AN INTEGRATED AND GENERIC VULNERABILITY ASSESSMENT SYSTEM FOR AIRCRAFT NONNUCLEAR SURVIVABILITY DESIGN

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Abstract

Vulnerability assessment is an important part in combat aircraft survivability design. This paper outlines the latest techniques and methods for assessing the aircraft vulnerability and introduces an integrated and generic Target Vulnerability Assessment System (TVAS 1.0) for aircraft nonnuclear survivability design. TVAS is characterized by: (1) The input aircraft or component geometric model is approximated by finite quadrangular patches, which has the good interface with the current FEA software; (2) Besides the underlying vulnerability computation capability, graphical display of the interaction of aircraft with threats is provided to help develop intuition for users; and (3) For a given single nonexplosive penetrator hit, the aircraft and component vulnerable areas, presented areas, and equivalent singly vulnerable areas are calculated, and threat ricochet is considered. For multiple hit vulnerability calculation, component overlapping and redundancy are taken into account. Moreover, exact kill probability calculation under the spray trajectories of fragments detonated from a missile at a given position, and blast envelopes for aircraft are provided. Application shows that: a) TVAS could give more realistic vulnerability computation; b) the system is useful for forming advice on the aircraft survivability enhancement or vulnerability reduction design; and c) it can apply to the vulnerability assessment of other vehicles such as missile, satellite, armor car, et.al..

1 Introduction

Aircraft combat survivability (ACS) is defined here as the capability of an aircraft to avoid or withstand a man-made hostile environment [1]. Survivability is composed of two focus areas: susceptibility and vulnerability. The probability of kill of the aircraft P_K (the aircraft killability) is the product of the probability of hit (the aircraft susceptibility) P_H and the conditional probability of kill given a hit (the aircraft vulnerability) $P_{K/H}$. Thus [1],

$$P_K=P_HP_{K/H} \qquad (1)$$

The probability of aircraft will survive the manmade hostile environment P_S is

$$P_S=1-P_K \qquad (2)$$

Aircraft vulnerability assessment is an essential part in combat survivability design. The current typical vulnerability assessment programs include BRL_CAD, FASTGEN, COVART, et.al [1-3]. The BRL-CAD and FASTGEN programs are preprocessing programs that are used to develop shotline or line-of-sight (LOS) descriptions, i.e., the list of components and fluid and air spaces that are intersected by each of the shotlines, for use as input to COVART. COVART is used to determine component and aircraft vulnerable areas and presented areas for the selected attack directions, and its limitations is that ricochet is not modeled.

In this paper, the latest techniques and methods for assessing the aircraft vulnerability are outlined, and an integrated and generic Target Vulnerability Assessment System (TVAS 1.0) for aircraft nonnuclear survivability

