MODAOST'S APPLICATION IN M/OD SHIELD OPTIMIZATION OF JAPAN'S PRESSURIZED MODULE

Yuan Jungang，Han Zengyao，Zheng Shigui，QU Guangji

China Academy of Space Technology, Beijing, China, 100094

Email：jungangyuan@126.com

ABSTRACT

China Academy of Space Technology has developed Meteoroid & Orbital Debris Assessment and Optimization System Tools (MODAOST) for implementing M/OD impact risk assessment and shield design optimization. Now the M/OD shield design optimization software in MODAOST has been validated by two test cases of cube and cylinder models, exhibiting its effectiveness, efficiency and stability, and it would be applied in the protection design of China's future manned spacecrafts. For further verifying the engineering practicability and effectiveness, and forming the shield optimization procedure, Japan's Pressurized Module (PM) in International Space Station is selected to implement M/OD shield optimization. According to the requirements and constrained conditions from the thickness variability of rear wall and bumper, three optimization strategies are established. Optimization results show that each optimization strategy could gain the mass saving of more than 200 kg compared with actual PM shields, which shows the effectiveness of the MODAOST's optimization function and the necessity of shield optimization.

KEYWORDS: Meteoroid/Orbital Debris; shield configuration; structural design optimization; MODAOST

1. INTRODUCTION

China Academy of Space Technology(CAST) developed MODAOST(Meteoroid & Orbital Debris Assessment and Optimization System Tools) to implement M/OD impact risk assessment and shield design optimization. MODAOST is composed of M/OD impact risk assessment software and M/OD shield design optimization software. The former is completed and calibrated with the standard test cases of IADC in 2004[1]. The latter is developed in 2007, and has been validated by two test cases of cube and cylinder models, exhibiting its effectiveness, efficiency and stability[2].

Japan's Pressurized Module is one of the manned modules of JEM in International Space Station, which was launched in 2008, and would be on the orbit for ten years. PM was shielded from M/OD impacts, and used different shield configurations respectively on the front side and on the rear side[3]. But it was not designed optimally on the base of mathematical optimization methods, thus the mass of its shield structures was not effectively distributed.

This paper will select PM as the example to implement shield optimization for further checking the engineering effectiveness of MODAOST and obtaining the process of M/OD shield optimization.

2. MODAOST SHIELD DESIGN OPTIMIZATION SOFTWARE

2.1. M/OD shield design optimization models

For simplifying the M/OD shield optimization, the shield configuration and shield material are usually selected beforehand according to the M/OD impact risk assessment results, and only the dimensional parameters of shield structures are optimized. From the engineering demands of M/OD shield, two kinds of shield optimization models are put forward. Mass minimization model is described by (1), which is aimed to minimize the mass of M/OD shields with constrains of certain PNP(Probability of No Penetration) index by M/OD impact. PNP maximization model is described by (2), which is aimed to maximize the PNP of spacecraft with constraints of certain shield mass index.

$$\begin{aligned}&\text{Min.}\quad \text{Mass}(X),\qquad X=\{t_{w1},m_{b1},S_1;\ \ldots;\ t_{wn},m_{bn},S_n\}\\&\text{s.t.}\quad [\text{PNP}]-\text{PNP}(X)\le 0\\&t_{wj}^L\le t_{wj}\le t_{wj}^U,\quad m_{bj}^L\le m_{bj}\le m_{bj}^U,\quad S_j^L\le S_j\le S_j^U,\ j=1,\ldots,n\end{aligned}\tag{1}$$

$$\begin{aligned}&\text{Max.}\quad \text{PNP}(X),\qquad X=\{t_{w1},m_{b1},S_1;\ \ldots;\ t_{wn},m_{bn},S_n\}\\&\text{s.t.}\quad \text{Mass}(X)-[\text{Mass}]\le 0\\&t_{wj}^L\le t_{wj}\le t_{wj}^U,\quad m_{bj}^L\le m_{bj}\le m_{bj}^U,\quad S_j^L\le S_j\le S_j^U,\ j=1,\ldots,n\end{aligned}\tag{2}$$

