this project is determined by the total amount of smoke screens and the duration of the smoke screen. It is considered that the smoke screen speed conforms to the overall distribution. The quality of the smoke screen agent in this project set as 1 000 g, and record the duration as 30 s. According to the smoke screen time and the quality of the aerosol, the smoke screen velocity at each moment is obtained; the smoke screen concentration value of different heights can be obtained by bringing it into the smoke screen concentration distribution equation; when the smoke screen concentration value is lower than a certain value, it is considered as invalid smoke. Furthermore, according to the smoke screen concentration threshold, the relationship between the smoke screen height and the smoke screen time can be obtained.

2.2 Atmospheric transmittance model of 1.06 μm laser

The transmittance of 1.06 μm laser in the atmosphere consists of two processes[17−18]: the absorption rate of laser $\tau_{ab}(L)$; the transmittance $\tau_{sc}(L)$ of the atmosphere to the laser, where L is the transmission distance of the laser in the atmosphere(km), and the total transmittance $\tau_t(L)$ of the atmosphere can be expressed as:

$$\tau_t(L) = \tau_{ab}(L)\cdot\tau_{sc}(L) \tag{7}$$

(1) The absorption transmittance of the atmosphere to 1.06 μm laser

For a 1.06 μm laser, ozone, carbon dioxide and water vapor in the atmosphere have obvious absorption effects, and the absorption effects of carbon dioxide and ozone can be ignored when the laser semi-active guidance is too long, only the absorption of water vapor can be considered.

$$\tau_{ab}(L) = 1 - ERF\left(0.0167\sqrt{W}\right) \tag{8}$$

Where, $W = F_k L$ is the amount of water vapor (mm), and F_k is the amount of water vapor per unit distance.

(2) Atmospheric scattering of 1.06 μm laser

Factors that cause scattering are smoke, clouds, rain, snow, dust, sand. Scattered particles can be divided into three categories: the first category includes smoke screen and cloud; The second category is aerosols in the atmosphere; The third category is rain and snow. The total scattering transmittance can be expressed as[19−20]:

$$\tau_{sc}(L)=\tau_1(L)\tau_2(L)\tau_3(L) \tag{9}$$

The transmittance of the first type of scattering source is:

$$\tau_1(L)=\mathrm{e}^{-\gamma(1.06)t} \tag{10}$$

$$\gamma(1.06)=\frac{3.912}{R_v}(1.93)^{-q} \tag{11}$$

Where, R_v is the visibility distance of 1.06 μm laser, and q is constant.

$$q=\begin{cases}1.3,\ R_v\geqslant 11\ \mathrm{km}\\ 0.585R_v^{1/3},\ R_v<11\ \mathrm{km}\end{cases} \tag{12}$$

The transmittance of the second type of scattering source is:

$$\tau_2(L)=\mathrm{e}^{-\frac{3.912}{R_v}L} \tag{13}$$

The transmittance of the third type of scattering source is:

$$r_1(L)=\mathrm{e}^{-\delta L} \tag{14}$$

3 Simulation and result analysis

3.1 Construction of digital simulation model of laser terminal guided projectile and jamming

In order to realize the simulation of the laser terminal guided projectile by the smoke screen, it is necessary to construct the six degree of freedom laser terminal guided projectile's ballistic equation and the interference model of the smoke screen on the laser terminal guided projectile[21−23]. Figure 1 shows the overall structure of the system and the input/output relationship between each part. The main modules include the dynamics of the laser terminal guided projectile, the kinematics of the center of mass, the guidance and control system, the target movement, and the miss distance calculation. The values mainly include the initial position, velocity and direction of the laser terminal guided projectile, the projectile attitude angle, the rolling angular velocity component of the projectile, and the target position coordinates; the output after the system operation mainly includes: the

