CONSTRUCTION OF THREE-DIMENSIONAL VULNERABILITY MODEL AND CALCULATIONS OF DAMAGE PROBABILITY OF SPACECRAFT IN DEBRIS ENVIRONMENT

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ABSTRACT

Space debris in near-Earth space constitutes a complicated environment with stochastic and statistic behavior. This makes the protecting parameters(Size or velocity of debris, for example) uncertain in designing the configuration of shielding structure of a spacecraft. Shielding measure is usually taken to reach a specific reliability goal. Calculation of the damage probability is often used in the reliability assessment, which is involved with statistical model of distribution and evolution, complicated interaction procedure between structure and debris. This paper outlined the theoretical models and algorithm used in developing our software for calculations of damage probability of spacecraft in debris environment.

1. INTRODUCTION

In recent years, problems on space debris have been paid sufficient attention by most aerospace countries. To study the space debris and learn its distribution and evolution, it is possible to adopt effective measure so as to get control of its increase in quantity, on the other hand, status of space debris may define one important aspect of the design environment in considering the structure protection of a spacecraft, which might also avoid further generation of space debris in case of possible collision accidental.

Space debris activities have been also proceeded in China. As a research in advance, BISSE (Beijing Institute of Spacecraft System Engineering) of CAST began its study on space debris in 1992, to meet the needs of its development of future large and long-life spacecraft. The aim of the research is to track the latest development on space debris, carry out theoretical study and software developing, and provide information to the policymaker on the risk status resulted from space debris. These studies include debris distribution and evolution, HVI, protection design and risk assessment.

(1) The long-term evolution of the debris cloud is simulated. The solar activity effect on orbital cloud is analyzed by statistics of debris orbital element' distribution in various phase(Ref.1).
(2) Our Hypervelocity impact studies focus on equation of state of material and numerical simulation. Dynamic response of material at high temperature and pressure during loading and unloading is described based on an energy dissipation model, some results still need to be determined by HVI experiments. MSC/DYTRAN software is used to calculate the relative low-velocity impact (without phase change occurrence)phenomena. Procedure of perforation, penetration and spallation of single wall impacted by debris at normal and oblique striking condition are simulated.
(3) Study on risk assessment is conducted coupling with simple protection design forms. The main work is made by utilizing the classical models, and developing software tools for damage probability calculation of spacecraft in a given debris environment. The software(RASISD) developed is based on a three-dimensional vulnerability model, for whitch two calculation methods are used in the software. Preliminary results are obtained for some supposed spacecraft configurations. (Ref. 2).

This paper will introduce the construction of three-dimensional vulnerability model and algorithm used in the software. Further studies on space debris are considered in the summary.

2. VULNERABILITY MODELING

2.1 System Failure Analysis

A large and long-life spacecraft is usually made up with several subsystems. Each subsystem is corresponding one or a series of components. To the hypervelocity impact by space debris, the vulnerability and the failure mode of each subsystem or component is different from each other, which depends on its inherent properties and functions executed in the whole spacecraft system.

The outside structure is the first component that will be impacted by space debris. If the objects it protected are the more robust subsystems such as a high-pressure RCS tankage, propulsion system components, the failure of penetration would depend on whether these objects are damaged or not. When the objects inside the structure are critical components such as computers, communication equipment, then, penetration or generation of secondary fragments due to spallation would result in system damage. In the case of pressurized module, gas leakage resulting from crack would lead to failure of the module. Vulnerable surface, such as optical surface, solar cell cover glasses, or special thermal coatings is another condition, in which, long-term action by small debris would cause pitting, eroding, or fracturing, and hence would lead to a certain kind of failure.

Three types of failure models for shielding structures are often used in analysis:

- Spallation model of single wall
- Bumper model of Whipple or MS shield
- Damage model of vulnerable surface

Empirical formula for the above models could be established through experiments or numerical simulations. However, the shielding structures of spacecraft considered may be different from each other. For example, utilization of new materials or thermal insulation layer etc makes anti-shock properties different. The parameters of the failure criteria should be determined by special experiments or numerical simulations.

Two failure models, single wall and whipple shielding, are considered in the software RASISD.

For single wall protection structure, the following equation can be obtained through dimensional analysis

$$p_t / d_p = c_t \rho_p^m v_p^n \qquad (1)$$

where p_t is the threshold thickness of the single wall in the case of spallation, d_p, ρ_p, v_p are the diameter, density and impacting velocity of a projectile, respectively, and c_t is the constant related to the wall material. Different value of parameter m and n may be chosen in different models, which depends on whether compressibility or strength of the wall material is considered to be more dominant during impact.

For Whipple shielding structure, Cour-Palais model (Ref.3) is used to calculating the failure condition in RASISD.

More detailed considerations are necessary on the failure criteria of the internal key subsystems or components impacted by debris, especially the debris cloud generated from the first impact. In addition, it is required that the relationship should be setup between interior and exterior, subsystems and components, for the completeness of the whole system failure analysis.

