COLLISION RISK ASSESSMENT FOR A SPACECRAFT IN SPACE DEBRIS ENVIRONMENT

Q. Tang, B. J. Pang, W. Zhang

Hypervelocity Impact Research Center, Harbin Institute of Technology,
P. O. Box 3020, Science Park, Harbin Institute of Technology, Harbin, 150080, P. R. China.,
tangqi@hit.edu.cn

ABSTRACT

A spacecraft in LEO (Low Earth Orbit) suffers the impact from the space debris so a method is needed to get the probability of survival before the spacecraft is launched into space to determine whether the spacecraft is safe. The paper presents a research on the risk assessment method, which is divided into three parts: the application of space debris environment model, technology of spacecraft modeling and the calculation of risk probability that is the kernel part of the research. A software "ARMOR", which has been developed using the production of the research, is introduced and the calibration has been performed with the benchmarks in the "Protection Manual". The results indicate the consistency between "ARMOR" and BUMPERII of NASA.

1. INTRODUCTION

A spacecraft in LEO suffers the impact from the space debris. This kind of hypervelocity impacts can lead to serious accidents due to the large kinetic energy, and result in the failure of partial functions of the spacecraft and even the termination of the whole mission. To survive in the space debris environment, many protection measures are adopted, such as Whipple shield, stuffed Whipple shield, multi-shock shield and so on (Christiansen E., 1993). These shields can enhance the defense of spacecraft. With the restriction of both mass and sizes, their parameters must be determinated according their effect. So a method is needed to get the probability of survival before the spacecraft is launched into space to decide whether the measures are effective and the spacecraft is safe.

Some methods have been achieved and those were implemented with computer codes. The codes include: BUMPER of NASA, BASE/DEBRIS of ESA, COLLO of ROSAVIAKOSMOS and so on. Some of the codes have been applied to the actual analysis (P. Beltrami Karlezi et al., 2001).

A standard M/OD risk assessment methodology for spacecraft has been established by IADC (IADC WG3 members, 2002). It shows basic procedure of risk assessment, and almost every codes accord with it approximatively. Considering both the methodology of IADC and actual research, in our research, the procedure is divided into three aspects: space debris environment model, spacecraft modeling and the calculation of risk probability.

2. SPACE DEBRIS ENVIRENMENT MODEL

2.1. Flux Description of Space Debris

Many space debris environment models adopt the concept of "flux", which is used to depict the distribution of space debris. But regrettingly, there still isn't a specific definition of flux. Having surveyed some main content about flux, especially the "Protection Manual" (IADC WG3 members, 2002) and the document of ORDEM2000 (Jer-Chyi Liou et al., 2002), a definition of flux is presented. The flux of space debris is defined as the expectation of certain particles with certain parameter, such as time, position, size, velocity and so on, which depends on the certain model, that pass a directional plane with unit area per unit time (Fig. 1) (Tang Q. el at., 2003).

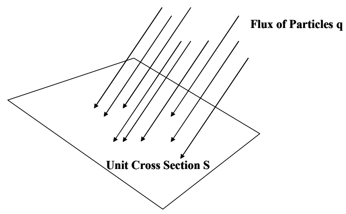

Figure 1. the definition of space debris flux

The flux is the differential of number expectation of certain space debris with time (Eq. 1)

$$F(\Delta t, \Delta\vec{r}, \Delta\delta, \Delta\vec{v}) = \frac{\partial^2 (q(\Delta t, \Delta\vec{r}, \Delta\delta, \Delta\vec{v}))}{\partial S \partial t} \qquad (1)$$

In fact, the density of space debris is directer concept for depicting the distribution of space debris. Its mathematical form of definition is

$$n(\Delta t, \Delta\vec{r}, \Delta\delta, \Delta\vec{v}) = \frac{d(q(\Delta t, \Delta\vec{r}, \Delta\delta, \Delta\vec{v}))}{dV} \qquad (2)$$

Only due to some historic reason, the flux is applied more widely in space debris environment model.