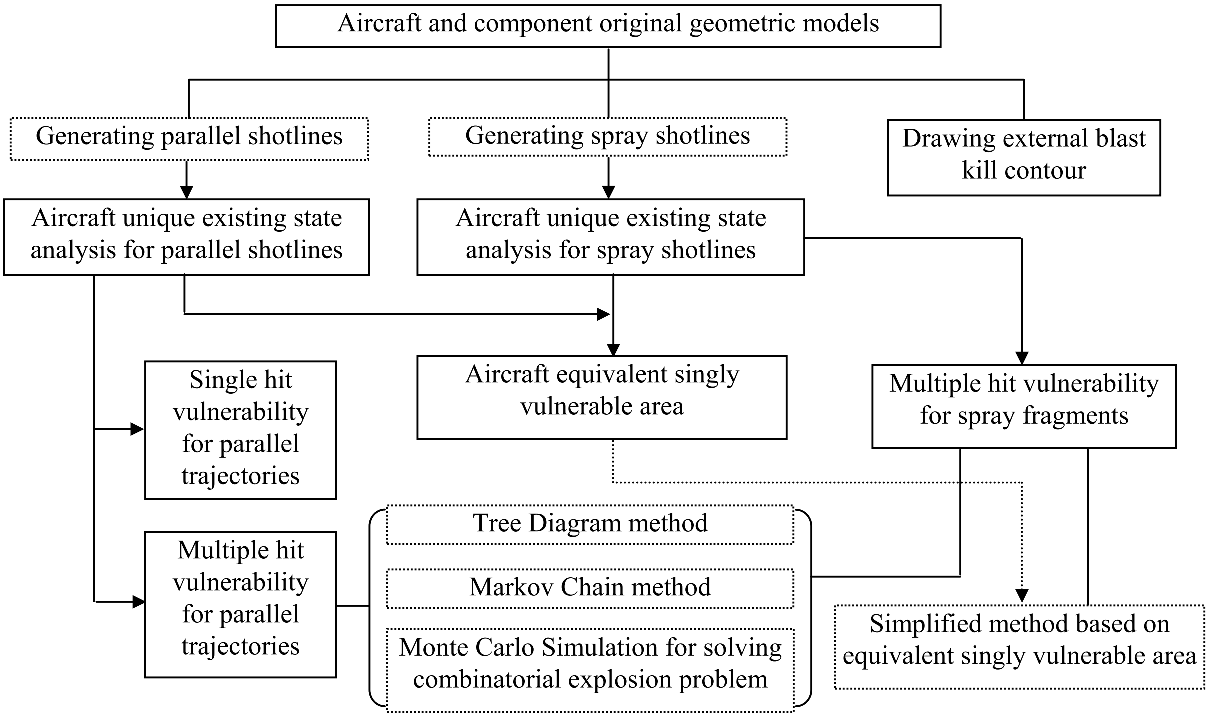

Fig.1 Flowchart for aircraft nonnuclear vulnerability calculation

design is developed. The main differences between TVAS and COVART are: TVAS has a inherent LOS data preprocessing sub-program, and rather than providing the complex shotline data as FASTGEN does, the sub-program only provides the necessary data, i.e., the unique existing states and the corresponding areas of aircraft subjected to a random hit for the attack direction considered, for vulnerability calculation. Moreover, TVAS provides the computations of aircraft equivalent singly vulnerable area, exact multiple hit vulnerability of aircraft considering component overlapping, component redundancy, and threat ricochet.

In the following, the basic assumptions and vulnerability calculation methodologies are introduced first. Then basic modules contained in TVAS are presented. Following is a hypothetical example to demonstrate the utility of the developed system. Conclusions and future work recommendations are given in the final section of this paper.

2 Assumptions and Methodologies

The main nonnuclear threats to aircraft considered in TVAS include nonexplosive penetrators (parallel trajectories), spray fragments from missile (spray trajectories), and blast wave. Fig.1 presents the vulnerability assessment methods concerning the above threats. The following introduces the assumptions and vulnerability calculation methods relative to this figure.

2.1 Assumptions

(1) Component when hit has only two states, namely kill or nokill;
(2) No commutative compound damage occurs; and
(3) Secondary threats, i.e., the shattered penetrator or spall ejected from the back face of the impacted plate, are not considered.

2.2 General Methodologies

2.2.1 Determination of aircraft unique existing states

According to assumptions (1), since each component when hit has two existing states, the aircraft existing states when hit could be determined according to Kill Tree [1, 3] and the