2.2 Vulnerability Data Structure

According to the above discussions, the following vulnerability data structure of the key subsystems and components impacted by space debris can be constructed:

```
Struct {
        Key Subsystem or Unit Name;
        Configuration;
        Layout Position;
        Protection Type;
        Failure Mode;
        Vulnerable Parameters;
        Cumulative Damage Factor
}Sub-object;
```

The principle of construction for the vulnerability data structure takes account of the four following aspects:

(1) Considering the geometrical properties, the relative position and embracing relation between subsystems and components are established, which is necessary to consider the shielding function of each other when studying impact;
(2) Influences of each subsystem or component, if failure, to the whole spacecraft are defined considering its function executed during mission;
(3) According to the protection approach and the physical properties of the subsystems or components, failure mode suitable to the object when impact by different debris source is determined, including the cumulative damage effect.
(4) The data structure should be convenient to conduct risk analysis and easy to make modification due to improvement of the model.

As the first step of software developing, RASISD only considered the outer structure of a spacecraft in damage analysis, due to the lack of failure knowledge of internal systems.

2.3 Construction of Geometrical Model

Configuration of modern large spacecraft is very complicated. Construction of its geometrical model could be done with CAD software. Parametrization and mesh are two ways to express three dimensional objects. Both of them can be used to construct the sub-system or component of the spacecraft considered, and form the overall geometrical model which is saved as data file with standard format, say DXF or IGES format, to be identified by the model-input interface of the software.

The overall geometrical model of the spacecraft is composed of numerous entities. Entities with same properties (protection type, failure mode, vulnerable parameters) are grouped into one computing unit.

According to the geometrical model constructed, the properties of each computing unit can be defined separately, and then the three dimensional vulnerability model of the spacecraft for damage probability calculation in space debris environment can be finally obtained.

3. CALCULATIONS OF DAMAGE PROBABILITY

Calculation of damage probability of a spacecraft in space debris environment is a statistical procedure, which is related to spacecraft mission, configuration, failure mode, space debris distribution and evolution.

To conduct reliability study of a spacecraft during a certain mission, the space debris environment in a specific orbit, and a specific lifetime have to be given first. The relative parameters include altitude and inclination of orbit, distribution of cumulative flux in different direction, distribution of velocity, and growth rate of space debris.

According to Poisson' distribution, the no-failure probability P of a spacecraft is a function of total failure number N_f resulted from debris impact during mission term T

$$P = \exp(-N_f) \tag{2}$$

In a space debris environment of flux density $\tilde{n}(t,x,v)$ with size distribution region D, velocity distribution region V, the total failure number of the spacecraft can be expressed as

$$N_f = \int_T dt \oiint_S ds \int_D dx \int_V f(s,x,v)A(t)\tilde{n}(t,x,v)dv \tag{3}$$

where S is a close surface region that contains the spacecraft, $A(t)$ is the normalization factor of flux density considering annual growth, $f(s,x,v)$ is the damage probability of a specific strike by a debris with given size and velocity. Definition of $f(s,x,v)$ may also consider the failure relation between interior and exterior, subsystems and components.

Two methods are often used in analyzing reliability of spacecraft in space debris environment. One is direct integration method, the other is Monte-Carlo method (Ref. 4).

3.1 Direct Integration Method

Direct integration method computes the exposed area of the spacecraft at different debris striking direction, analyzes the failure condition, and make integration of failure number directly.

It is difficult to use direct integration method in studying the complicated procedure of interaction between secondary debris generated from first impact and the internal systems or components.

3.2 Monte-Carlo Method

Monte-Carlo method, also named as statistical experimental method, computes the failure number by simulating the real procedure of space debris acting on a spacecraft during mission through computer.

According to the flux density function $\tilde{n}(t,x,v)$ of diameter and velocity, debris with diameter d and velocity v, is generated passing through a random position s, Ray tracing technique is used to judge the striking point at the spacecraft, and $f(s,x,v)$ is calculated with the failure models. With a sufficient number of strike by the generated debris, the total failure number with satisfactory precision can be obtained by

$$N_f = \int_T \sum_{i=1}^{N} f(s_i,x_i,v_i)A(t_i) \Big/ N \, dt \tag{4}$$

It is possible and simple with Monte-Carlo method to analyze the damage procedure of interaction between secondary debris and the internal systems or components. However, it is very time consuming in computation to get the desired precision. Parametrization expression of the geometrical model of spacecraft may be used to shorten the amount of calculation.

The above two methods are tried in development of RASISD (Fig.1), but two of them are limited to the studies of interaction between outer structure of spacecraft and debris currently.

Several combinations of simple geometrical object are used to make calculations, which are proven to fit the analytic results. Visualizations of geometrical model and computation results are made to check the correctness of the analysis in the software.

