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Aircraft vulnerability modeling and computation methods based on product structure and CATIA

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Redundancy

Abstract Survivability strengthening/vulnerability reduction designs have become one of the most important design disciplines of military aircraft now. Due to progressiveness and complexity of modern combat aircraft, the existing vulnerability modeling and computation methods cannot meet the current engineering application requirements. Therefore, a vulnerability modeling and computation method based on product structure and CATIA is proposed in sufficient consideration of the design characteristics of modern combat aircraft. This method directly constructs the aircraft vulnerability model by CATIA or the digital model database, and manages all the product components of the vulnerability model via aircraft product structure. Using CAA second development, the detailed operations and computation methods of vulnerability analysis are integrated into CATIA software environment. Comprehensive assessment data and visual kill probability Iso-contours can also be presented, which meet the vulnerability analysis requirements of modern combat aircraft effectively. The intact vulnerability model of one hypothetical aircraft is constructed, and the effects of redundant technology to the aircraft vulnerability are assessed, which validate the engineering practicality of the method.

1. Introduction

Aircraft combat survivability is defined as the capability of an aircraft to avoid or withstand a man-made hostile environment, and includes two aspects as susceptibility and vulnerability. Vulnerability assessment and reduction are important measures to improve aircraft's survivability. Currently, survivability strengthening/vulnerability reduction designs have become one of the most important design disciplines of military aircraft. The newest manned and unmanned combat aircraft, such as F/A-18E/F, F/A-22, F-35, "Global Hawk", "Predator", etc., have adopted survivability strengthening/vulnerability reduction measures in the initial research phases,[1–5] and carried out detailed vulnerability assessment about material selections and equipment dispositions, etc.[6–9]

Vulnerability modeling and quantitative computation are two major important and complicated aspects for vulnerability

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assessment. For improving efficiency and accuracy of vulnerability assessment, lots of programs and software have been developed by American researchers, to name a few, vulnerability modeling software BRL-CAD, shot-line generation programs SHOTGEN and FASTGEN, vulnerable area computation program VAREA, vulnerable area and repair time computation program COVART, missile endgame computation programs ESAMS, JSEM, AJEM, etc.[5,10]

Some colleges and aircraft design institutes in China started vulnerability modeling and quantitative computation research in the 90s of the 20th century, e.g., Northwestern Polytechnical University developed a vulnerability modeling method and corresponding vulnerability assessment software AVCAS based on finite elements,[11,12] Nanjing University of Science and Technology developed vulnerability assessment software for aircraft to fragment warheads ATVASS,[13] China Academy of Engineering and Physics developed warhead lethality/target vulnerability assessment software WLTVAS,[14] etc. At the same time, some vulnerability assessments of aircraft and missiles were taken by Chinese researchers,[15–17] and vulnerability modeling and computation software were improved, but these methods and software still have some disadvantages in practical applications, for example, too simple models, comparatively complicated modeling methods, excessively intricate analysis processes, insufficiency visualization, and so on. These disadvantages greatly limited assessment and improvement of combat aircraft's vulnerability.

In this paper, a vulnerability modeling and computing method based on product structure and CATIA software is proposed in sufficient consideration of modern combat aircraft's design characteristics. With this method, an aircraft vulnerability model including diverse configuration, complex structure, large systems, etc., can be constructed. That can ameliorate modeling efficiency and model accuracy, and provide good three-dimensional manipulation and visualization.

On that foundation, initial vulnerability computation methods are improved by CAA second development, which makes analysis operations, e.g., vulnerability attribute setting, shot-line generation, kill tree construction, and kill impact assessment, become convenient. Detailed vulnerability data and kill probability Iso-contour, with respect to single hit, multi hits, and missile fragment hit, can be presented. This method can also provide references for other large complicated weapon systems' vulnerability modeling and computation.

2. Aircraft vulnerability modeling method based on product structure

The basic requirement of vulnerability modeling is to describe geometry characteristics, physical characteristics, kill modes, etc., of the whole aircraft and its components by a series of models or data. These information is stored and managed by a computer, and is used to vulnerability computation.

2.1. Basic modeling steps

Modeling based on patch is a widely used vulnerability modeling method. With this method, the configuration and component models of aircraft are constructed by finite element software, such as MSC.PATRAN, and the data files used to describe the aircraft's configuration and components are constituted by mesh plotting.[12] With increasing complexity of modern combat aircraft, modeling based on patch cannot meet the vulnerability modeling requirements in the aspects of time and precision. Now the design of modern advanced combat aircraft generally adopts large CAD/CAE/CAM software, and CATIA is widely used in major aircraft design institutes of China as an advanced design and analysis platform. One key use of CATIA in aircraft design and analysis is carrying out product modeling, assembly, management, and state control based on aircraft product structure. All the components of the aircraft, including configuration components, structure components, system components, etc., are constructed as three-dimensional digital models and stored in computer database. The congregation of all the three-dimensional digital models is namely the aircraft digital prototyping. Therefore, modeling based on the aircraft product structure is actually a process of constituting the whole aircraft digital prototyping by fully making use of the component digital models and the management capability of product structure tree on aircraft products, systems, and whole aircraft as per the specific requirements of vulnerability analysis. The basic steps are shown in Fig. 1.