2.2. Universal Model of Space Debris

At present, there are some space debris environment models, such as ORDEM2000 and ORDEM96 of NASA, MASTER99 and MASTER2001 of ESA, SPDF

Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 18-20 April 2005
(ESA SP-587, August 2005)

of RASA and so on. Although there is obvious distinction between these models, none of them is thought to be the best of all. The risk assessment tools should support multiple models, even future models. We designed a universal space debris model to achieve it. The universal model adopts the flux defined as Eq. 2 and includes two parts: meteoroid submodel and orbital debris submodel. The universal model mainly origin from ORDEM2000 and meteoroid model in the NASASSP-30425B and also is fit for other some models. Tab.1 is the typical data structure of universal model that contains distribution data of space debris.

Table 1. The data format of space debris flux

parameter	lower limit of size	fraction of speed	sampling speed	fraction of direction interval	sampling direction1	sampling direction2	density of mass	flux
unit	m	no	km/s	no	rad	rad	g/cm^3	$1/(m^2.yr)$

For a certain space debris environment model, a user can transform it into universal format that is regulated by above universal model. Our risk assessment tools was designed to accept universal data, and then it can achieve the compatibility for multiple environment models.

3. SPACECRAFT MODELING

Spacecraft model that is the object of risk assessment contains all information relative with spacecraft,. These information include: geometry, orbital parameters and attitude parameters, type and parameters of shield structures, failure criteria and so on. Then, the spacecraft model is constructed and the geometry, kinematics and shield structure are taken into account as three submodels.

3.1. Geometry

Geometry submodel is constructed at the three levels: whole spacecraft, modules and elements. Whole spacecraft contains multiple modules that are divided into many elements. The module is a basic unit of shield configuration and assessment result. The data of shield configuration is attached on it as a property of module and after risk assessment result can be give at every module. The element is a basic unit of calculation and the object of arithmetic procedure. The risk probability of every element is obtained then integrates them together, and all risk probability can be determined. Considering the convenience of calculating risk probability, there are only two kinds of elements allowable: triangle type and quadrangle type.

3.2. Kinematics

Due to the nonuniformity of temporal and spatial distribution of space debris, the orbit and attitude of the space debris affect the impact result, so the kinematics parameters should be considered. Kinematics submodel contains all operational parameter of spacecraft that includes two classes: orbital parameters and attitude parameters. The orbital is described with classical orbital parameters. The attitude is described with two kinds of movement modes: three-axis stabilization and single-axis stabilization. The former is keeping static relative to reference frame while the latter is rotating around a certain axis relative to reference frame. Moreover, every mode has two alternative reference frames: orbital frame and earth centered initial frame, so there are totally four kinds of movements.

3.3. Protection

The protection submodel includes shield type, parameters and corresponding failure criteria. Every shield is depicted as ballistic limit equation, which determines the diameter of critical particle. We have considered four typical shields and two kinds of failure criteria. They are single plate shield, Whipple shield, stuffed Whipple shield, Mesh double-bumper shield and depth of crater, penetration, separately. Moreover, the impact is also thought as a kind of failure criteria in order to the convenience of implement.

4. CALCULATION

4.1. Single Impact

After the building of spacecraft model and the import of space debris environment model, a method for the risk probability calculation was designed. Firstly, reviewing the definition of flux of the space debris mentioned above, a single impact can be constructed as that (Fig. 2): a beam of particles (space debris) with a certain character parameters, including position, size, speed, direction of velocity and density of mass, which is depicted as Eq. 3, impacts perpendicularly a plate with a unit area.

$$F = F(\Delta\vec{r}, \Delta\delta, \Delta\vec{v}, \Delta\rho) \qquad (3)$$

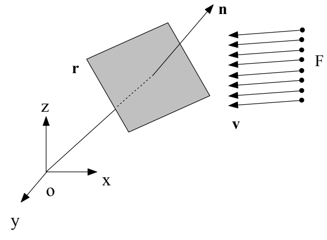

Figure 2. A single impact

The number expectation of single impact is

$$N = F \cdot S_r \cdot \Delta t \quad (4)$$

Here, S_r is effective area and it is given by

$$S_r = \begin{cases} S(\vec{n} \cdot \vec{v}) & \vec{n} \cdot \vec{v} > 0 \\ 0 & \vec{n} \cdot \vec{v} \le 0 \end{cases} \quad (5)$$