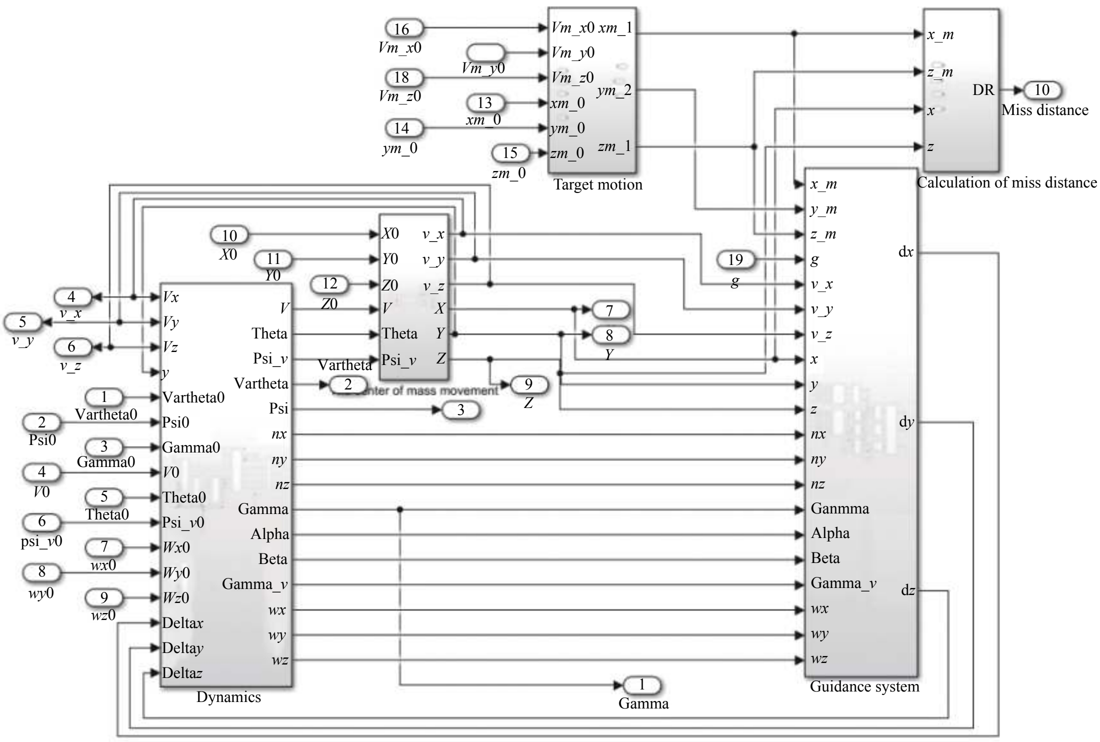

Fig.1 General structure and input/output relationship of the digital simulation system of laser terminal guidance projectile

laser terminal guided projectile position coordinates, the projectile rotation angular velocity. The miss distance of the laser terminal-guided projectile's impact point relative to the target position. Among them, the laser terminal guided projectile dynamics module mainly calculates the speed and angular velocity of the laser terminal guided projectile; the target motion information mainly provides the target's motion parameters and motion calculation; the center of mass kinematics module mainly calculates the spatial position of the laser terminal guided projectile coordinates. The guidance and control system includes modules such as smoke interference model and guidance control system, which are mainly responsible for calculating the line-of-sight angular velocity of the relative movement of the projectile and eye. The entire system contains more than 20 modules of various sizes. These model modules are coupled with each other according to the complex information transmission relationship within the laser terminal guided projectile.

3.2 Flight simulation test of laser terminal guided projectile under jamming condition

Take the interference of copper powder smoke screen as an example, the initial position of the laser terminal guided projectile (0, 0, 0), initial velocity is 1 000 m/s, the ballistic inclination is 45°, the ballistic deflection is 2°, the roll angle speed is 100 rad/s, the yaw rate is 0 rad/s, the pitch rate is 0 rad/s, the target is at a standstill, the smoke screen has an action time of 35 s, and the relative coordinates of the target distance from the laser terminal projectile are (10 000, 0, 100), the miss distance is 60 m, and the interference result is shown in Fig.2.