2.2. Aircraft product structure

The precondition of modeling based on product structure is the construction and management of the aircraft product structure tree. Aircraft product structure tree is a hierarchy system which takes the product (aircraft configuration, aircraft structure, aircraft system, etc.) as an operating object, and disassembles the product level-by-level according to certain taxonomies and in terms of corresponding disciplines, characteristics and structural subjecting relationships.[18,19] One product can consist of some sub-products with different hierarchies, and every product has one and only product number, which is used to identity and manage the product. The fractionizing degree of the bottom product depends upon the expecting analysis precision, for example, a flight control actuator can be disassembled as actuator cylinder, actuator pole, actuator control, and hydraulic tubes. Each part of the four is constructed as an independent sub-product. Whether the whole actuator would be killed when one sub-product is killed depends upon the kill logic of the sub-products vs the actuator. The actuator can also be constructed as one product, and then the actuator

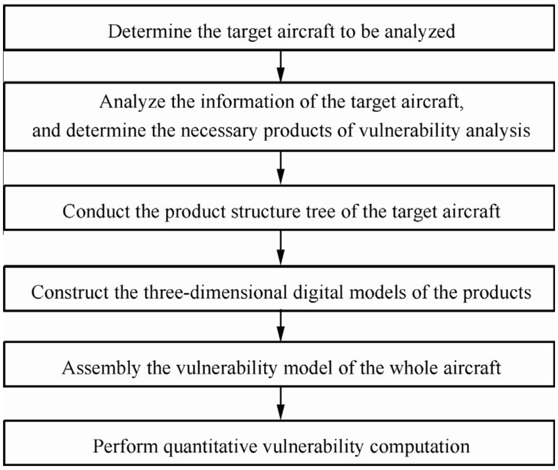


Fig. 1 Vulnerability modeling steps based on product structure.

would be killed if any part is killed. Generally, the parts of the bottom product should have the same kill level and kill mode.

One aircraft product structure tree constituted by the method in this paper is shown in Table 1. The first hierarchy of the tree consists of three parts, i.e., aircraft configuration, aircraft structure, and aircraft system, and every part of the three consists of some sub-products. Limited by paper length, only two hierarchies are given here.

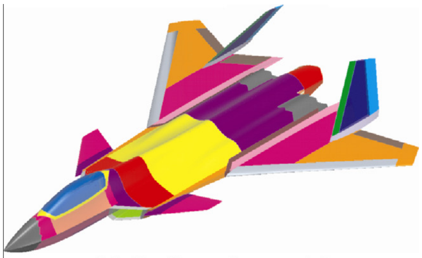
2.3. Aircraft product modeling

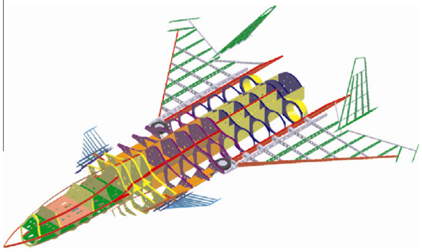
After the aircraft product structure tree is constituted completely, corresponding product models can be constructed. The product models are constructed from low hierarchy to high hierarchy, and every bottom product is constructed as a component. The modeling operations are carried out in CATIA software environment directly. Using CATIA, diverse complex configuration surfaces can be constructed in the Shape Module, and all kinds of complex part entity can be created in the Mechanical Design Module. After all the product models are constructed, they can be assembled in the Assembly Design Module according to the aircraft product structure tree.[20] By farther precise adjusting and orientating, the final integrated aircraft vulnerability model can be constituted. Actually, at the aircraft's detailed design phase, all the product models are constructed by relational system specialties and stored in the computer database. Therefore, vulnerability researchers only need to download the required product models and assemble them, which decreases a mass of intermediate modeling processes. As a product structure model exists in CATIA environment as assembling mode, researchers can change the product dispositions conveniently without any modification of other parameters, which means that researchers do not need to reconstruct the model when they need to assess the vulnerability characteristic of different dispositions.

Table 1 One aircraft product structure tree with two hierarchies.