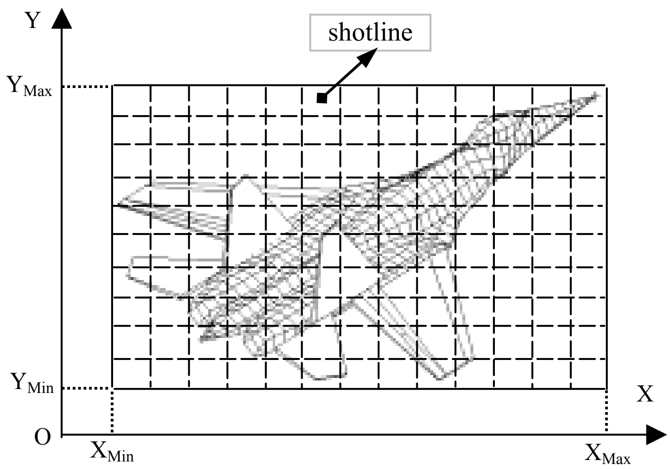

Fig.2 Shotlines for parallel trajectories

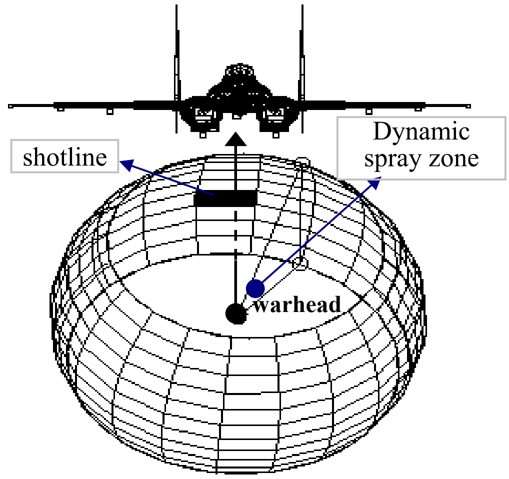

Fig.3 Shotlines for spray trajectories

states of each component. The purpose of aircraft unique existing state analysis is to determine the categories of unique existing states and the corresponding areas (or the corresponding existing probabilities). It can be performed by the following steps:

(1) Generate shotlines in planar grid for parallel trajectories (Fig.2) or in curved face grid for spray trajectories (Fig.3).

(2) Trace the path of each shotline through the aircraft and determine the velocity and mass of threat by empirical equitation (i.e. JTCG/ME [4], in which ricochet is considered), component thickness and shotline obliquity, and the vulnerable area corresponding to each component cell.

(3) Using the 'vulnerable are decomposition method in the overlapping region of components' [5], analyze the aircraft existing states and the corresponding areas at the hit of each shotline.

(4) Summarizing the aircraft existing states and the corresponding areas corresponding to each shotline, the aircraft could exist in the three kinds of states: aircraft kill state, no-component-kill state, and redundant states. Aircraft kill state refers to the component or combinatorial states among components that could lead to the kill of aircraft. No-component-kill state refers to the state that no critical component is killed. Redundant states refer to the states that are except aircraft kill state and no-component-kill states. It should be mentioned that the number of aircraft kill state and no-component-kill state is one. However, the number of redundant states could be more than one.

2.2.2 Single penetrator hit vulnerability

The vulnerability of the aircraft for a particular threat aspect is usually expressed as the probability the aircraft is killed given a uniformly distributed hit anywhere on the presented area of the aircraft $P_{K/H}$, or as the single hit vulnerable area of the aircraft A_V. $P_{K/H}$ is related to A_V by [1, 3]

$$P_{K/H} = A_V / A_P \tag{3}$$

where A_P denotes the projected area of aircraft in the plane normal to the approach direction of threat. From the analysis of aircraft unique existing states, one can know the area corresponding to aircraft kill state determined by subsection 2.2.1 is the single hit vulnerable area.

2.2.3 Determination of aircraft equivalent singly vulnerable area

The single hit vulnerable area is not a reliable criterion as to the vulnerability of the aircraft [2], since it cannot completely include the contribution of the multiply vulnerable components (i.e., redundant components) to the aircraft vulnerability. It is for this reason that an 'equivalent' singly vulnerable area A_{VE} concept has been devised in reference [2] for considering the effect of multiply vulnerable components on the vulnerability of an aircraft. A_{VE} is expressed as [2]

$$A_{VE}=A_{V0}/E(Z) \quad (4)$$

where $E(Z)$ is the expected number of hits on vulnerable area required to kill an aircraft, and A_{V0} is the sum of vulnerable areas of components. References [2, 6] give the formulas for calculating $E(Z)$ of aircraft consisting of one or more singly vulnerable components and a set of identical multiply vulnerable components. Two general methods, Monte Carlo simulation based method (MCS) and aircraft multiple hit vulnerability based method (AMHV), for calculating aircraft equivalent singly vulnerable area for the case in which (*a*) the multiply vulnerable components of each set do not have the same vulnerable area, and (*b*) aircraft vulnerable components can overlap in any arbitrary manor, could be found in reference [7].