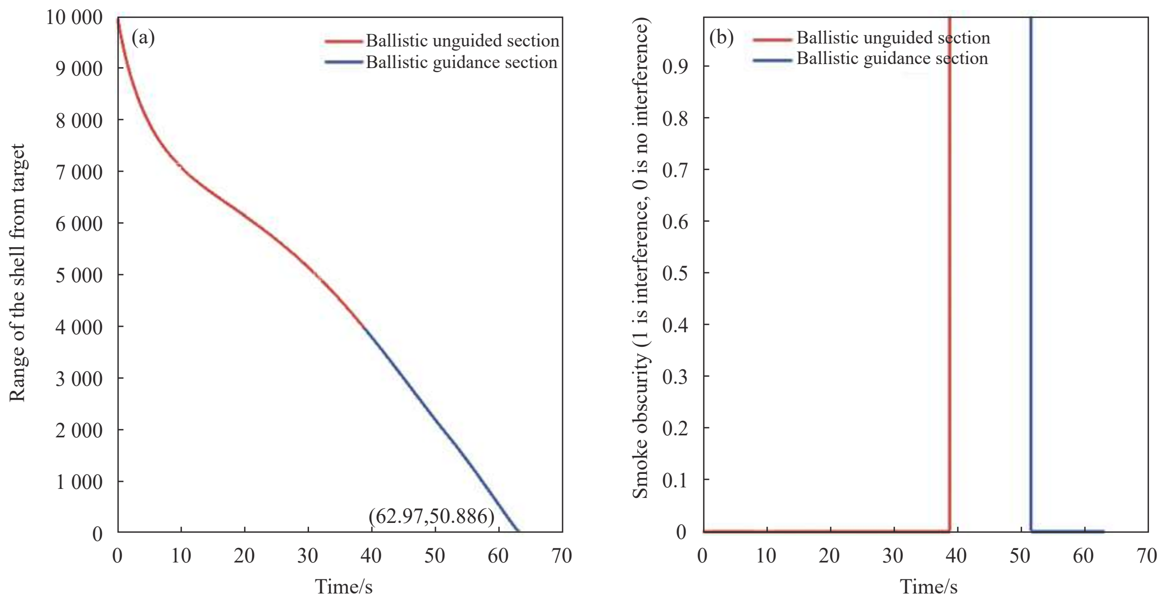

Fig.2 Distance curve and the interference result of the projectile with the initial velocity of 1 000 m/s and the ballistic deflection angle of 2°

The initial position of the laser terminal guided projectile is (0, 0, 0), the initial velocity is 900 m/s, the ballistic inclination is 45°, the ballistic deflection is 5°, the roll angular velocity is 100 rad/s, and the yaw angular velocity is 0 rad/s, The pitch rate is 0 rad/s, the target is at a standstill, the smoke screen action time is 35 s, and the relative coordinates of the target distance from the laser-guided projectile is (10 000, 0, 100), the miss distance is 122 m, and the interference result is shown in the Fig.3.

In order to verify the influence of the smoke screen on the laser terminal guided projectile, the initial value of the system is the initial position of the laser terminal guided projectile (0, 0, 0), the initial velocity is 1 000 m/s, the the trajectory angle is 45°, and the ballistic deflection angle is 5°, the roll angular velocity is 100 rad/s, the yaw angular velocity is 0 rad/s, the pitch angular velocity is