Product code	Product name
0	Configuration
0_01	Config-fore fuselage
0_02	Config-middle fuselage
0_03	Config-rear fuselage
0_04	Config-left canard wing
0_05	Config-right canard wing
0_06	Config-left wing
0_07	Config-right wing
0_08	Config-left V tail
0_09	Config-right V tail
1	Structure
1_01	Strut-fore fuselage
1_02	Strut-middle fuselage
1_03	Strut-rear fuselage
1_04	Strut-left canard wing
1_05	Strut-right canard wing
1_06	Strut-left wing
1_07	Strut-right wing
1_08	Strut-left V tail
1_09	Strut-right V tail
1_10	Strut-front gear
1_11	Strut-left main gear
1_12	Strut-right main gear
2	System
2_01	System-engine
2_02	System-auxiliary power
2_03	System-flight control
2_04	System-avionics
2_05	System-weapon
2_06	System-fuel
2_07	System-hydraulic
2_08	System-electromechanical
2_09	System-power supply
2_10	System-environment control
2_11	System-safety
2_12	System-cockpit
2_13	System-wiring harness

According to public literatures and based on typical configuration characteristics, basic structure layouts, and typical system compositions of modern advanced combat aircraft, a hypothetical aircraft is proposed, and its vulnerability model constituted by the method in this paper is shown in Fig. 2. The model consists of 328 bottom product components, which includes 68 configuration components of 9 configuration segments, 106 structure components of 12 structure segments, and 154 system components of 13 aircraft systems.


(a) Configuration model


(b) Structure model

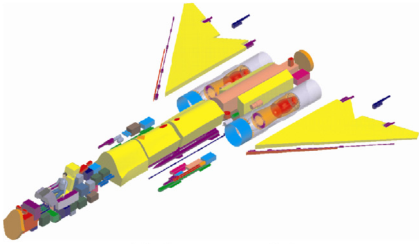

(c) System model

Fig. 2 Vulnerability model of one hypothetical aircraft based on product structure.

3. Quantitative vulnerability computation based on aircraft's product structure model

With CATIA software, on one hand, the aircraft's product structure model can be constructed conveniently, and on the other hand, the methods and operations of quantitative vulnerability computation can be integrated into CATIA environment as window toolbar via CAA second development. The basic process of quantitative vulnerability computation based on aircraft's product structure model is shown in Fig. 3.

3.1. Component attribute setting

The component (viz. the bottom product) attributes of aircraft product include component material, kill level, kill mode, and revision coefficient of six directions' kill probability. The setting is carried out in the setting window generated by CAA secondary development. If a user selects one product in CATIA, the setting window will auto search the serial number and name of the product itself and its lower hierarchies' products, and then the user can set the component attributes of these products one by one.

The materials included in the method of this paper in total are 17 kinds, i.e., aluminum alloy, titanium alloy, steel, composite materials, hydraulic oil, fuel, water, user defined material, etc. For some special materials (such as materials of cockpit canopy and radome), the user can simulate their characteristics by setting their ballistic limit constants via user defined material. The ballistic limit constants can be obtained by simulation, test, or qualitative assessment.

The kill categories include attrition kill, mission abort kill, and user-defined kill. Four attrition kill levels are defined as *KK*, *K*, *A*, and *B* level. Mission abort kill level is defined as *C* level. User-defined kill level is mainly used for some special non-attrition kills, such as configuration damage, structure damage, and so on. The kill modes include penetration, combustion, and explosion. Every kill mode has corresponding kill criterion formulas.[21] Although these formulas are obtained by tests, they are universal to some extent. In order to satisfy characteristics of different aircraft and product components, the user can revise the kill probability coefficient of six basic directions (front, back, left, right, up, and down).

One simple revising method of component kill probability coefficient is: supposed the projection area of one component in one attack direction is S_{p}, and the critical area of this component is S_{cri}, then the revising coefficient can be expressed as

$$p = S_{\mathrm{cri}}/S_{\mathrm{p}} \tag{1}$$

3.2. Shot-line generation

Compared with the size of aircraft and its components, the size of projectile or fragment is relatively smaller, so the motion of every projectile or fragment can be described as a shot-line. In this paper, an approach called "three-dimensional shot-line scanning approach" (3DSSA) is applied to obtain the pre-process data of shot-lines.

Fig. 4 is a schematic representation of the 3DSSA. The basic processes of this approach are: in CATIA environment, take the three-dimensional size of the product structure model as limitation, take the defined size of the shot-line grid cell as spacing, and generate parallel lines one by one according to the attack direction. For each line, carry out intersecting computations with the aircraft's surfaces and inner components, and then the hitting parameters, i.e., the serial numbers, names, materials, thickness, and dimensional positions of those intersected components, are obtained. Form these parameters as shot-line description data files to provide necessary input for next vulnerability computation.

