Research on Vulnerability and Damage Assessment of Tactical Ballistic Missile

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Abstract. The threat of TBM (Tactical Ballistic Missile) on the battlefield makes it an important intercept target of anti-missile system. In order to effectively evaluate the damage degree of TBM when intercepted, the system and function characteristics of TBM were analyzed with "Iskander" TBM as an example, the missile vulnerability model was constructed, the vulnerability and damage assessment program was developed, and the damage assessment test methods of TBM were summarized. The research results will help to carry out real-time evaluation of the damage effect of antimissile system towards TBM.

1. Introduction

TBM is mainly used to assault high value targets such as enemy groups, missile launching positions and air defense positions. It has become one of the most threatening weapons on the battlefield and the competing development of many countries because of its long range, high hit accuracy, great power and strong penetration ability[1]. Looking at the development of TBM on the world, U.S. Army Tactical Ballistic Missile System, the only active tactical ballistic missile system in service, can carry biochemical warheads, lethal explosive warheads, ground penetrating warheads to destroy hard and underground targets, cluster sub-carrier warheads to attack airport runways and precision terminal guided sub-carrier warheads, which launched using M270 Multiple-barrel rocket launcher. At present, the countries and regions that have purchased the missile system are the United States, Bahrain, France, Germany, Greece, South Korea, Turkey, Poland, Taiwan and so on. In the Gulf and Iraq wars, the United States used about 560 of these missiles to destroy enemy airports, air defense systems and command centers and other targets. The United Nations Department of Defense Strategic Capability Office (SCO) begun to implement the army's new long-range tactical ballistic missile project (the Army's Long-Range Precision Firepower project) to meet the demand for precision strike capability in future "multi-area warfare". The Russian "Iskander" TBM can carry a variety of warheads, such as cluster munitions, high explosive bombs, penetrating munitions, ground penetrating bombs, air combustion bombs and electromagnetic pulse bombs, which can strike command posts and communication hubs, large group armies, fire strike equipment, air defense and anti-missile facilities, berth at airports, aircraft and helicopters, important industrial and energy facilities and other targets.
The India TBM mainly includes the "fire" series and the "Earth" short range series. The ROK Army is mainly equipped with "Xuanwu-2A" and "Xuanwu-2B" ballistic missiles with missile bodies similar to the Russian-made "Iskander" tactical missiles. DPRK's active tactical ballistic missiles include short-range missiles Mars-5, Mars-6, Scud-D and KN-02, medium-range ballistic missiles Labor-1, Labor-2, medium and long-range Taepodong-1, Taepodong-2 and KN-08[3,4]. France is mainly equipped with Hades tactical ballistic missiles[5].

With the TBM playing a higher tactical strike capability on the battlefield, the anti-missile system of intercepting TBM has been gradually valued and developed by many countries[6-8]. Vulnerability analysis and damage assessment of TBM has gradually become a research hotpot in academic field[9-10]. In the present work Russian "Iskander" tactical ballistic missile was taken as an example to research the system and functional characteristics of TBM, develop vulnerability analysis and damage assessment software, investigate damage effect assessment test methods.

2. System and Function Characteristics

"Iskander" TBM is mainly composed of missile body system, guidance system, fuze and warhead system, control system, thrust system and power system. The system structure model is shown in Figure 1.

![Figure 1. System structure model](image)

As the carrier of warhead and missile equipment, the missile body system guarantees the corresponding working and storage environment, generates aerodynamic force, including maneuvering force and control force, and carries static and dynamic loads under ground working conditions and air flying conditions. The guidance system receives the matching position data from the real-time image processing system, forms the guidance command according to the flight deviation of the actual position and the pre-positioning position of the missile, and sends it to the control system. The control system responds to the command signal sent by the guidance system, and forces the missile to change the flight direction by changing the corresponding normal control force. The control system stabilizes the attitude or angular velocity of the missile and controls the missile according to the signal from the guidance system. Laser fuze is used in the fuze and warhead system. The fuze detects the target by receiving the laser beam which is reflected by the target. It can get rid of the dependence of the fuze on the target and realize the wide range detection of the target to meet the requirement of the missile attack. When the missile and target encounter, the fuze chooses the best time for the warhead to destroy the target effectively. Thrust system is a device that provides flight power for the missile to ensure that the missile obtains the acceleration, velocity and range required by tactical and technical specifications. In some cases, it can also be used to generate control force and maneuvering power. The power system provides electric source, gas and other power sources to the equipment on the missile during the whole process from takeoff to hitting the target.