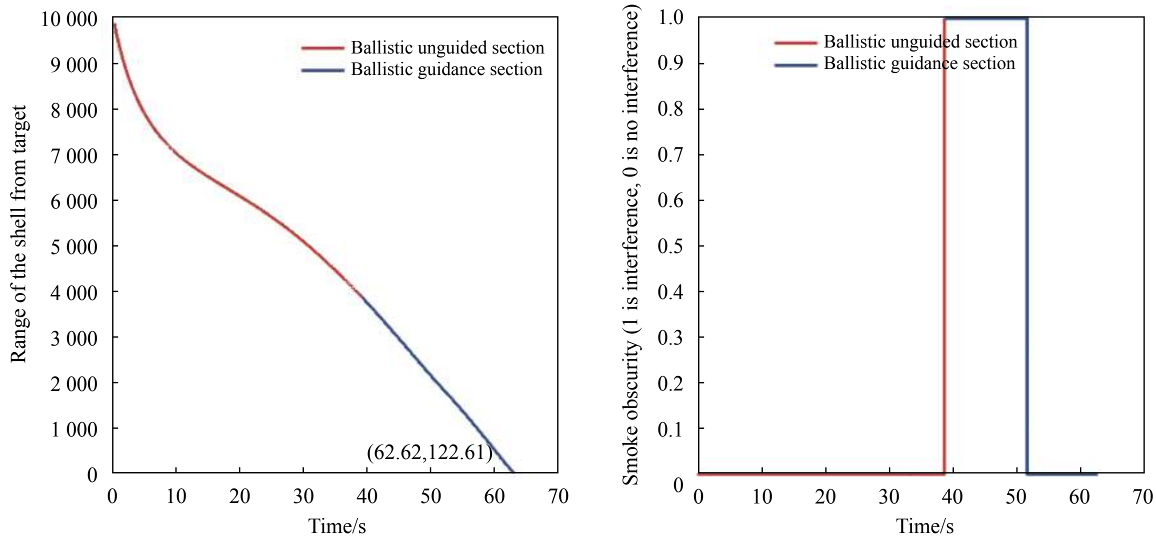

Fig.3 Distance curve and the interference result of the projectile with the initial velocity of 900 m/s and the ballistic deflection angle of 5°

0 rad/s, the target is at a standstill, and the relative coordinates of the target distance from the laser terminal projectile are (10 000, 0, 100), taking the interference of copper powder smoke screen as an example, simulated the movement trajectory of the laser-made missile pellets under different smoke launch times (25 s, 30 s, 35 s, 45 s, 55 s). The simulation results are shown in Fig.4-Fig.9.

From the simulation results of Fig.2 and Fig.5, it can be seen that the ballistic deflection angles are 2° and 5°, and the misses caused by smoke interference are 51 m and 464 m, respectively. From the simulation results of Fig.3 and Fig.5, the initial velocities of the terminal guided projectiles are 900 m/s and 1 000 m/s, respectively, and the misses caused by the smoke interference are 112 m and 464 m respectively; this is because the distance between the projectile and the target is relatively large when the smoke interference ends, and the laser terminal guided projectile itself is overloaded. It is difficult to adjust its trajectory and miss distance, resulting in a large miss of the laser terminal-guided projectile. From the results of five different smoke screen action time in Fig.4 to Fig.9, it can be seen that when the smoke screen has an action time of 25 s and 55 s, and the distance between the projectile's impact point and the target is within 5 m the

