Analysis and study on the ballistic design of small-caliber grenade anti-UAV

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Abstract. With the rapid development of UAV technology, the use of unmanned weapons on the modern battlefield has innovated the combat mode and changed the form of warfare. In order to ensure national security and deal with potential war risks, it is imperative to carry out research on anti-drone weapons and equipment. Compared with the electromagnetic signal jamming and interception network anti-UAV technology, based on the existing small-caliber grenade launch platform, the technology of using projectile explosion fragments and shock waves to destroy the enemy's UAV equipment has the advantages of lower cost, faster research and development, more complete damage and higher fault tolerance. Based on fluid mechanics, projectile design theory, internal and external ballistics theory and numerical simulation technology of modern weapon systems, this paper reasonably optimizes the shape of small-caliber grenades, and uses the characteristics of prefabricated fragmentation explosion to damage different parts of the UAV, so as to achieve the effect of anti-UAV.

Keywords: anti-drone grenade, numerical simulation, prefabricated fragments, damage model.

1. Introduction

Since the beginning of the 21st century, major countries in the world have actively looked to the future, strategically and systematically planned the development of next-generation weapons and equipment, accelerated the deployment of offensive and defensive equipment systems, and actively promoted equipment with stealth, intelligence, and multi-function as the main characteristics [1]. Under nuclear prevention, future conflicts will be informationized, intelligent, and integrated, and will become a common trend in the development of weapons and equipment in the future. The main problems and difficulties in the research of small-caliber grenade [2] anti-UAV include technical challenges, cost-effectiveness considerations, and uncertainties in practical applications. It is mainly reflected in the problems of difficult detection and identification and low interception efficiency. Low, slow, and small UAVs are often difficult for traditional radar systems to detect and track effectively due to their small size and low flight altitude. With the development of artificial intelligence technology [3], future UAVs will be more intelligent and autonomous, which will undoubtedly further increase the difficulty of confrontation.

The difficulty lies in the complexity of the munition design [4], and the design of small-caliber grenades needs to take into account a variety of factors, such as armor-piercing ability, composite damage effect, etc., which require complex design and accurate calculations. The anti-drone guided missile uses ground high-power radar for tracking and navigation in the pre-flight stage, and uses inertial navigation in the mid-flight section to fly to the terminal position of 500-1000 m away from the target, and uses the image seeker for homing guidance, and detonates the warhead through the proximity fuse to destroy the target. In addition, there are many complex problems that need to be dealt with after the UAV has been tested and identified, and the use of electromagnetic interference technology [5] requires a high environmental foundation, and the impact on the electromagnetic environment is inevitable.

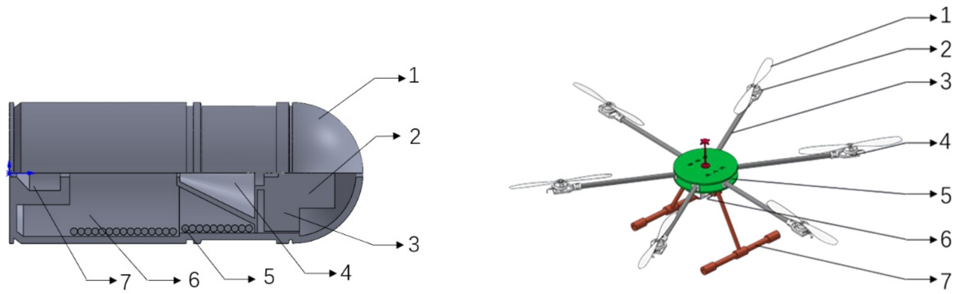
The first is jamming and blocking: jamming and blocking equipment is a more common anti-UAV system, which interferes with the hardware or communication of UAVs by means of sound waves and electromagnetic waves, so as to force UAVs to land automatically or return directly. The second is direct destruction [6]: the commonly used destruction methods of attack UAVs include conventional fire attacks, missile attacks, microwave attacks, laser attack weapons, and combat UAVs.

2. Finite element modeling of grenades and UAVs

In order to simulate the damage to various parts of the drone after the grenade explosion, it is necessary to first perform finite element modeling analysis on the grenade and the drone, and the following are the detailed steps:

(1) Define the objectives of the analysis. When the explosives explode, the metal casing and prefabricated fragments form natural fragments that propagate at very high speeds, and finally are hit by shock waves and high-speed natural fragments, so the explosion simulation of a grenade is carried out.

(2) Geometric modeling. Simplified modeling of UAVs and grenades by means of designed drawings and three-dimensional structures, the simplified model is as follows.



a) Simplified model of the grenade: 1 – warhead; 2, 3 – fuze; 4 – ignition chamber; 5 – prefabricated fragments; 6 – explosives; 7 – primer device

b) Simplified model of the drone: 1, 2, 3 – UAV take-off device; 4, 5, 6 – UAV fuselage part; 7 – UAV landing gear section

Fig. 1. Simplified models of grenades and UAVs

(3) Material property definitions. The main material of the grenade is made of explosives and a metal casing, in which the material for setting the grenade is structural steel, the wing material of the UAV is carbon fiber, and the landing gear and other parts are set as PC material.