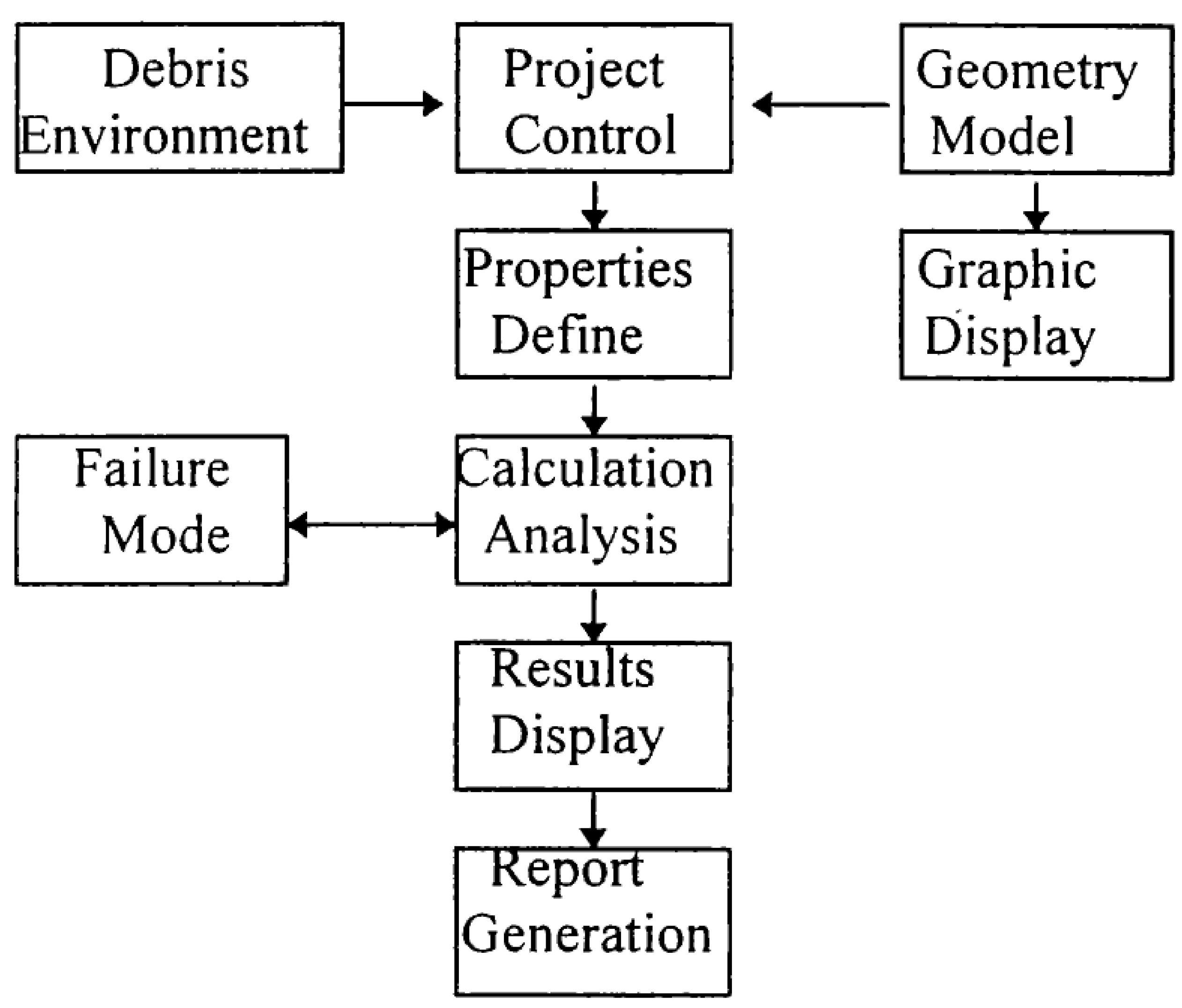

Figure 1. Flow Scheme of RASISD

Sample calculation is made with supposed models and real space debris environment. With the numerical analysis, the overall reliability of the spacecraft and the detail damage risk of the area are obtained, and it seems that the results are reasonable.

4. SUMMARY

The present study is preliminary, and the aim is to develop a tool gradually for an effective assessment to the shielding design of spacecraft during mission.

Discussions in the paper show that the software development is not difficult, however, besides acquisition of the reliable debris environment model, determinations of the various failure modes of different systems against impact with various source of space debris are complicated and crucial in the practical applications. Thorough study on HVI through experimental study and hydrocode simulations could provide failure parameters to increase the suitability of the software, but it seems to be impossible to realize the study due to high cost and various different shielding structures. This problem may be solved by developing some standard protection structures and conducting series of simulations and experiments through cooperation in the interested countries, to form a data base for failure mode of HVI with standard format, which would be used in both protection design and the risk assessment.

5. REFERENCES

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Chapter 9

Space Debris Mitigation