Numerical Simulation of Kinetic Kill Vehicle Impacting Biological Submunition Payloads

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Abstract. Damage behavior of biological submunition payloads directly impacted by Kinetic Kill Vehicle (KKV) is studied by numerical simulation based on Autodyn-3D software. Target characteristics and structure equivalent model of the biological submunition payload and KKV are analyzed and obtained. Three factors including hit-point position, strike angle and KKV’s diameter are chosen to study the damage behavior. Three types of damage behaviors of biological submunitions, including deformation, partial disintegration and completely disintegration occur in simulation. As for influencing factors, hit-point position has little influence on damage effect when hit-point is not at either ends. While number of damaged submunitions firstly increases and then decreases with increasing of strike angle when hit-point is near the center of the submunition payload. For the given KKV, number of damaged submunitions increases significantly at the strike angle of 60° compared with the vertical impact. With increasing of the KKV’s diameter, number of completely disintegrated submunitions increases dramatically and the damage degree and deformation range of the payload skin gradually increases. Research in this paper could provide useful references for the optimization structural of KKV, selection of terminal encounter condition, and assessment of kinetic midcourse anti-missile interception.

1. Introduction
Hit-to-kill Kinetic Kill Vehicle (KKV) is considered as one of the main means current midcourse anti-missile systems take [1]. The KKV is released when the interceptor reaches a certain height and speed. With the capability of autonomous flight and target identification, it can directly collide with and destroy the payload bay of the ballistic missile through its huge kinetic energy [2]. However, due to different and complex factors, there are considerable technical risks in whether the incoming ballistic missile warhead payload can be destroyed at one stroke even under the successful encounter [3], especially for the payloads of chemical or biological submunitions. They will pose a great threat to the ground environment and personnel safety once the submunitions containing chemical or biological agents that are not destroyed fall to the ground [4].

Theoretical calculation, simulation test on ground and numerical simulation are usually used to research the damage of KKV directly impacting the submunition payloads. McHenry et al. established ALPHAKV and OPTKV analysis models based on TATE invasion pit theory [5]. The U.S. Navy and Air Force conducted a series of experiments to figure out damage effects the quarter-size KKV can cause to the simulate re-entry missile warhead under high-speed collision [6]. Richard M. Lloyd et al.
carried out experiments to find out damage effects the penetrator can do to the simulated chemical and biological submunition payloads under high-speed collision [7]. Jin XK et al. carried out ground-based simulation test of impact of large mass high-speed explosively formed penetrator on chemical submunition payloads [8]. At present, it is rather difficult to obtain the real and systematic KKV and damage data because the ground-based simulation test is limited by the ground ultra-high speed launch technology, the target reality and the cost.

In fact, as a process of high-speed collision, the action process of KKV and submunition payloads involves a variety of dynamic responses and hydrodynamic actions related to multiple factors, such as the geometry, size, impact angle, position and velocity of the KKV. Based on nonlinear dynamical software platforms (such as ANSYS/ LS-DYNA and AUTODYN), scholars from various countries have conducted detailed researches on the mechanical behavior and damage effect of chemical submunition payloads under the impact of KKV [9]. However, there are few studies on the damage of KKV directly impacting the biological submunition payloads. Especially, the damage mechanisms of biological submunition payloads are not well understood by now.

In the paper, the target analysis and structure equivalence of the biological submunition payloads and the KKV are firstly carried out. On this basis, the damage effects of KKV against biological submunition payloads under different hit-points, strike angles and interceptor diameters are studied using the AUTODYN-3D software. Then the damage mechanism of KKV directly impacting the biological submunition payloads is analyzed according to the simulation results.

2. Structure and equivalent model of payload and KKV

2.1. Equivalent model of biological submunition payloads

Ballistic missile warhead generally adopts the structure design of tapered thin-wall shell, which is mainly composed of shell, thermal protection top, fuze and arming system, payload and auxiliary devices (such as penetration device and reentry control system) [10]. According to the different structures and functions, ballistic missile warhead can be generally divided into three sections, which are generally connected by aluminum alloy frames. The overall structure layout of a typical ballistic missile warhead is shown in Figure 1(a). Visual description can be implemented by reasonably simplifying the structure to establish a 3D solid model of the ballistic missile warhead based on the structure and functional characteristics of the warhead. The front section of a ballistic missile warhead is approximately a sharp cone while the payload section and the tail section are approximately a frustum. Each section is defined by the bottom diameter $D_i$ and length $L_i$, as shown in Figure 1 (b).

![Figure 1](image-url)

**Figure 1.** Structure layout and equivalence of ballistic missile warhead: (a) Overall layout of a typical ballistic missile warhead and (b) Equivalent model of the structure of the ballistic missile warhead.