2.2.4 Multiple hit vulnerability for parallel trajectories

Two exact calculation methods, namely Markov Chain or Tree Diagram, are commonly used to analyze the aircraft multiple hit vulnerability. Reference [5], based on 'vulnerable area decomposition method in the overlapping region of components' extends the two methods so that they can deal with the case where the components can overlap in an arbitrary manner.

Since the dimension of Markov transition matrix or the number of tree branches increases exponentially along with the increasing number of redundant components, when the total number of redundant components reaches a certain amount, the 'combinatorial explosion' is unavoidable. The exact calculation methods, namely Markov Chain and Tree Diagram, only apply to the case where the number of redundant components is small. To solve the 'combinatorial explosion' problem, Monte Carlo technique could be used, by comparing all the existing states of aircraft to 'Model of Filling Boxes with Balls' [6] and by randomly and uniformly sampling the threat hit locations, to calculate the aircraft cumulated probability of kill [8].

2.2.5 Multiple hit vulnerability for spray trajectories

The vulnerability of aircraft to externally detonating warhead is usually analyzed in two separate tasks [1,3]. The first task is a determination of the aircraft's vulnerability to the blast, and the second examines the aircraft's vulnerability to the fragments and penetrators. The aircraft probability of kill $P_{K/D}$ by fragments could be calculated by Markov Chain, Tree Diagram, or Monte Carlo method mentioned in subsection 2.2.4. It should be noted that the fragments travel along spray trajectories rather than parallel trajectories, hence, Fig.3 should be used to generate shotlines.

Poisson approach (simplified method) for calculating the vulnerability of nonredundant aircraft at missile fragments is expressed as [1-3]

$$P_{K/D} = 1 - \exp(-\rho \cdot A_V) \quad (5)$$

where ρ is the fragment density in the spray. By substituting A_{VE} for A_V the approach can calculate the $P_{K/D}$ for an aircraft that may have multiply vulnerable components [2].

2.2.6 Blast kill contour

Aircraft vulnerability to external blast is usually expressed as an envelope about the aircraft where the detonation of a specified charge weight of spherical uncased pentolite high explosive will result in a specified level of damage or kill to an aircraft. Detonation outside of such an envelope will result in little or no damage to the aircraft or in a lesser kill level [1]. Visualization of the envelope is achieved by constructing isocharge weight contours about the aircraft for a given kill level and altitude in all planes of interest [2]. Reference [9] recommends the following four typical planes. Three of the planes are mutually orthogonal. These planes are usually designed as A, B, C, and D. Plane D contains the aircraft main axis and is parallel to the wingspan. Plane C also contains the aircraft main axis and is perpendicular to plane D. Plane A is perpendicular to the aircraft main axis, but intersects some critical components or subsystems in the forward section of the aircraft such as the crew compartment or the wingspan. Plane B is parallel to plane A but intersects some critical components or subsystems in the rear of the aircraft such as the horizontal or vertical stabilizer.

In this paper, for a rough estimate, a square-root law is assumed for the distance D vs the HE weight W [10],to construct the envelope,

$$D = k\sqrt{W} \tag{6}$$

where k is in the range of 0.3 to 0.5 $m/kg^{1/2}$.

3 Introduction of Main Modules in TVAS

The developed Target Vulnerability Assessment System TVAS has five main modules illustrated in the following.