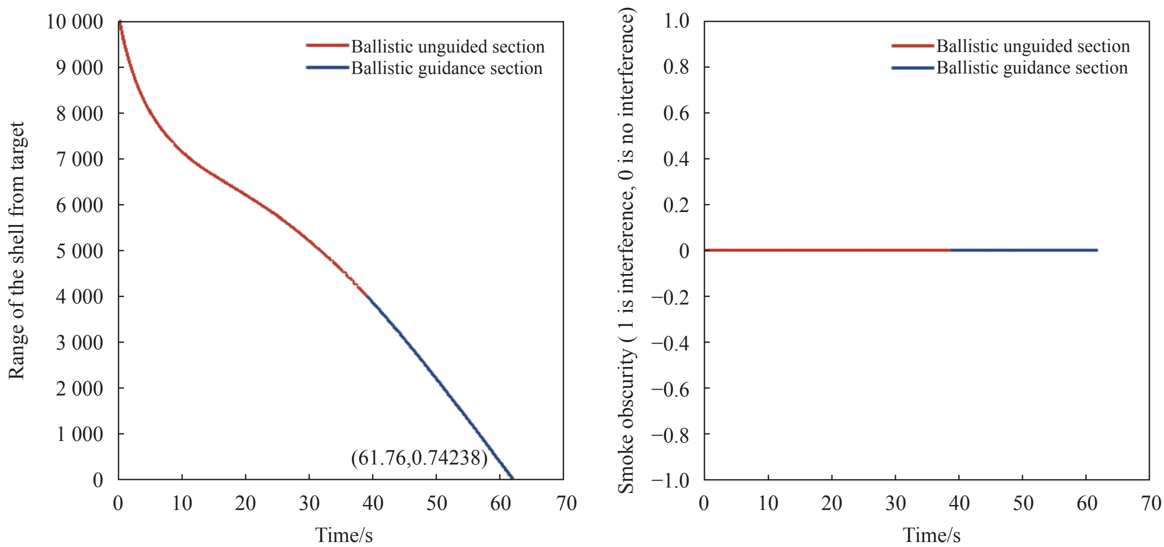

Fig.4 When the formation time of the smoke screen is 25 s, the distance curve of the projectile to the target and the interference situation

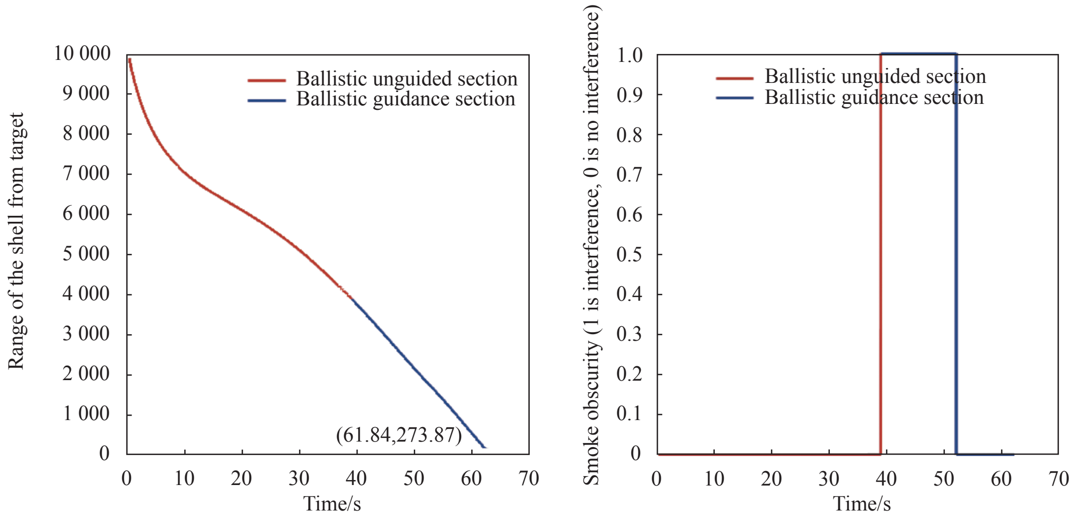

Fig.5 When the formation time of the smoke screen is 30 s, the distance curve of the projectile to the target and the interference situation