3. Vulnerability Analysis and Damage Assessment Software

3.1. Software Design

The basic idea of missile vulnerability analysis and damage assessment is as follows. Firstly, read the original data according to the target design drawings and photographs, and draw the 3D graphics of the target. Then according to the principle of material equivalence or function equivalence, combined with the analysis of the key components of missile, the equivalent geometric model of missile vulnerability is given, which provides the target data platform for penetration paths of shooting lines.
Secondly, Monte Carlo method is used to simulate the intersection point coordinates and the penetration paths between the shooting lines and the geometric model of the target. Then, according to the characteristic parameters and damage mechanism of the projectile, the physical damage state of the components encountered by each shooting line in its penetrating path is calculated, and the approximate kill probability of each key component is given by statistical method combined with the damage criterion of the components. Finally, according to the requirement of target combat mission, the functional system is divided, and the functional damage level is defined in each functional system. The corresponding functional reduced-order logic damage tree graph is established. According to the connection relation of key components in the damage tree, the overall damage probability of each functional system is given by a certain logical operation. The vulnerability analysis and damage assessment process of the missile is shown in Figure 2.

![Figure 2](image-url)

**Figure 2.** The vulnerability analysis and damage assessment process of the missile

The software system consists of eight function modules: user management module, warhead model parametric design and import module, target model parameter design and import module, damage criterion and criterion database, damage calculation module, missile target damage visualization module, missile target damage result and report output module and help document module. According to the relationship between functional modules, the logical relationship model of the system between them is constructed, as shown in Figure 3.

![Figure 3](image-url)

**Figure 3.** Logical relationship model of the system
3.2. Missile Vulnerability Analysis and Damage Probability Calculation

3.2.1. Damage Mode. The missile's battlefield mission is to accurately guide the missile warhead to the target area, timely and reliable detonates the warhead to damage the target. The possible damage modes of the missile are: (1) not accurately flying toward the target (yaw), (2) not detonating the warhead (dumb bomb), (3) catastrophic damage (disintegration). The mechanism leading to these damage modes is very complex. For example, under the action of fragments or shock waves, the deformation, bending of missile local body, breakage, deformation of the wing may cause aerodynamic asymmetry and make the missile yaw. The seeker and control system damage, fuel leakage, engine failure may cause the missile not to fly to the target accurately. Damage to the fuze and detonation sequence of a missile may lead to a dummy. If the inflammable and explosive components (such as warheads and fuel tanks) carried by the missile are impacted by high-speed fragments, combustion or explosion may occur, resulting in the disintegration of the whole missile.

3.2.2. Damage Rank. The classification and description of the damage level of the missile is shown in Table 1

| Level | Description | Possible reasons |
|-------|-------------|------------------|
| K     | Missile disintegration immediately | The warhead or solid rocket motor is detonated, or the connecting mechanism is interrupted. |
| F     | The missile failed to complete its scheduled task (the Guidance system, Control system or fuze function is failure, thrust power of thrust system does not meet the requirement). | |
| P1    | The thruster system is slightly damaged, the thrust of missile is lowered, the acceleration capability is weakened, or the thrust direction is out of control. | Breakdown of engine shell and nozzle leads to gas leakage. |
| P2    | The thruster system is badly damaged, and the missile has no thrust action. | The solid engine is detonated. |
| C1    | The control system is slightly damaged, the servo system is slightly distorted, and the rudder surface can be damaged, and the servo mechanism is slightly damaged. | The control box and signal amplifying circuit are damaged, and the servomechanism is slightly damaged. |
| C2    | The control system and servo system are seriously damaged, and the missile is out of control. | Inertial guidance gyroscopes and accelerometers are slightly damaged, and optical guidance systems are slightly damaged. |
| N1    | The guidance system is slightly damaged, and the error of data collection and receiving is increased. | The inertial guidance system and optical guidance system are seriously damaged. |
| N2    | The guidance system is badly damaged, the guidance function fails, and the missile loses its target. | The guidance system and optical guidance system are seriously damaged. |
| W1    | Warhead can not be reliably detonated. | The fuze is damaged |
| W2    | The warhead is detonated in advance. | Warhead charge is detonated. |

3.2.3. Damage Tree. Damage tree is a functional reduced-order logic tree graph, which can reflect the logical connection between the key components in the system. The overall damage probability of each
functional system can be calculated by a certain logical operation using the damage tree. K level damage tree and F level damage tree in the boost phase of TBM are shown in Figures 4 and 5.