Due to Poisson's distribution, relative impact probability is

$$P = \exp(-N) \quad (6)$$

4.2. Arithmetic of Integration

Secondly, on the assumption that the total impact/failure number expectation of the spacecraft with complex geometry is the superposition of all single impact events', an integration relation for determine the total impact probability can be derived. The expectation of impact number of whole spacecraft can be determined by an integral relation

$$N = \int_{\vec{r}} \int_{s} \int_{\vec{v}} \int_{\delta} \int_{\rho} F \cdot S_r \cdot \Delta t d\vec{v} d\delta d\rho ds d\vec{r} \quad (7)$$

Here the number expectation of single impact is the integrated function and the domains of integration are restricted by certain problem. To implement it with computer, Eq. 7 must be transformed into numeric format as Eq. 8

$$N = \sum_{\vec{r}} \sum_{s} \sum_{\vec{v}} \sum_{\delta} \sum_{\rho} F \cdot S_r \cdot \Delta t \Delta \vec{v} \Delta \delta \Delta \rho \Delta s \Delta \vec{r} \quad (8)$$

It's a numeric integration based on the discretization of domain of integration. All domains are easily discretized except the direction domain of velocity, which is a space with the size of 4π. We adopted a kind of directional discretization method derived from Fuller's design of polyhedron. The method is illustrated in the Fig. 3 and it divides total direction space into 320 patches intending on uniformity as more as possible.

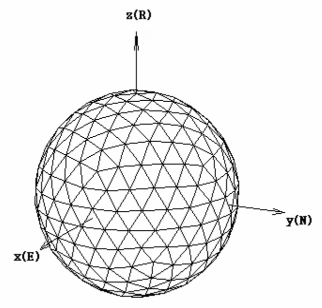

Figure 3. The directional discretization of velocity

4.3. The Effects of Shadowing

Furthermore, to get more accurate risk probability, the effects of shadowing should be considered, which is omitted in above assumption. The assumption of superposition thinks that expectation of total impact number is the sum of all expectation of single impact number, that is, all single impact event are independent each other. But at least at the level of different elements, this is rough enough to lead to obvious error. Similar to the diffusion of beam of ray, an element can posited on front of the other one, so the latter is shielded and its impact number decrease. The phenomenon is called "effect of shadowing", and it makes the coupling between different elements and reduces the expectation of total impact number.

A new arithmetic on effect of shadowing is stated as two steps: estimating the spatial relationship among all elements and calculating the exposed area of every element. The first step is judging according as following next four conditions orderly:

- Is there superposition between the encompass box of "shielding" element and one of the "shielded";
- Is the "shielding" element on front of the "shielded", referring to the inverse direction of incidence;
- Is the "shielding" element far enough from the "shielded";
- can the sampling point in the "shielded" element be projected in the inner of the "shielding".

And the detailed procedures utilize the arithmetic in the field of computer graphics.

The second step is implemented as following rule: the exposed area of a shielded element is its projected area along the incidence while the one of an unshielded one is zero. The rule brings definite error because of omitting the part shield of the element, but reduced the complexity of arithmetic. Considering the effect of shielding, Eq. 5 is corrected with a factor which denotes the fraction of exposed area in the total area of certain element.

5. CALIBRATION BY BENCHMARKS

5.1. Software "ARMOR"

We've developed a computer software "ARMOR" using above methods. ARMOR was developed at the platform of MSC/PATRAN®, which was a commercial software for the pre-processing and post-processing of FEA.

5.2. Calibration and Results

The impact risk assessment tools can be validated by the "benchmarks" provided by IADC (IADC WG3 members, 2002). The benchmark case includes three groups of cases and ARMOR can calculate some of them under the same conditions as BUMPERII of NASA, which means geography of spacecraft, BLEs and space debris environment model ORDEM2000. the paper given the most important results as Tab. 2.