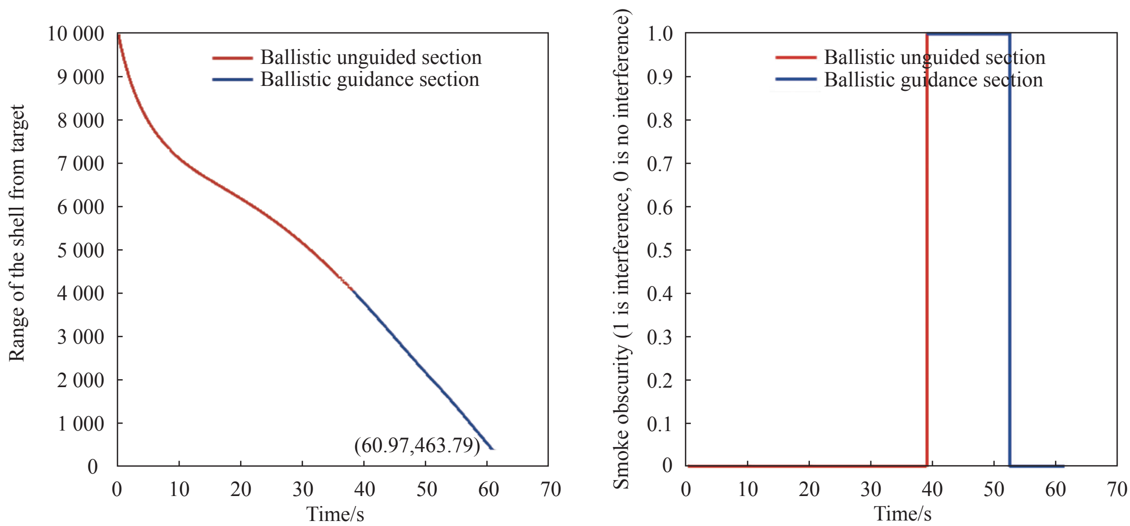

Fig.6 When the formation time of the smoke screen is 35 s, the distance curve of the projectile to the target and the interference situation

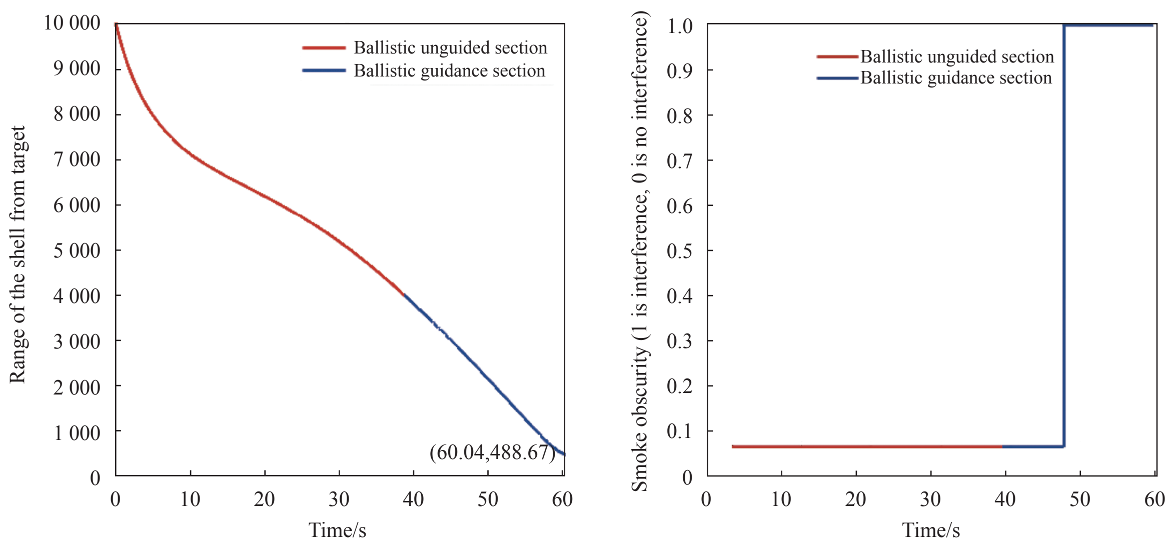

Fig.7 When the formation time of the smoke screen is 45 s, the distance curve of the projectile to the target and the interference situation