![Figure 4. K level damage tree](image)

![Figure 5. F level damage tree in the boost phase](image)

### 3.2.4. Damage Probability Calculation

The kill probability of components $P_{k/h}$ can be calculated by the following formula.

$$P_{k/h} = \frac{A_v}{A_p}$$

Where, $A_v$ represents the total vulnerable area of a component. $A_p$ indicates the total area of presentation for a component.

The method of "shooting line scanning" can be used for calculating $A_v$ and $A_p$ when the component hit by a single fragment. In this method, a plane mesh (the length of the mesh is $a$ and the width of the mesh is $b$) is laid flat on the quadrilateral finite element projection model of the component, and shooting lines (assuming a total of $N$ lines) are generated in each element of the plane mesh. Scanning the target surface and accumulating the number of mesh elements on the surface of the component from shooting line 1 to shooting line $N$. The number of elements is multiplied by the area of the element $(ab)$ to get the $A_p$.

$A_v$ can be calculated by the formula as follows.

$$A_v = \sum_{i=1}^{N} P_{k/hi}$$

where, $P_{k/hi}$ is the kill probability of the missile mesh unit hit by the firing line $i$ and can be calculated according to the kill model. The killing mode (penetration, ignition) of each component and the killing probability of each component under a given attack should be considered in the calculation process. In the process of killing probability calculation, the parameters such as the incident velocity, the incident direction and the mass of the fragment should be considered. When calculating these parameters, the
occlusion effect of key components and non-key components should be considered. Therefore, it is necessary to calculate the velocity, direction and mass change of fragments after striking the target skin or components.

According to the damage criterion of each component and the number of effective fragments hitting each component, the damage probability of each component can be calculated. Combined with the damage tree of the target, the damage probability of the whole target can be obtained as follows.

\[ P = 1 - \sum_{j=1}^{w} (1 - P_j) \]  

(3)

where, \( P_t \) and \( P_j \) denote the damage probability of the whole target and the damage probability of component \( j \) respectively. \( w \) denotes the number of components.

4. Damage Effect Assessment Test Method

Damage assessment of Intercepted TBM is an important link in ballistic missile defense system. The effectiveness of this assessment directly affects the re-interception capability of the system. Damage assessment is generally divided into two levels. The first level is to evaluate whether the interceptor hit the target, and the second level is to evaluate the damage degree of the target payload hit by the interceptor. At present, the damage effect evaluation methods mainly include the radar detection method which is widely used and the optical detection method which is not yet mature.

The use of radar detection for damage assessment mainly includes two aspects. (1) The damage of the missile is judged by judging the yaw trajectory. This judgment method is mainly aimed at the functional or structural damage of the warhead impacted by kinetic energy projectile or the impact of interceptor explosion shock wave, but no explosion occurs. When the warhead is impacted by external impact force, the flight trajectory changes greatly. Meanwhile, the influence of warhead maneuver avoidance trajectory on damage assessment should be considered. (2) When a warhead explodes under the direct impact of a kinetic energy projectile, the warhead and the shell break into debris clouds of different sizes and velocities. If the fragments are small enough, the target will disappear on the display of the tracking radar after the explosion. Thus, the complete damage of the target can be judged. However, if the intercepted target explodes and produces large debris, the radar will mistake it as the target and affect the damage assessment of the target [11].

At present, the main system of missile damage assessment by optical detection means is the space-based damage assessment system being developed by the United States, named SKA(Sky Kill Assessment)[12]. The SKA system mainly relies on a series of infrared sensor networks on commercial satellites as the implementation platform. In the experiment, infrared and visible images of the interceptor impacting the threatening target are obtained by the spaceborne infrared sensor. Based on real-time assessment algorithm, SKA quickly assesses whether interception projectile successfully intercept and destroy the threat targets. The key technologies of the evaluation system are the acquisition and processing of the collision image, and the processing of the spatial, spectral and luminance characteristics of the fireball based on the collision image.

5. Conclusion

In the present work, Russian "Iskander" tactical ballistic missile was taken as an example to research the System and functional characteristics of TBM, vulnerability analysis and damage assessment software was developed, damage effect assessment test methods were investigated. The research results will help to carry out real-time evaluation of the damage effect of antimissile system for tactical ballistic missile interception.

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