A shot-line grid of the hypothetical aircraft in (45°, 45°) attack direction generated by 3DSSA is shown in Fig. 5. The grid cell size is 100 mm × 100 mm, and there are 9664 shot-lines intersecting with the aircraft in total.

3.3. Kill tree construction

After setting the aircraft's component attributes, the kill tree of every kill level can be constructed by logical AND gate, OR gate, and VOTE gate which are used in reliability analysis. The kill tree can exactly describe the logical relationships between the component kill and the aircraft kill. In order to be stored and computed easily by a computer, the kill tree should be conversed into min-cutset aggregations by min-cutset solving arithmetics.[15] Min-cutset aggregation is a basic event aggregation which means: if all the basic events occur, the top event would occur. A simple kill tree is shown in Fig. 6.

In the kill tree construction process based on the product structure model, the product codes and names can be filtered and listed level by level according to their system. When the detailed kill logic is determined, the products can be chosen and combined as an expanding kill tree, as shown in Fig. 6. In this kill tree, all the products and logic gates can be added, deleted, and modified by clicking directly. After the whole kill tree is constructed, the min-cutset aggregation can be solved by the program via specific min-cutset solving arithmetics, and stored in the kill tree database.

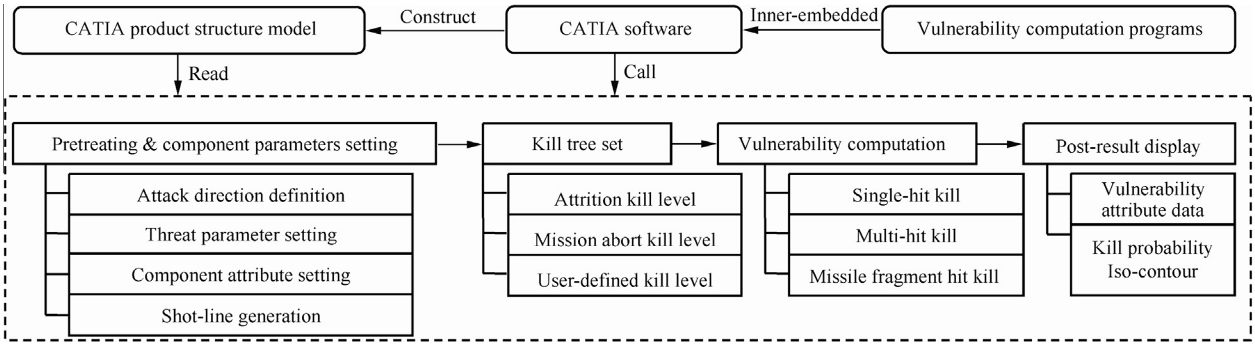


Fig. 3 Basic processes of vulnerability computation based on aircraft's product structure model.

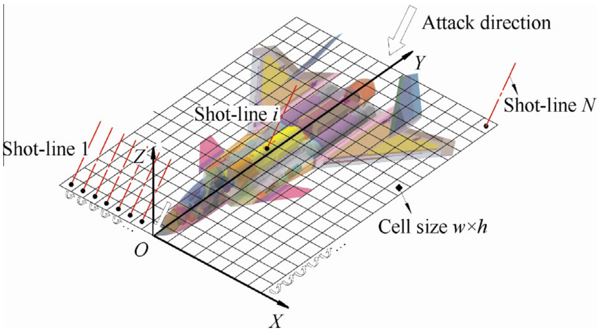


Fig. 4 A schematic representation of 3DSSA.

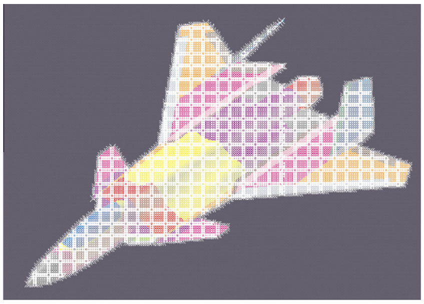


Fig. 5 Shot-lines of one hypothetical aircraft in (45°, 45°) attack direction.

3.4. Vulnerability computation theory

On foundation of shot-line's pretreating data and combined with the min-cutset aggregations, the aircraft's vulnerability attributes such as kill probability, vulnerable area, presented area, etc., can be computed. The basic computing steps are listed as follows:

(1) Take the pretreating data of shot-lines as input, compute the threat's motion state inside the aircraft, and then the intersecting parameters, i.e., hitting velocity, hitting angle, threat weight, threat size, etc., can be presented.
(2) Compute the kill probability of each component under each shot-line according to the kill criteria formulas, and then compute the vulnerable area and the kill probability of each shot-line according to the detailed kill models.
(3) To compile statistics of all the shot-lines' vulnerable areas and kill probabilities, obtain each component's and the whole aircraft's vulnerable areas and kill probabilities.