3.1 Data file preparation

Two input files should be prepared for TVAS, aircraft input file and component input file. Part of the geometric data in the two files could be output from the widely used finite element modeling or analysis software, such as MSC/PATRAN or MSC/NASTRAN, et.al.. The information in aircraft data file includes: the coordinates of aircraft centroid, node numbering of each finite quadrangular patch, node coordinates, patch material and thickness, et.el.. The information in component data file includes: number of patch constituting to each component, node numbering of each finite quadrangular patch, node coordinates, patch material and thickness, component criticality (1 for critical component, and 0 for noncritical component), component kill modes, and the contribution of component kill to aircraft kill expressed as the 'minimal cut sets', data for calculating the probability of kill given a hit on component, et.al..

3.2 Graphical display

Graphical display module provides: 1) three views of aircraft or each component, front view, side view and below view; 2) the interaction region of aircraft with fragments of missile; 3) the transformation of geometry, such as translation, rotation, scaling, et.al.; 4) other preferences setting such as color palette, shading, transformation factor, rotation factor, scale factor, and rotation axis, et.al..

3.3 Threat parameter setting

As is mentioned earlier, three kinds of threat are considered in TVAS, nonexplosive penetrator (parallel trajectories), missile with fragments warhead (spray trajectories), and blast wave. The nonexplosive threat parameters include the size, material, relative velocity with aircraft, shape (sphere, cube, diamond, parallelepiped), et.al. Missile parameters include the fragment type, size, material, number of fragment, detonation location, charge material, charge mass ratio to metallic case, static spray angel or charge detonator location, velocity, azimuth and elevation angel relative to aircraft, et.al. As to the blast wave threat, the following factors are considered to draw envelopes: different flight heights of aircraft, different charge masses, different charge types (TNT, RDX, B, HMX, et.al), and typical blast planes.

3.4 Global setting

This module is used to set the size of planar grid or curved face grid for shotline generation, the methods for calculating multiple hit vulnerability (Markov Chain, Tree Diagram, Monte Carlo, Poisson approach, or simplified method based on equivalent singly vulnerable area), the method for calculating equivalent singly vulnerable area (MCS or AMHV), empirical penetration equation selection (THOR or JTCG/ME), et,al..

3.5 Results output

The TVAS outputs the following vulnerability assessment results.

3.1.1 Single hit vulnerability (parallel trajectories)

It may output the component shielding relationship and the single hit probability of kill distribution either numerically or graphically; the aircraft presented area, vulnerable area, equivalent singly vulnerable area, probability of kill given a hit at arbitrary hit aspect or 26 standard aspects; and the component presented area, vulnerable area, probability of kill given a hit at arbitrary hit aspect or 26 standard aspects.

3.1.2 Multiple hit vulnerability (parallel trajectories)

It may output the aircraft cumulated vulnerable area or probability of kill, the vulnerable area or probability of kill based on event, at the threats of multiple hits.

3.1.3 Multiple hit vulnerability (spray trajectories)

It may output the aircraft cumulated vulnerable area or probability of kill at the threats of fragments of a missile.

3.1.4 Blast wave vulnerability

It may output the blast kill contours at the typical blast planes.

4 Example

Using TVAS, the vulnerability of a hypothetical fighter aircraft is assessed, and part of the vulnerability assessment results are listed below.

4.1 Single hit vulnerability

The distribution of probability of kill given a hit on the example aircraft by a 6.5-g and 2000-m/s steel spherical penetrator with elevation 45^o and azimuth 45^o is shown in Fig.4. Fig.5 and Fig.6 show the $P_{K/H}$ and A_{VE} for the aircraft at the 26 standard views (the six major aspects: front, back, left, right, top, and bottom, and all 45 deg angels from the major six [1]). The average vulnerable areas for each of the 55 critical components at the standard 26 threat aspects are shown in Fig.7 and the relative vulnerability of critical components is obvious, which are useful to form advice on the aircraft vulnerability reduction design (component redundancy with separation, component shielding, et.al.) .

4.2 Multiple hit vulnerability (parallel trajectories)

The cumulated probabilities of kill after 1-30 threat (elevation 45^o and azimuth 45^o) hits for the example aircraft is shown in Fig.8.