According to different types of payloads, ballistic missile warheads can be roughly divided into nuclear, high-explosive, chemical and biological warheads. For the biological submunition payloads, it is mainly composed of submunitions and separator. Each payload can carry hundreds of submunitions which are densely arranged in the payload bay. The typical structure of biological submunition
payloads is shown in Figure 2 (a). Mainly composed of shell, fuze and biological warfare agents, biological submunitions are usually spherical and small. According to the structural characteristics of the biological submunition payloads and the submunitions, the equivalent model of the biological submunition payloads is shown in Figure 2 (b). The submunitions are closely arranged. The thickness of the submunition’s skin is represented by $h_1$.

![Figure 2](image)

**Figure 2.** Geometry structure and equivalence of the biological submunition payloads: (a) Typical structure of biological submunition warhead and (b) Equivalent model of the submunition payloads.

### 2.2. Equivalent model of KKV

Hit-to-kill KKV is the main type of interceptor used by the midcourse anti-missile system of the United States. Main anti-missile systems of US include the Ground-Based Midcourse Defense System (GMD), using Exoatmosphere Kill Vehicle (EKV), and the Navy’s Full Theater Defense System (NTW), using Lightweight Exoatmospheric Projectile (LEAP)[11].

The internal structure of the KKV mainly includes the detector, attitude and orbit control propulsion system, inertial measurement combination, data processing and guidance system and computer, etc. The geometry and physical parameters of these components are difficult to obtain due to their different shapes and complex distributions. KKV relies on direct impacting to kill incoming warhead, as a result, its damage efficiency is closely related to its size distribution and mass characteristics. Therefore, the basic dimension is mainly considered when KKV is equivalent, according to its structural characteristics and layout, while the specific materials and structures of its internal structure and component size can be ignored. For EKV, it can be divided into two section: the front section and the tail section, as shown in Figure 3. For LEAP, it can be regarded as a homogeneous cylinder, as shown in Figure 4.

![Figure 3](image)

**Figure 3.** Simplified and equivalent model of EKV
3. Numerical method and material model

3.1. Numerical method
The numerical simulation was carried out based on the nonlinear dynamics software AUTODYN-3D, and the pre-processing was done on the Truegrid software. In numerical simulation, the partially equivalent model of the biological submunition payload is shown in Figure 5, which included of a skin and submunitions. Usually, the geometric shape of the skin is simplified as a frustum. The material of it is 45# steel, the thickness is 2mm, the upper and bottom diameters are 220mm and 320mm respectively, and the length is 420mm. To simplify the calculation, number of submunitions in each layer is the same. The geometric structure and array of submunitions are shown in Figure 5 (b). A total of 84 spherical submunitions are arrayed equally in seven layers. The material of the shell is 1006 steel, the thickness is 1mm and the diameter is 50mm. The biological agent filled inside is replaced by water in the simulation. The skin, submunition shell and water were calculated by the Lagrange method. Among different KKV's, the configuration of LEAP is chosen in numerical simulation. Relevant data shows that the mass of a certain type KKV is about 5kg [12]. In this paper, the material of KKV is aluminum. On the premise that the mass and dimensions of the KKV are basically unchanged, considering the aspect ratio, the diameter and length of the KKV are 100mm and 240mm respectively. The numerical model of the KKV is shown in Figure 5 (d).

![Figure 5. Numerical model of biological submunition payloads and KKV: (a) Payload skin, (b) Submunition arrangement, (c) Submunition, and (d) Geometrical model of KKV.](image)

3.2. Material model
The numerical simulation model consists of four parts: payload skin, submunition shell, biological agent and KKV. Detailed material strength models and EOSs are shown in Table 1. Material parameters in simulation were derived from the material library in AUTODYNNTM [13], as shown in Table 2.

| Part     | Materials | EOS | Strength model | Failure model | Erosion |
|----------|-----------|-----|----------------|---------------|---------|

![Table1. Material strength models and EOSs.](image)
Payload skin

| Material   | Shock | JohnsonCook | JohnsonCook | Plastic stain 0.2 |
|------------|-------|-------------|-------------|-------------------|
| #45 steel  |       |             |             |                   |
| Submunition shell

| Material   | Shock | JohnsonCook | JohnsonCook | Plastic stain 0.2 |
|------------|-------|-------------|-------------|-------------------|
| 1006 steel |       |             |             |                   |
| Biological agent

| Material   | Shock | JohnsonCook | JohnsonCook | Plastic stain 0.2 |
|------------|-------|-------------|-------------|-------------------|
| Water      |       |             |             |                   |
| KKV

| Material   | Shock | JohnsonCook | JohnsonCook | Geometric stain 2.0 |
|------------|-------|-------------|-------------|---------------------|
| Aluminum   |       |             |             |                     |