3.4.1. State-of-motion of threat

Fig. 7 is a schematic representation of the state-of-motion of threat inside the aircraft. In this figure, there are three lethal components in the attack direction (shot-line). $p_{\mathrm{k/h}i}$ is the kill probability of component i at the given shot-line hit. After the threat penetrates the aircraft's outer skin, the components in the attack direction could be hit by the threat whose velocity (V) and weight (W) have undergone losses. If the residual velocity of the threat after penetrating the aircraft's outer skin is higher than the ballistic limit velocity V_{50} of the component, the threat could penetrate the component, and its velocity and weight would undergo losses again. The other components in the ballistic trajectory could be hit similarly. At last, the threat leaves the aircraft, or stops moving inside the aircraft, or is left in the component inside.

In this paper, the ballistic trajectory and state-of-motion after the threat hitting the metal plate are computed by the JTCG/ME equations, and the detailed computing process is described in Refs.[22,23]. The ballistic trajectory and state-of-motion after the threat hitting the composite material plate are computed by a physical method, and the detailed computing process is described in Ref.[24]. The limit ballistic velocity of the composite material plate is

$$V_{50} = (1+\lambda)\left\{\frac{2\sigma_{\mathrm{s}}}{K_{\Psi}\rho}\left[\exp\left(\frac{K_{\Psi}\rho S_{\max}h}{m_{\mathrm{f}}}\right)-1\right]\right\}^{1/2} \tag{2}$$

where V_{50} is the ballistic limit velocity, m/s; σ_{s} the shear strength limit of punching type, Pa; K_{Ψ} the inertial resistance coefficient of the threat; ρ the material density, kg/m^3; $S_{\max}$ the max cross section area of the threat, m^2; h the thickness of the plate, m; m_{f} the mass of the fragment, kg; λ a correction coefficient with a value of 0.05–0.25.

3.4.2. Kill criteria of component

After the state-of-motions of the threat are obtained, the kill probability of the component can be computed according to the specific parameters. For metal material, the statistical formula of kill probability is obtained based on duralumin material, thus the thickness of a component with different materials should be equivalent to its thickness with duralumin material. The equivalent formula[25] is

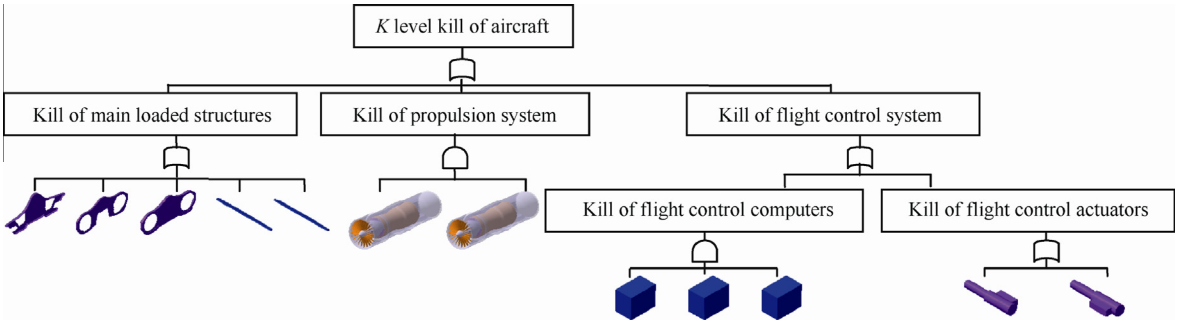


Fig. 6 A schematic representation of K level kill tree.

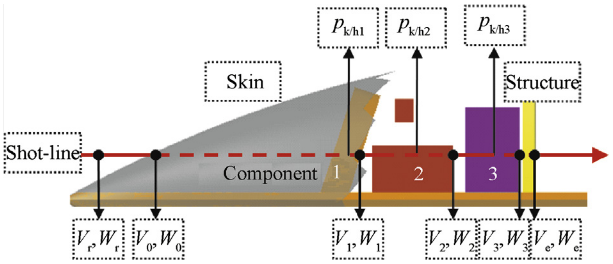


Fig. 7 A schematic representation of the state-of-motion of threat inside the aircraft.

$$\delta_{st} = \delta_x \left(\frac{\sigma_x \rho_x}{\sigma_{st} \rho_{st}} \right)^{2/3} \tag{3}$$

where δ_{st} is the equivalent thickness of the material, cm; δ_x the real thickness of the material, cm; σ_x the tensile strength limit of the material, MPa; ρ_x the density of the material, kg/m^3; σ_{st} the tensile strength limit of duralumin material; ρ_{st} the density of duralumin material.