Table 2 Result of "simple station"

Module	single plate			Whipple shield		
	BUMPERII	ARMOR	ε	BUMPERII	ARMOR	ε
Box	4.677E-01	3.877E-01	-1.3%	1.070E-05	7.655E-06	-3.4%
Port	1.078E+00	9.318E-01	-2.4%	1.904E-05	1.604E-05	-3.3%
Starboard	7.929E-01	7.727E-01	-0.3%	1.225E-05	1.188E-05	-0.4%
Trailing	2.473E+00	3.041E+00	9.2%	2.782E-05	3.680E-05	10.0%
Earth	1.348E+00	1.429E+00	1.3%	1.951E-05	2.085E-05	1.5%
Total	6.159E+00	6.562E+00	6.5%	8.933E-05	9.324E-05	4.4%

Tab. 2 is the results of case of "simple station" that is the most complex one of three groups. The table contains the expectation of impact probability and failure probability resulted from BUMPERII and ARMOR and the error between them. The result indicates that the impact on front module is more serious than the impact on the back and the sides is in the middle. This distribution accords with the general rule. On the other hand, every error of impact probability is less than 5% and the error of failure probability is less than 10% and this shows the consistency between them.

6. DEMONSTRATION

To demonstrate the software"ARMOR", an example has been performed. The model is an assumed spaceship which nominal orbit is as same as ISS, that is: 41.6°, 400km, and the assessment duration is from 1st Jan, 2005 to the end of this year. The attitude of the model is as follows: roll 0°, pitch 0° and yaw 0°. The main body is equipped with typical Whipple protection shielding and the wrings are supposed as single mental plates. Fig. 4 is the distribution fringe of failure probability.

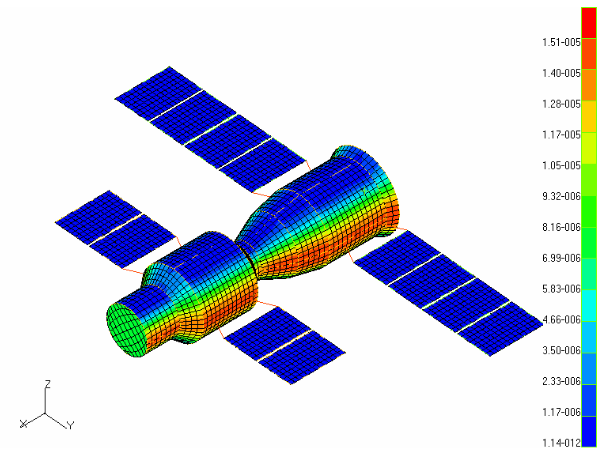

Figure 4. The failure probability of spacecraft

7. CONCLUSION

During the research on the risk assessment, several results and conclusions can be obtained.

- The methodology that divides the whole research into three parts was advanced and applied.
- A new arithmetic of effect of shielding was designed and the result shows its efficacy to a certain extent.
- An internal relation to determine the expectation of impact number was derived.
- The comparison and analysis indicated the consistency between ARMOR and BUMPERII.

8. REFERENCES

Christiansen E., Design and Performance Equations for Advanced Meteoroid and Debris Shields. *Journal Impact Eng.*, Vol.14, pp145-156, 1993

P. Beltrami Karlezi, G. Drolshagen, M. Lambert, Impact Risk Assessment for the ATV Using ESABASE/ DEBRIS. *Proc.3rd European Conference on Space Debris*, ESA Publication SP-393, pp. 629-632, ESOC, Darmstadt, Germany. 19-21, March 2001.

IADC WG3 members, *Protection Manual ver.3* , 2002.

Tang Q., Pang B. J. and Zhang W., Analysis of the Parameters in Space Debris Environment Engineering Model. *Chinese Space Science and Technology*, vol. 24, 22-27, 2004.

Jer-Chyi Liou, Mark J. Matney, Phillip D. , Anz-Meador, Donald Kessler, Mark Jansen and Jeffery R. Theall, The New NASA Orbital Debris Engineering Model ORDEM 2000, *NASA/TP—2002-210780*, 2002.