Table 2. Materials parameters of the KKV and biological submunition payloads

| Materials | $\rho$ (kg/m$^3$) | $G$ (GPa) | $A$ (MPa) | $B$ (MPa) | $n$ | $C$ | $m$ | $T_m$ (K) | $T_{room}$ (K) | $f$ | $c_0$ (m/s) | $S$ |
|-----------|------------------|-----------|-----------|-----------|-----|-----|-----|-----------|-----------------|-----|-------------|-----|
| #45 steel | 7.85             | 77        | 507       | 320       | 0.28| 0.064| 1.06| 1793      | 300             | 2.17| 4569        | 1.490|
| #1006 steel | 7.89          | 81.8      | 350       | 275       | 0.36| 0.022| 1.03| 1811      | 300             | 2.17| 4569        | 1.490|
| Aluminum  | 2.78             | 27.6      | 265       | 426       | 0.34| 0.015| 1.00| 775       | 300             | 2.00| 5328        | 1.338|
| Water     | 1.0              |           |           |           |     |     |     |           |                 | 0.00| 1647        | 1.921|

4. Results and discussions

We choose three factors to study the damage effect of KKV directly impacting biological submunition payloads, including hit-point position, strike angle and KKV’s diameter. The terminal encounter condition of biological submunition payload and KKV is shown in Figure 6. Where point A, B, C are hit-points, $\theta_{SA}$ is strike angle, $v$ is velocity of KKV, $v_t$ is velocity of payload, $v_r$ is relative impact velocity.

4.1. Influences of hit-point

In order to study the influence of hit-point on damage effect, three different hit-points A, B and C are chosen respectively, as shown in Figure 6. The relative impact velocity is $v_r = 3000$ m/s while the strike angle is $\theta_{SA} = 90^\circ$. The typical damage effect of biological submunition payloads is shown in Figure 7 when hit-point is A. It can be seen that the skin is seriously deformed and penetrated both front and rear. The submunitions in the penetration path of KKV completely disintegrate, causing the internal biological agent leaking. According to simulation results, three layers of submunitions along the penetration path are seriously damaged, and 36 submunitions are completely disintegrated under the high-velocity impact of the KKV. Submunitions in the fourth layer are damaged to varying degrees by the collision of submunitions in the upper layer, and part of them are seriously deformed. The lower three layers of submunitions remain intact because they are far from the impact area.

Figure 6. Terminal encounter condition of KKV against the payload.
The typical damage effect of biological submunition payloads is shown in Figure 8 and Figure 9 when hit-point is B and C, respectively. When hit-point is B, the middle three layers of submunitions are seriously damaged, causing the biological agent completely leaking. Submunitions in the second and sixth layers near the penetration path are also damaged to varying degrees. In particular, the shells of some submunitions in the second layer are fractured, causing the biological agent partly leaking. When hit-point is C, the lower three layers of submunitions are seriously damaged and biological agent inside submunitions in the fourth layers leaks partly meanwhile. However, the upper three layers of submunitions almost remain intact.

Simulation results show that the hit-point has a certain influence on the number of damaged submunitions in the warhead. More submunitions are damaged when the hit-point is near the centre than near either end. However, there is little difference in the number of leaked submunitions when the KKV impacts two ends of the payload. When the KKV directly impacts the payload, it mainly depends on kinetic energy to destroy the submunitions. For a given KKV, when impact velocity and angle keep the same, the maximum kinetic energy is obtained by the submunitions along the penetration path, resulting in the complete fragmentation of the submunition shell and the leakage of biological agent. The kinetic energy obtained by the submunitions outside the penetration path gradually decreases, meanwhile the effect of secondary collision is also weakened, causing a gradual reduction in the damage effect of submunitions. Therefore, under the circumstances that number of

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**Figure 7.** Numerical simulations of KKV impacting point A: (a) Top view of payload, (b) Top view of submunitions, (c) Side view of payload, and (d) Side view of submunitions.

**Figure 8.** Numerical simulations of KKV impacting point B: (a) Top view of payload, (b) Top view of submunitions, (c) Side view of payload, and (d) Side view of submunitions.

**Figure 9.** Numerical simulations of KKV impacting point C: (a) Top view of payload, (b) Top view of submunitions, (c) Side view of payload, and (d) Side view of submunitions.
submunitions in each layer keeps the same, the number of fully damaged submunitions will be fewer when the KKV impact two ends of the payload. When hit-point is not at either ends, the KKV of a given size covers the same number of submunitions, so the difference in the number of severely damaged submunitions is very little.