4.3 Multiple hit vulnerability (spray trajectories)

In this example, the missile elevation and azimuth angel are both 0 deg. The missile velocity is 500 m/s, with the static leading spray angel of 50 deg, the static trailing spray angel of 120 deg, and the TNT charge. The TNT mass ratio to metallic case is 1.0. The missile warhead contains 1000 sphere fragments with the diameter of 1.16 cm. The aircraft flies at the height of 5000 m, with the velocity of 300 m/s. The distributions of probability of kill at the detonation locations around the aircraft are shown in Fig.9. After calculation, we know the leading and trailing dynamic spray angels are 48 deg and 117 deg, respectively. As is shown in Fig.9, the trailing and leading spray lines of missile divide the area around the aircraft into five regions. Any detonation within III and I will result in hits on part of the target by part of the fragment spray. Any detonation within zone II will result in the entire fragment spray hitting part of the aircraft, and detonations within zone IV result in part of the fragment spray hitting the entire target. Any detonation within zone V will result in zero fragments hitting the aircraft. In general, the optimal fuse design of missile should direct the missile to detonate within region II or IV [1], since the hit number of fragments on aircraft and the kill probability is relatively large, and the kill probability mainly depends on the distance of missile with aircraft in the two regions.

4.4 Blast envelops

In the plane parallel to the aircraft lift (plane C), the blast kill contours at sea level with different TNT charge masses are shown in Fig.10. The figure shows the envelopes have the inclination to extending outwards implying that the kill effects increase with the increasing charge masses.

5 Conclusions and recommendations

In sum, compared with the existing assessment software or programs, the developed system has