The vector X comprises of design variables of all shield

Proc. '5th European Conference on Space Debris', Darmstadt, Germany 30 March – 2 April 2009, (ESA SP-672, July 2009)

components, which are the rear wall thickness t_{wj}, the total bumper areal density m_{bj}, and the overall distance between outer bumper and rear wall. The subscript j denotes the number of shield component, and n represents the total number of shield components. $Mass(X)$ is the mass of protection system, which comprises of mass of bumpers and rear wall and spacing, i.e. $Mass(X) = Mass_{Wall} + Mass_{Shield} + Mass_{Spacing}$. $[MASS]$ is the maximum allowable mass of protection system. $PNP(X)$ denotes the practical probability of no penetration that the protection system provides, and $[PNP]$ is the minimum allowable probability of no penetration that the protection system should provide.The superscripts L and U respectively represent the lower and upper boundaries of the jth variable.

The two models are applicable to nearly all the common shield configurations, for example single shields, Whipple shields, stuffed Whipple shields, multi-shock shields, and mesh double-bumper shields.

2.2. Shield optimization algorithms

M/OD shield optimization problems are characteristic of discontinuity and nonlinearity and multimodal. Meanwhile, the optimization assessment takes relatively much time. All these add difficulties to the optimization algorithms. Firstly, the suitable optimization algorithms should not use differential information; Secondly, they should have strong global search capability and high search efficiency.

We selected differential evolution (DE)[4] as the shield optimization algorithm, which is a new evolution algorithm. Its evolution process is similar to genetic algorithm (GA), which needs three operations such as selection, mutation and crossover. But the mutation mechanism and selection range of DE is different from GA. DE is superior in stronger global and local search capability and higher search efficiency comparatively to GA.

For shield optimization, we studied DE with a great number of tests, obtaining the methods of choosing variants, determinating population size, crossover factor and scaling factor[5]. Several tests showed that DE is the effective algorithm for M/OD shield optimization.Besides, we constructed hyper genetic algorithm(GA+Powell) with general genetic algorithm and Powell algorithm, which is relatively effective for shield optimization.

2.3. MODOAST framework

The shield design optimization software system in MODOAST provides two optimization functions of mass minimization and PNP maximization, and provides optimization algorithm selections of DE and GA+Powell.

The framework of shield optimization software system is composed of integration platform, pre-processing and post-processing modules, and application modules.The integration platform is developed from PATRAN platform, and it includes PCL functions library, database management, implement control, and I/O interfaces.Pre- and post-processing modules are also developed from PATRAN. They provide geometrical modeling, finite element modeling, orbital parameters determination, M/OD environmental models selection, and optimization results displaying.Application modules mainly include preliminary design of shield structures, optimization modeling, optimization assessment, optimization algorithm library, optimization solver.

3. M/OD SHIELDING OF JAPAN'S PRESSURIZED MODULE IN ISS

PM was shielded against M/OD impacts, which is shown in fig. 1. The shield type on the front sides (150 degrees) is stuffed Whipple structure, and the other sides is the simple Whipple structure. The detailed parameters are shown in fig. 2 and 3[3].

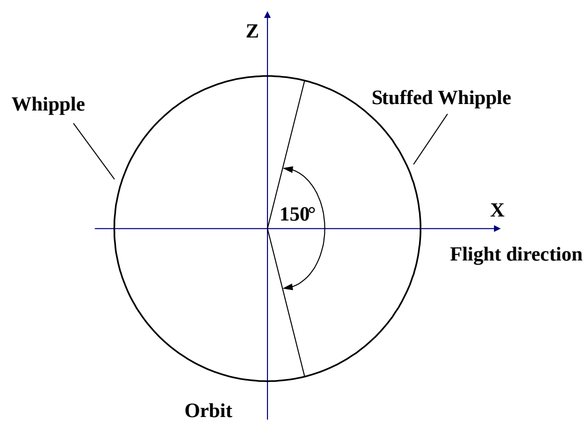

Fig. 1. M/OD Shield Scheme of PM

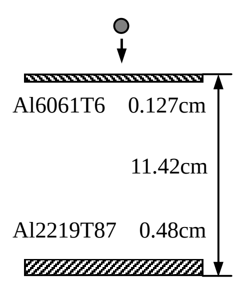

Fig.2. Parameters of the Actual Whipple Shield on PM

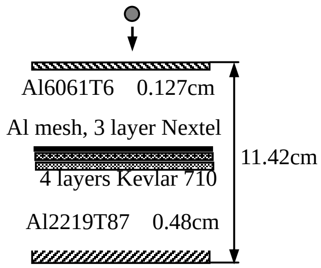

Fig.3. Parameters of the Actual Stuffed Whipple Shield on PM

4. M/OD IMPACT RISK ASSESSMENT OF PM

Three cases of the protection scenario have been assessed by MODAOST:

- Only simple Whipple structure (Fig. 2)in PM
- Only stuffed Whipple structure (Fig. 3)in PM
- Actual protection case (simple Whipple structure+ stuffed Whipple structure) in PM

In assessment, the M/OD environment models ORDEM2000 and NASA SSP-30425, and the ballistic limit equations by Christiansen[6] are adopted. Furthermore, the shielding effect by other ISS modules is not considered. Before implementing M/OD risk assessment, the surface of PM is divided into 12 elements along the circumferential direction, which can be seen in the figure 4. The third element is facing to the flight direction.

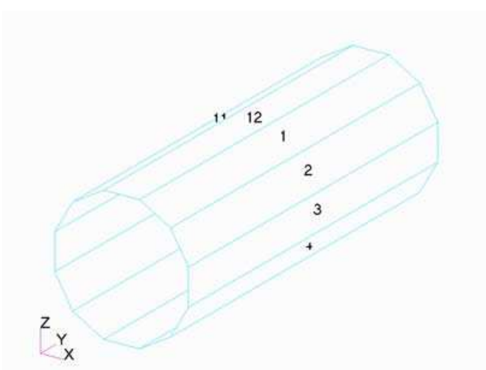

Fig. 4 . 12 Elements of PM

Tables 1 and 2 show the following assessment results:

- PNP of the actual PM shields is 0.9992 which exceeds the allocated value of 0.9814.
- If the PNP =0.9992, the average Number of Penetration (NP) of M/OD on each element of PM should be 6.6693e-5.

When the simplel Whipple shield illustrated in figure 2 is adopted, only the NP of the 1st -5th elements exceed the average value. Thus, the 1st－5th elements could be shielded by Stuffed Whipple structures, and the 6th－12th elements could be shielded by simple Whipple structures.

Table 1. NP and PNP of M/OD on Entire PM

Shield schemes	NP	PNP
Whipple Shields	5.2816e-3	0.9947
Stuffed Whipple Shields	5.2043e-4	0.9995
Actual Shields	8.1843e-4	0.9992

Table 2. M/OD NP on Each Element of PM Surface

Element No.	Whipple	Stuffed Whipple	Actual Shields
1	3.3998e-4	5.0564e-5	5.0564e-5
2	7.1089e-4	1.2756e-4	1.2756e-4
3	8.7025e-4	1.6438e-4	1.6438e-4
4	5.7242e-4	1.2003e-4	1.2003e-4
5	2.0063e-4	4.2052e-5	4.2052e-5
6	2.2233e-5	1.9615e-6	3.3533e-5
7	1.0965e-6	2.0480e-7	1.7899e-6
8	3.0001e-6	9.3467e-7	5.2138e-6
9	5.9227e-6	1.7250e-6	1.0893e-5
10	9.1597e-6	1.6529e-6	1.9334e-5
11	2.3970e-5	2.3158e-6	5.4092e-5
12	9.0307e-5	7.0434e-6	1.8898e-4

5. DESIGN OPTIMIZATION FOR PM SHIELD

5.1. Optimization strategies

Three assumptions are taken prior to the optimization process:
(1) Shield materials are identical to the actual PM shields;
(2) Total distance between the bumper and rear wall is fixed at 11.42cm similarly to the actual PM shields;
(3) Rear wall width of the 12 elements are identical.

Three optimization strategies are employed as follows:
(1) There are two optimization variables: the bumper thickness of five Whipple shield elements and the total areal density of the bumpers of seven stuffed Whipple shield elements. The rear walls thicknesses are all set to 0.48cm.
(2) There are twelve optimization variables: each bumper thickness of five Whipple shields and each total areal

density of the bumpers of seven stuffed Whipple shields. The rear walls thicknesses are all set 0.48cm.