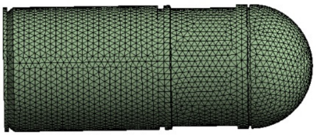
Table 1. Properties of different materials

Name	Structural steel	Carbon fiber	Pc
Density (g/cm^3)	7.85	1.55	1.20
Elastic modulus (GPa)	200	230	2.4
Poisson's ratio	0.28	0.3	0.38

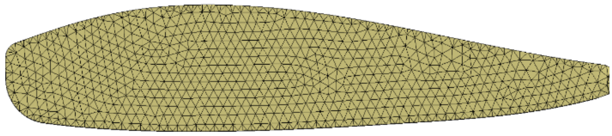
(4) Meshing. For the UAV structure, the UAV wing part is divided by a triangular mesh, and the landing gear part is divided by a quadrilateral meshing. For grenades, triangular meshing is applied locally.

In addition, the mesh should be encrypted in the stress-hit area, and the mesh can be relatively sparse in the area with a simple structure and low stress.

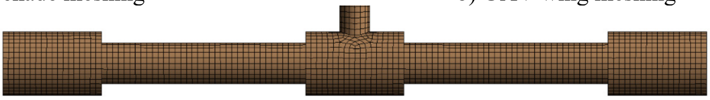
(5) Boundary conditions and loads. In order to obtain the initial velocity after the grenade explodes, explosives are added to the grenade, which explodes in a very short time. The multi-material ALE algorithm is used for air and explosives, while the Lagrangian algorithm is used for prefabricated fragments.



a) Grenade meshing



b) UAV wing meshing



c) Landing gear meshing

Fig. 2. Meshing of different parts

(6) Analysis of results. By establishing the model and meshing of the grenade and the UAV, to establish the foundation for the subsequent simulation, the explosion simulation of the grenade is first needed to determine the velocity of the fragmentation explosion, and then the damage level of the human machine is determined according to the collision between the velocity of the fragment and the UAV components.

3. Grenade fragmentation explosion simulation

The initial rate of the fragmentation is that the grenade bursts and disperses under the influence of the energy released by the expansion, the explosion product continues to act on the fragment, the cycle continues to accelerate, and when the fragment finally reaches the equilibrium with the air resistance under the action of the fragmentation product, the velocity of the fragment reaches the maximum. It can be obtained according to the explosion equation:

$$m_e E = E_f + E_w, \tag{1}$$

where: m_e – fill the energy of the explosives; E – the amount of energy released by a unit of explosives; E_f – fragmentation kinetic energy; E_w – the kinetic energy generated by the detonation.

With the theoretical formula, it is possible to simulate the speed at which a grenade explosion produces fragments.

In the explosion simulation, the fragments are attached to the explosive in advance, and the diameter of the fragments is set to 2 mm, which is used to simulate the simulation after the grenade explosion. The number of prefabricated fragments is 620.

Fig. 3. Prefabricated fragments and TNT models

(1) Model of explosives. The explosive model of the grenade uses a TNT-filled explosion, when building the model, it can be designed as a cylinder to simulate the actual TNT charge structure. for TNT materials, because explosions occur, high-explosive properties need to be added, as well as explosion equations.

(2) Boundary conditions for explosives. Fill the outside of the explosive with air to set the boundary conditions. The mesh for the air domain adopts the ALE mesh, for ease of calculation, the ALE grid size for the air domain is 2.5 mm.

(3) Analysis of the results of the explosion. Through the simulation of the setting of the fragments and the filling of explosives, the results of the fragmentation explosion can be obtained.

Table 2. Explosion parameters of TNT

Name	Numeric value (Pa)
Equation of the coefficient of state A	3.7377E+11
Equation of the coefficient of state B	3.7471E+09
Equation of the coefficient of state R_1	4.15
Equation of the coefficient of state R2	0.9
Equation of the coefficient of state omeg	0.35

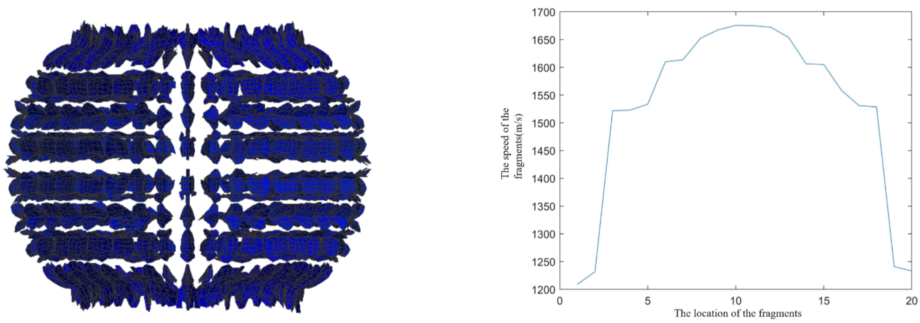


Fig. 4. Fragmentation detonation results

According to the simulation results, the grenade explosion will produce a large number of fragments in an instant, forming a network of fragments from the inside out. The simulation results show that the grenade forms a fragmentation net at the moment of explosion, and the fragments are mainly distributed within 45 degrees, and the speed of the fragments can reach 1200-1700 m/s.