Three kill criteria are mainly considered for the kill modes of components. They are penetration, combustion, and explosion. The kill probability formulas are listed as follows.[21]

(1) Kill criteria of penetration

Penetration kill is mainly aimed at the aircraft structure and equipment. Supposed $p_{k/hij}$ is kill probability of component i at given hit j, for metal material, the penetration probability is

$$p_{k/hij} = \begin{cases} 0 & E_s \le 4.5 \\ 1 + 2.65\exp(-0.34E_s) - 2.96\exp(-0.14E_s) & E_s > 4.5 \end{cases} \tag{4}$$

where E_s is specific kinetic energy received by unit component thickness, (kg·m/cm^2)/mm.

$$E_S = \frac{m_f v_f^2}{2S_{mw}h_{eq}} \tag{5}$$

where v_f is the hitting velocity, m/s; S_{mw} the mean windward area of the threat, cm^2; h_{eq} is the equivalent thickness of the component, cm.

For composite material, the kill probability can be computed by

$$p_{k/hij} = \frac{1}{1 + \exp\left\{ -\left[\frac{\alpha}{2\eta V_{50}} \left(v_h - \frac{(1+\eta)V_{50} + (1-\eta)V_{50}}{2} \right) \right] \right\}} \tag{6}$$

where α is the curve fitting coefficient; η the adjusting coefficient of penetration velocity with a value of 0.2–0.5, $(1+\eta)$. V_{50} the velocity with complete penetration, and $(1-\eta)V_{50}$ the velocity without penetration.

(2) Kill criteria of combustion

Combustion kill is mainly aimed at the aircraft fuel tanks. The combustion effect depends on the specific impulse of the threat, the explosion altitude, and the fuel tank structure. The specific impulse of the threat is

$$I = m_f v_f / A_p \tag{7}$$

where A_p is the effective presented area of the threat, and the unit of I is kg·m/(cm^2·s).

With respect to single threat that fires fuel in a fuel tank at ground, the experiential formula of combustion probability is

$$p_{com} = \begin{cases} 0 & I \le 1.57 \\ 1 + 1.083e^{-0.43I} - 1.96e^{-0.15I} & I > 1.57 \end{cases} \tag{8}$$

As the air temperature and air pressure fall down with increasing altitude, the fuel temperature falls down synchronously. Moreover, the oxygen content is low at high altitude, so the combustion probability decreases while the explosion altitude increases. If the explosion altitude is higher than 16 km, the fuel would not fire when the threat hits the fuel tank. The combustion probability at high altitude is

$$p_{k/hij} = p_{com}\left[1 - \left(\frac{H}{16} \right)^2 \right] \tag{9}$$

where H is the explosion altitude of the threat, km.

(3) Kill criteria of explosion

Explosion kill is mainly aimed at aircraft weapons and ammos. When the threat impacts the ammos, blast may be generated in the detonator cylinder. When the blast spreads in the detonator, the pressure, density, and temperature at the wavefront increase rapidly, which generates asymmetrical stress inside the detonator, and stress peaks may appear at some points, which would heat local area and result "hotspots". If the temperatures of these "hotspots" are higher than the decomposing temperature of the detonator, the detonator may explode. The more "hotspots" are generated inside the detonator at unit time, the higher explosion probability is.

The experiential formula of explosion probability summarized by experiments, viz., p_{ex}, is

$$p_{ex} = \begin{cases} 0 & U_j < 0 \\ 1 - 3.03\exp(-5.6U_j)\sin(0.34 + 1.84U_j) & U_j > 0 \end{cases} \tag{10}$$

$$U_j = \frac{10^{-8}A_1 - a_1 - 0.065}{1 + 3a_1^{2.31}} \tag{11}$$

$$A_1 = 5 \times 10^{-3} \rho_d m_f^{2/3} v_f^3 \tag{12}$$

$$a_1 = 5 \times 10^{-2} \rho_s b_s / m_f^{1/3} \tag{13}$$

where ρ_d is the density of the detonator, kg/m^3; ρ_s the shell density of the ammo, kg/m^3; b_s the shell thickness of the ammo, cm.

3.4.3. Vulnerability attributes

(1) Single-hit vulnerability attributes

The presented area of component i can be expressed as

$$A_{Pi} = \sum_{j=1}^{M} (w \times h) \tag{14}$$

where M is the number of the grid cells hit by shot-lines at the component surface.

The presented area of the whole aircraft can be expressed as

$$A_P = \sum_{j=1}^{L} (w \times h) \tag{15}$$

where L is the number of the shot-line grid cells on the aircraft.

The vulnerable area of component can be expressed as

$$A_{Vi} = \sum_{j=1}^{M} (p_{k/hij} \times w \times h) \tag{16}$$

Assume $P_{k/Hi}$ is the kill probability of component i:

$$P_{k/Hi} = \frac{A_{Vi}}{A_P} \tag{17}$$

After the kill probability of every critical component is obtained, the aircraft kill probability, $P_{K/H}$, and the aircraft vulnerable area, A_V, can be obtained according to detailed kill tree.