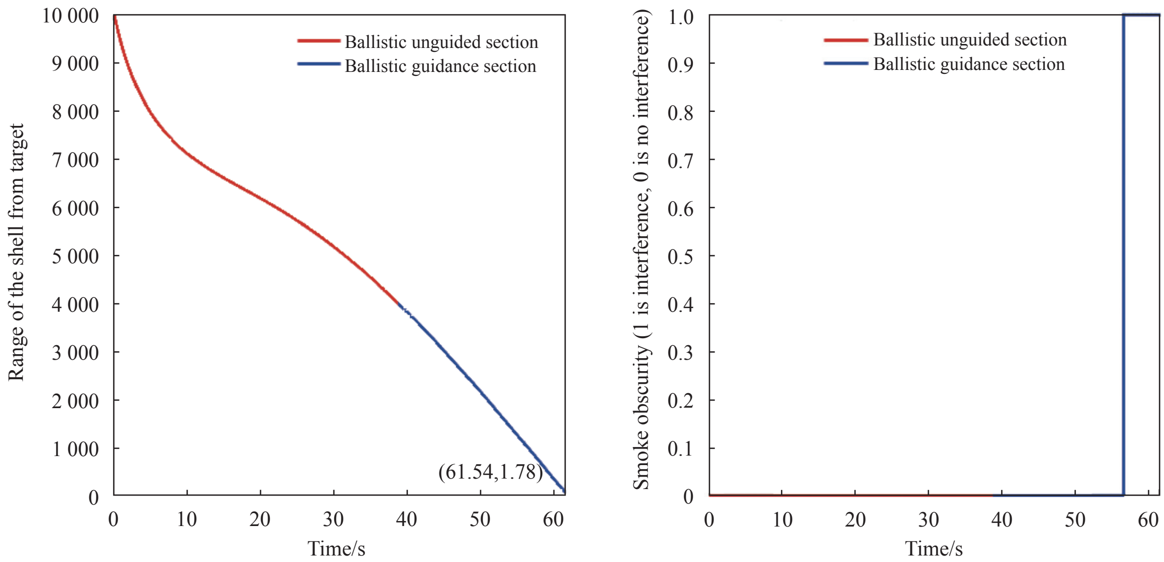

Fig.8 When the formation time of the smoke screen is 55 s, the distance curve of the projectile to the target and the interference situation

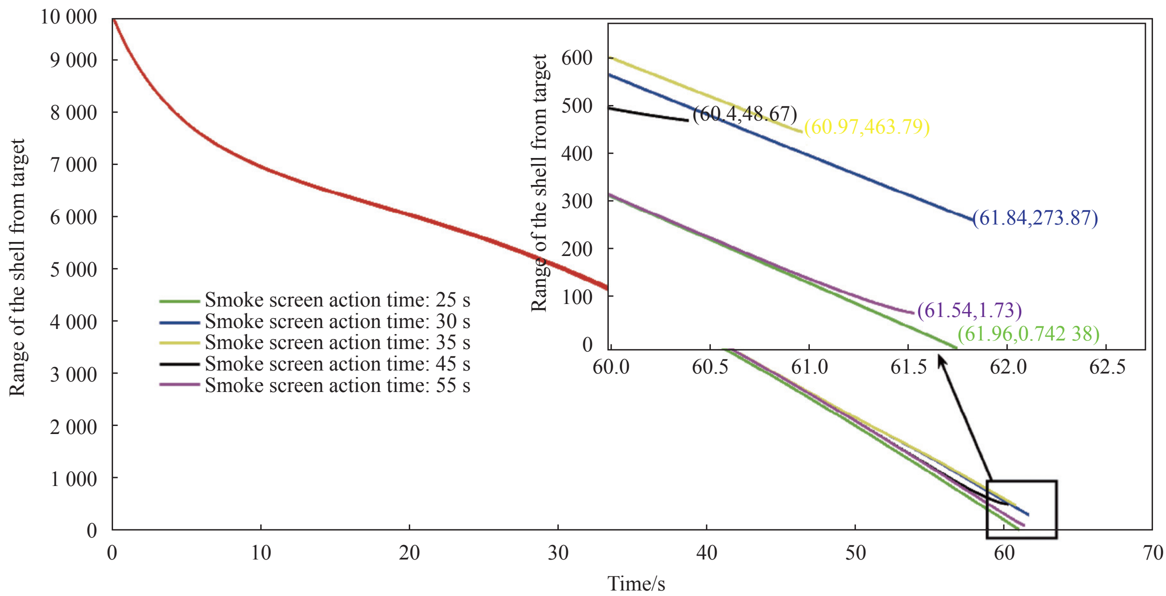

Fig.9 Horizontal plane trajectory of the projectile under different smoke screen formation time