(3) There are thirteen optimization variables: each bumper thickness of five Whipple shield elemens, each total areal density of the bumpers of seven stuffed Whipple shield elemens, and the rear wall thickness.

The boundaries of above variables are constrained:

- Al 6061 bumper: 0.1～0.3cm in thickness, or 0.2713～0.8139 g/cm^2 in areal density;
- Al mesh in the stuffed Whipple: 0.012 g/cm^2 in areal density;
- Nextel: 1～6 layers, or 0.1～0.6 g/cm^2 in areal density;
- Kevlar: 1～6 layers, or 0.032～0.192 g/cm^2 in areal density;
- Rear wall width: 0.2～0.7cm.
- Total bumper areal density of Stuffed Whipple elements: 0.4153～1.6179 g/cm^2

In addition, the constraint for PNP in all optimizations is 0.9992.

5.2. Optimization results

We use the shield design optimization software in MODAOST to optimize the shield structures of PM. The table 3 presents the optimization results, which include optimum variables, total assessment iteration times, bumper mass, total shield mass, saved mass， and PNP of various optimum shield systems.

Table 3. Optimization Results of PM Shield in Each Optimization Strategy

Shield element No.	Actual shields		Shield optimization strategy 1		Shield optimization strategy 2		Shield optimization strategy 3	
	Stuffed Whipple shield(cm)							
	t_w	m_b	t_w	m_b	t_w	m_b	t_w	m_b
1	0.48	0.785	0.48	0.4153	0.48	0.4153	0.428	0.4153
2	0.48	0.785	0.48	0.4153	0.48	0.4153	0.428	0.4153
3	0.48	0.785	0.48	0.4153	0.48	0.4153	0.428	0.4153
4	0.48	0.785	0.48	0.4153	0.48	0.4153	0.428	0.4153
5	0.48	0.785	0.48	0.4153	0.48	0.4153	0.428	0.4153
	Whipple shield(cm)							
	t_w	t_b	t_w	t_b	t_w	t_b	t_w	t_b
6	0.48	0.127	0.48	0.134	0.48	0.100	0.428	0.161
7	0.48	0.127	0.48	0.134	0.48	0.100	0.428	0.100
8	0.48	0.127	0.48	0.134	0.48	0.100	0.428	0.100
9	0.48	0.127	0.48	0.134	0.48	0.100	0.428	0.126
10	0.48	0.127	0.48	0.134	0.48	0.100	0.428	0.161
11	0.48	0.127	0.48	0.134	0.48	0.113	0.428	0.161
12	0.48	0.127	0.48	0.134	0.48	0.164	0.428	0.161
Assessment iterations	—		1005		24840		31410	
Rear wall mass(kg)	2019.78		2019.78		2019.78		1800.77	
Bumper mass(kg)	779.40		568.48		514.60		579.34	
Total mass(kg)	2799.18		2588.26		2534.38		2380.11	
Saved mass(kg)	—		210.92		264.8		419.07	
PNP	0.9992		0.9992		0.9992		0.9992	

- Compared with actual PM shields, each optimization strategy could gain the mass saving of more than 200 kg compared with actual PM shields.
- Optimization strategy 2 is more effective compared with Optimization strategy 1.
- Optimization strategy 3 is only used to indicate the rear wall's contribution to the PNP, although the thickness of rear wall is determined by other requirement.

6. CONCLUSIONS

Work in this paper demonstrates the necessity of carrying out design optimization for M/OD shields, and further tests the engineering effectiveness of MODAOST's optimization function. Now the optimization results mainly depend on the precision of M/OD environment models and ballistic limit equations.

In particular, precision of the existing ballistic limit equations of stuffed Whipple shield doesn't reflect the effects of all design variables and was developed only for M/OD impact risk assessment. More detailed ballistic limit equations of Stuffed Whipple shields could be developed in order to integrated all the important parameters.

Shield optimization could be implemented according to the following procedures:
(1) Perform the division of spacecraft surfaces, and set out the M/OD impact risk assessment;
(2) Analyze the impact risk of each element, and determine the suitable shield configurations;
(3) Initially design the shield structures for optimization;
(4) Accomplish the shield optimization, and obtain optimal shield schemes.

7. REFERENCES

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