(2) Multi-hit vulnerability attributes

The traditional solving methods of multiple-hit kill probability are the "kill tree diagram method" and "Markov chain method". These two methods are both based on aircraft's independent existing states, however, when the amount of redundant components increases, the computation of multi-hit could have "combination explosion" problem. At this time, the computing time would become very long. However, modern combat aircraft adopt a great deal of redundant components, therefore, to solve the "combination explosion" problem in computation, a method called "random multi-hit spots based on Monte-Carlo simulation" is adopted in this paper. The basic steps of this method are:

(1) Generate the aircraft's single-hit shot-lines firstly and obtain the kill probabilities of these shot-lines by a single-hit computation method.
(2) By Monte-Carlo simulation, generate n shot-lines randomly on the aircraft in each simulation round to simulate n times hits, as shown in Fig. 8.
(3) By using the results of single hit and the kill tree, compute the multi-hit result of each simulation round.
(4) By great amount of simulation (the simulation rounds are not less than 1000), the mean kill probability of multi hits can be obtained.

3.5. Vulnerability result presentation

The computing results of vulnerability have two types, one is data result presented as data files, which can provide presented area, vulnerable area, kill probability of each component and the accumulative presented and vulnerable areas, kill probability of the whole aircraft; and the other is kill probability Iso-contour presented as figures, which can intuitively show the vulnerable area and single-hit kill probability distribution of the aircraft with respect to one attack direction, and can index the serial numbers and names of the components which are hit by threat at any attack position. The drawing steps of kill probability Iso-contour are described as follows:

(1) Divide the kill probability between [0, 1] into 10 equal sections, and endow each section with one index color.
(2) Take the plane vertical to the attack direction as the drawing plane.
(3) Begin from the first shot-line, and if the shot-line hits the vulnerable area of the aircraft, the shot-line grid cell is filled with the index color defined in Step (1) according to the cell's kill probability, or if the shot-line hits the non-vulnerable area of the aircraft, the shot-line grid cell is filled with the index color of 0 kill probability.
(4) Fill the shot-line grid cells with an index color one by one until all the shot-line grid cells are filled.

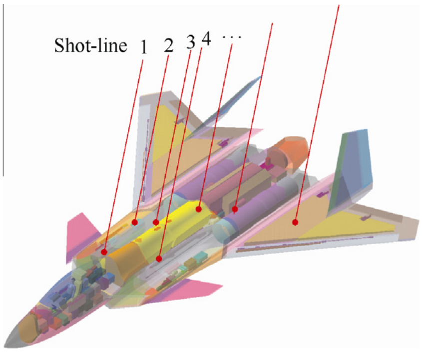


Fig. 8 A schematic representation of random multi-hit spots.

4. Case study

Based on the aircraft vulnerability model constructed above, the effects of redundancy technology to aircraft vulnerability are assessed.

The aircraft system components include 12 groups of dual redundant components, five groups of triple redundant components, six groups of four redundant components, and lethal redundant components of B kill level are 18 groups. Now reduce the redundancies of B kill level redundant components and assess the aircraft vulnerability before and after redundancy reduction. The redundancy states before and after redundancy reduction are shown in Table 2.

Assume the threat parameters are: 23 mm armor piercing incendiary (API), the projectile length is 99.3 mm, the projectile mass is 194.4 g, the hitting altitude is 3000 m, and the hitting velocity is 1800 m/s. The attack directions are (45°, 45°) and (45°, −45°), and the hitting times are 1, 3, and 5. When the hitting times are 3 and 5, the Monte-Carlo simulation

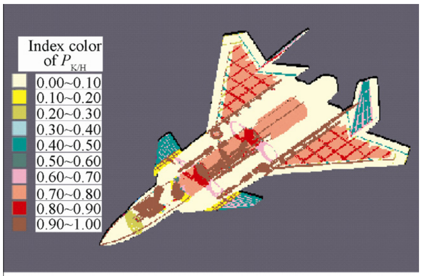
Table 2 The initial and reduced redundancy states.