4.2. Influences of strike angle

When the hit-point and impact velocity keep the same, the strike angle determines the damage effect of KKV directly impacting submunition payloads. To study the influence of strike angle on damage effect, three strike angles of 30°, 60° and 90° are chosen respectively. The relative impact velocity keeps constant \( v_r = 3000 \text{ m/s} \) and the hit-point remains point B. When the strike angle is 30° and 60°, the typical damage effect of biological submunition payload is shown in Figure 10.

At a strike angle of 30°, completely disintegration occurs to some submunitions in each layer and number of them is 42. In specific, one submunition in the first layer is seriously disintegrated, three submunitions in the second layer, eight in the third, fourth, fifth and sixth layers and six in the seventh layer are completely disintegrated. Number of damaged submunitions turns to 53 at a strike angle of 60°. In specific, submunitions in the first layer keep intact, four submunitions in the second layer, six in the third layer, all in the fourth, fifth and sixth layers and seven in the seventh layers are completely disintegrated.

![Figure 10](image1.png)

**Figure 10.** Numerical simulations of different strike angle: (a) 30° and (b) 60°.

Simulation results show that the strike angle has a significant influence on the number of damaged submunitions when the hit-point is near the center of the payload. Comparing Figure 8 and Figure 10, with the strike angle increasing from 30° to 90°, number of damaged submunitions firstly increases and then decreases. When the strike angle is 60°, the number of damaged submunitions reaches the maximum. This is mainly because, based on the volumetric overlap method [8], there are most submunitions in the penetration path of KKV at a strike angle of 60°, causing the best damage effect.

4.3. Influences of KKV’s diameter

The size and material characteristics of the KKV also have strong influence on the damage effect. The influence of KKV’s diameter on the damage effect is studied for the KKV with a given material under the same terminal encounter condition. Diameters of 80mm, 100mm and 150mm are chosen respectively, with the length keeping the same. Relative impact velocity keeps constant \( v_r = 3000 \text{ m/s} \) and the hit-point remains point B. When the diameter of KKV is 80mm and 150mm, the typical damage effect is shown in Figure 11 and Figure 12 respectively.

![Figure 11](image2.png)

(a) (b)

![Figure 12](image3.png)

(c) (d)
Figure 11. Numerical simulations of KKV with a diameter of 80mm: (a) Top view of payload, (b) Top view of submunitions, (c) Side view of payload, and (d) Side view of submunitions.

Figure 12. Numerical simulations of KKV with a diameter of 150mm: (a) Top view of payload, (b) Top view of submunitions, (c) Side view of payload, and (d) Side view of submunitions.

As shown in Figure 11, with a diameter of 80mm, impact of KKV cause submunitions in the middle three layers seriously damaged, especially the fourth layer. Ten submunitions in the third and the fifth layers are also completely disintegrated. However, submunitions in the upper two layers and lower two layers are almost undamaged.

When the diameter of KKV increases to 150mm, damage effect of biological submunition payload is very significant, as shown in Figure 12. Submunitions in the middle three layers are completely disintegrated, and submunitions in the second and sixth layer are seriously disintegrated, remnants of which are less than half of the original ones. Some submunitions in the first and seventh layer are also deformed by the secondary collision of submunitions in the nearby layer. With the increase of diameter of KKV, number of completely disintegrated submunitions increased greatly. Meanwhile, it can be seen from side view that damage degree and deformation range of payload skin gradually increase.

For biological submunition warheads, once the submunition containing biological agent falls to the ground, it will pose a great threat to the safety of personnel and the environment. Therefore, in order to minimize the additional damage to the ground, it is required to destroy as many submunitions as possible, preferably all submunitions. According to simulation results in this paper, when the diameter of KKV is relatively small, the strike angle has a great influence on the number of damaged submunitions. But for a given terminal encounter condition, the diameter of KKV has the decisive influence on the number of fully damaged submunitions.

5. Conclusions
Damage behavior of biological submunition payloads directly impacted by KKV were studied by numerical simulations. Several conclusions are presented as follows:
(1) Target characteristics and structure equivalent model of the biological submunition payloads and KKV are analyzed, and a numerical simulation model for the damage analysis of KKV directly impacting biological submunition payloads is established.
(2) Simulation results show that the damage effects of biological submunition payloads directly impacted by KKV is strongly influenced by hit-point, strike angle and the diameter of KKV. Compared with hit-point and strike angle, the diameter of KKV has a decisive influence on the damage effect.
(3) Three damage behaviors of biological submunitions, including deformation (no fluid leakage), partial disintegration (partial fluid leakage) and completely disintegration (complete leakage) occur in the simulation. In terms of damage mechanism, severe damage of submunitions is manly caused by the direct impact of KKV, meanwhile slighter damage is manly caused by the secondary collision of adjacent submunitions and the high-speed injection of liquid inside the submunitions.
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