4. Fragment damage analysis

In order to obtain the damage of the drone part by grenade fragments, it is necessary to first know the failure equation of the material. The function of plastic flow of the metal under the dynamic load impact:

$$\sigma = (A + B\varepsilon_P^n)(1 + C\ln\dot{\varepsilon}^*)(1 - T^{*m}), \tag{2}$$

where: σ – equivalent flow stress; A – yield strength; B – strain hardening constant; C – strain rate sensitivity coefficient; n – strain hardening index; $\dot{\varepsilon}^*$ – the equivalent plastic strain rate.

The failure model of the material is:

$$\varepsilon_B = \left[D_1 + D_2 e^{D_3 \sigma^*}\right][1 + D_4\ln\dot{\varepsilon}^*][1 + D_5\ln\dot{\varepsilon}^*], \tag{3}$$

where: ε_b – plastic strain at failure; D_1, D_2, D_3, D_4, D_5 – failure model parameters. The strain rate and compression process under the impact of a detonation can be expressed by the Glennesen equation of state:

$$p = \frac{\rho_0 C^2 \mu \left[1 + \left(1 - \frac{\gamma_0}{2}\right)\mu - \frac{\alpha}{2}\mu^2\right]}{\left[1 - (S_1 - 1)\mu - S_2 \frac{\mu^2}{1 + \mu} - S_3 \frac{\mu^3}{(1 + \mu)^3}\right]} + (\gamma_0 + \alpha\mu)E. \tag{4}$$

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For metal materials, the way to judge its failure is the maximum equivalent plastic strain, when it exceeds a certain value, the material will fail, and the maximum equivalent plastic strain of steel materials is generally 0.02. For fibrous materials, there are their own failure guidelines. Different areas of the UAV model are divided according to the failure equation.

After determining the material failure criterion of the UAV and the fragmentation velocity generated by the grenade explosion, it is necessary to set up the fragments to simulate the damage of different parts of the UAV at a speed of 1200 m/s to determine whether the grenade has the effect of destroying the UAV

First of all, the damaged parts of the drone are partitioned.

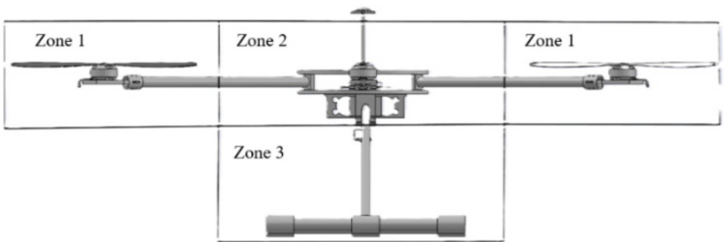

Fig. 5. Drone simplified partition model

Then, through the explosion simulation results of the grenade, the fragments are set to simulate the attack on the vulnerable area. In order to facilitate the simulation and ignore the divergence of fragments in different directions, a plurality of spherical fragments with a size of 2 mm are set above the UAV wing and landing gear components, and the initial velocity of the fragments is set to 1200 m/s vertical strike.

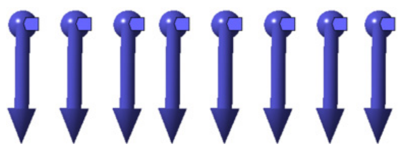

Fig. 6. Distribution of fragments and direction of impact

Finally, according to the simulation results, the results of the grenade anti-drone can be analyzed and evaluated according to the material failure criterion.

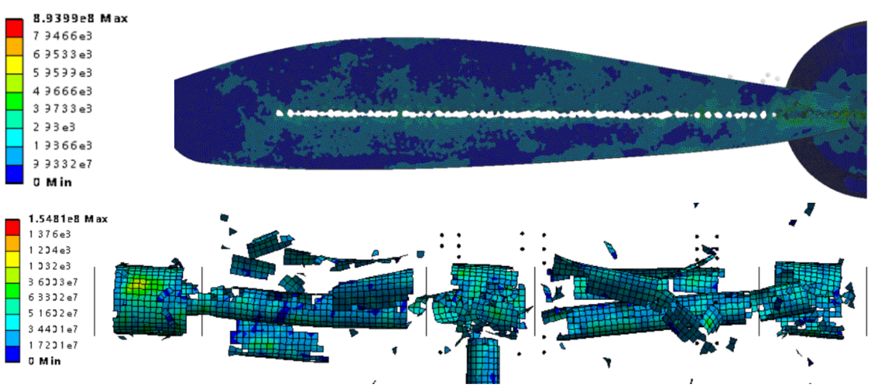

Fig. 7. The drone part was hit by fragments

According to the simulation results of the fragmentation strike UAV, the fragments generated when the grenade explodes can cause damage to different parts of the unmanned one. Through the study of small-caliber grenades, after the grenade flies to the detonation point, the fuse detonates by the effect, and you can choose to detonate at a fixed point by air explosion or rely on impact, because it is an air explosion and use shrapnel to destroy micro UAVs, so it doesn't hurt that the strike.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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