Component name	Initial redundancy	Reduced redundancy
Oxygen bottle	Four	Dual
Hydraulic gas bottle	Four	Dual
Electric-load management unit	Four	Single
DC/AC current convertor	Four	Dual
Power distribution box	Triple	Dual
Flight control computer	Triple	Two
Actuator control box	Triple	Single
Electromechanical management computer	Triple	Single
Engine	Dual	Dual
Aircraft accessory drive gear	Dual	Dual
Hydraulic pump	Dual	Single
Hydraulic oil tank	Dual	Single
Dynamotor	Dual	Dual
Battery	Dual	Single
Flight power control box	Dual	Single
Gas/fluid radiator	Dual	Single
Navigation module	Dual	Single

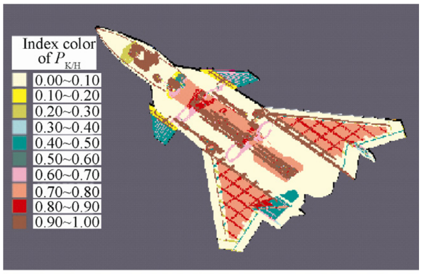
rounds are both 10000. The single-hit kill probability Iso-contours of initial redundancy are shown in Fig. 9, and the single-hit kill probability Iso-contours of reduced redundant are shown in Fig. 10.

By comparing Fig. 9 with Fig. 10, it can be seen that the vulnerable area after redundancy reduction increases, especially the region of fore fuselage where the products dispose densely.

The aircraft vulnerability data before and after redundancy reduction are shown in Table 3.

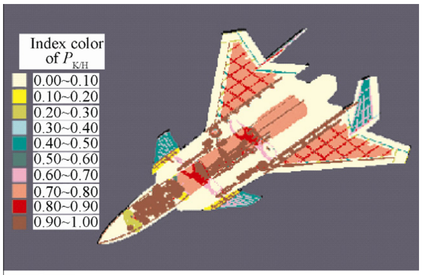


(a) Attack direction (45°, 45°)

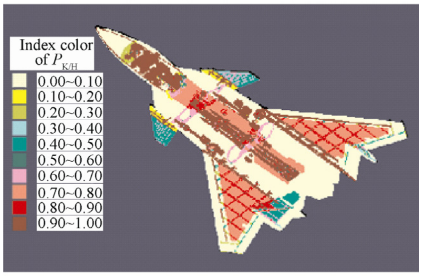


(b) Attack direction (45°, −45°)

Fig. 9 Kill probability Iso-contours of initial redundant.



(a) Attack direction (45°, 45°)



(b) Attack direction (45°, −45°)

Fig. 10 Kill probability Iso-contours of reduced redundant.

Table 3 Aircraft vulnerability data before and after redundancy reduction.

Redundant state	Hitting times	Vulnerable area (m^2)		Kill probability	
		(45°, 45°)	(45°, −45°)	(45°, 45°)	(45°, −45°)
Initial redundant	1	22.74	22.94	0.2350	0.2425
	3	52.46	53.83	0.5421	0.5563
	5	92.43	95.22	0.9552	0.9840
Reduced redundant	1	38.16	36.58	0.3945	0.3868
	3	75.34	74.45	0.7786	0.7694
	5	91.78	95.64	0.9485	0.9883

It can be seen that redundancy increasing can improve the aircraft vulnerability notably. At single-hit case, the kill probability is reduced approximately 15% compared to the reduced redundancy state; at 3-hit case, the kill probability is reduced more than 20% compared to the reduced redundancy state, and the improving effect is the most notable. When the hitting number increases to 5 times, the kill of the aircraft is remarkable and the redundancy technology cannot improve the aircraft vulnerability effectively.

5. Conclusions

(1) The vulnerability modeling method based on product structure and CATIA, which constructs the aircraft configuration components, structure components, and system components directly by CATIA software, and manages products/components of different hierarchies by product structure, reduces vulnerability modeling complexity and improves modeling effectiveness together with model accuracy. Furthermore, the method can sufficiently use the digital model database of modern aircraft designs, which can meet the vulnerability analysis requirements of modern combat aircraft with large complicated systems effectively.

(2) By using the component operating and managing functions of CATIA, the vulnerability model based on product structure can carry component attribute setting, shot-line generation, kill tree construction, etc., conveniently, which enables researchers to easily obtain the aircraft vulnerability attributes with respect to different component materials, kill modes, and kill logics. That can provide useful guidance for the selection/improvement of component materials and damage suppression measures. Besides, the assembling characteristics of the product structure model allow researchers to adjust the component dispositions conveniently when they analysis the vulnerability characteristics with different component dispositions. Moreover, the vulnerability analysis environment based on CATIA makes the operating and analyzing processes have good visualization.

(3) The quantitative vulnerability computation based on product structure and CATIA makes sufficient use of the existing mature computation methods, takes diverse component materials, e.g., aluminum, titanium, composite materials, some kinds of fluid, etc., into consideration, and contains three kill modes, i.e., penetration,

combustion, and explosion. The vulnerability attributes with respect to non-explosive impactor's single-hit, multi-hit, and missile fragments hit can be given and excellent visual kill probability Iso-contours can be presented, which provide good references for precise vulnerability analysis of modern aircraft.

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