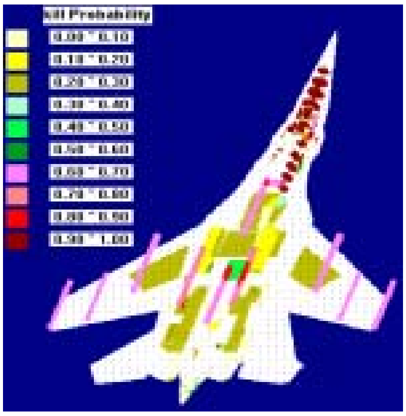

Fig. 4 Probability of kill distribution

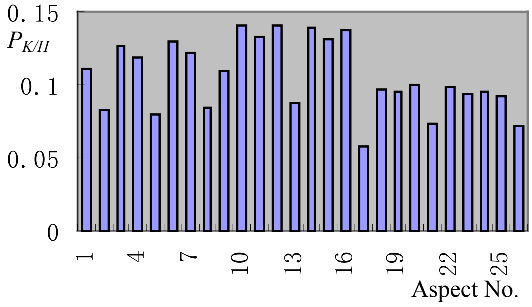

Fig.5 Probability of kill for 26 aspects

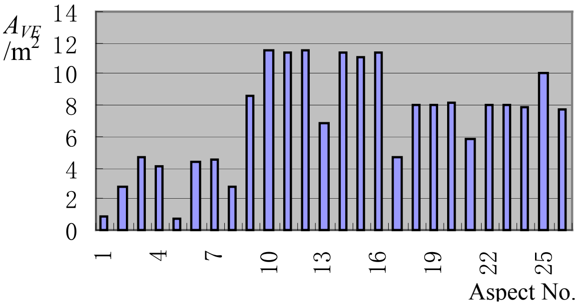

Fig.6 A_{VE} for 26 aspects

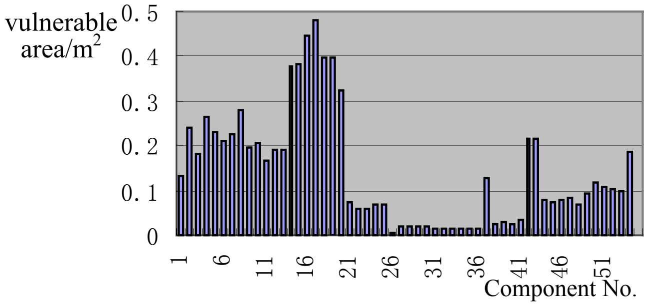

Fig.7 Average vulnerable areas of each component

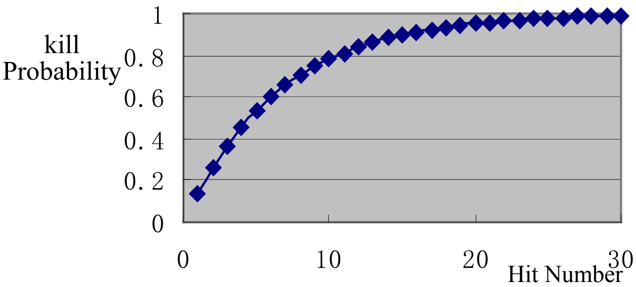

Fig.8 Aircraft cumulated kill probability

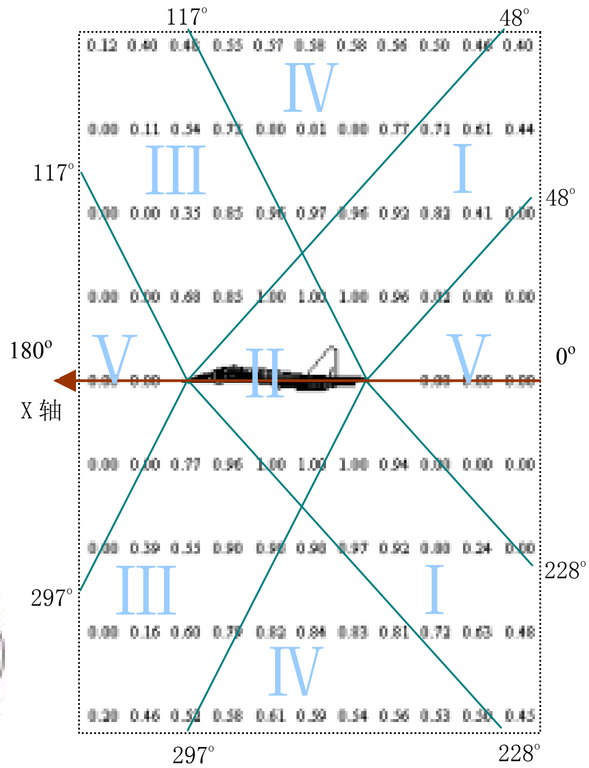

Fig.9 Kill probability distribution at detonation points around an aircraft

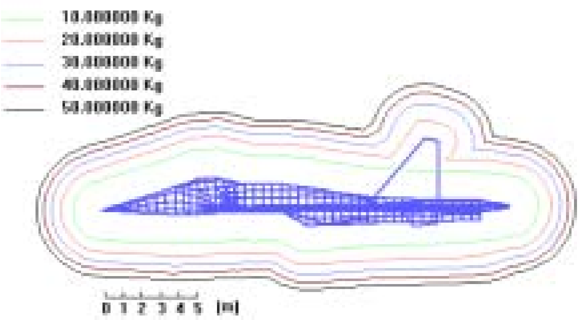

Fig.10 Blast contours on plane C

the following advantages: (1) it has considered the ricochet when assessing the aircraft vulnerability at the threat of nonexplosive penetrator. (2) it has considered the effect of redundant components on the vulnerability at the threats of missile. The above two show the assessment results are more realistic. And (3) it provides multiple output formats of assessment results and intuitively shows the vulnerable region. Application shows that the generic system can provide the measures of the relative vulnerability of different components of an aircraft, or the relative vulnerability of different aircrafts. This is useful for forming advice on the aircraft survivability enhancement design. In addition, the system can apply to the vulnerability assessment of other vehicles such as missile, satellite, armor car, et.al..

Furthermore, future work related to TVAS is recommended:

a) Improve the drawing of blast kill contours by deeply studying the blast wave reflection mechanism, airframe and control surface damage threshold, et.el..
b) Provide the vulnerability assessment of aircraft at the threat of internal detonation.
c) Add the missile warhead categories, such as discrete rod, continuous wards, et.al..

Acknowledgements

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