smoke screen interference is invalid; the smoke screen action time is at 30 s, 35 s, and 45 s, the distances between the projectile's impact point and the target were 273 m, 464 m, and 489 m, respectively, indicating that the smoke screen interfered with the seeker of the laser terminal-guided projectile. Different smoke screen formation times have different interference effects on shells. If the smoke screen is formed too early or too late, the interference will fail. In addition, when the smoke screen formation time is close to the start time of the terminal guidance, the impact on the shell's falling point is the greatest. The earlier the smoke screen formation time or the later the shell's final landing point is closer to the target.

It can be seen from Fig.9 that under different smoke screen formation times, the horizontal plane trajectory and the image of the distance between the projectile and the target can be seen. When the smoke screen is formed too early or too late, the interference fails; although the projectile can hit the target, its movement trajectory is different. When the smoke screen is formed too early, the falling angle in the longitudinal plane is larger, while when the smoke screen is formed later, the falling angle is smaller. It can be seen from the horizontal plane trajectory diagrams of the projectiles under different smoke screen formation times that the simulation stopped when the projectile finally landed. Due to the influence of the smoke screen, the projectiles with the moke screen formation times of 30 s, 35 s, and 45 s did not reach the missile target when the projectile had landed, and the smoke screen interfered. In the horizontal plane trajectory diagram of the projectile and the distance between the projectile and the target, we can also see the interference of different smoke screen timings on the trajectory.

3.3 Application analysis of interference simulation results strategy

In the summary, the projectile landing is used as the simulation stop condition. When the smoke screen is formed in the unguided center of the laser terminal guided projectile, the smoke screen is affected by the meteorological conditions, and the smoke screen spreads, resulting in the smoke concentration being too low and the laser transmission rate increasing. The influence of the smoke screen on the laser seeker ends, and it finally hits the target. When the smoke screen forms a smoke screen in the guidance section of the laser terminal guided projectile, the laser terminal guided projectile always flies towards the target because there is no smoke screen in the guidance section at the initial stage. When the smoke screen is first formed, the width and height of the smoke screen have limited shielding ability. And after the smoke screen is formed, the projectile is close to the target, and the air attenuation of the laser is greatly reduced. At this time, the seeker of the projectile can still receive the reflected laser signal, and the projectile can be guided normally and hit the target. When the guidance section of the laser terminal-guided projectile begins, a smoke screen is formed. At this time, because the laser terminal-guided projectile is far away from the target, the attenuation of the laser by the atmosphere cannot be ignored, and the smoke screen has an attenuation effect on the laser. In this case, the smoke screen has the longest laser attenuation time. When the smoke interference ends, the projectile has a relatively long deviation from the target. The laser terminal-guided projectile itself is overloaded, and it is difficult to adjust its trajectory and miss the target. The laser terminal-guided projectile has the largest amount of miss, and its interference effect is the best.

4 Conclusion

This paper studies the interference simulation system of the smoke screen to the laser terminal guided projectile, which can realize the simulation simulation of the uncontrolled trajectory and the trajectory of the guidance section. Considering the influence of the smoke timing of the smoke screen on the laser terminal guided projectile, the smoke screen attenuation laser is introduced into the external ballistic equation of the laser terminal guided projectile, and the simulation of the interference of the smoke screen on the laser terminal guided projectile is realized, which can reflect the smoke screen interference laser terminal guided projectile external ballistic action process. When the guidance section of the laser terminal-guided projectile begins, a smoke screen is formed. The laser terminal-guided projectile has the largest amount of miss and its interference effect is the best. It provides auxiliary decision-making for combat training and effectiveness evaluation of typical smoking ammunition.

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