# PAPER • OPEN ACCESS

# Simultaneous size and shape optimization for satellite adapter by using patran command language

To cite this article: X R Zhao et al 2020 J. Phys.: Conf. Ser. 1509 012009

View the article online for updates and enhancements.

# You may also like

- <u>Observing the Sun as a Star: Design and</u> <u>Early Results from the NEID Solar Feed</u> Andrea S. J. Lin, Andrew Monson, Suvrath Mahadevan et al.
- <u>A prototype scalable readout system for</u> <u>micro-pattern gas detectors</u> Qi-Bin Zheng, , Shu-Bin Liu et al.
- Micromachined contactless pin-flange adapter for robust high-frequency measurements

S Rahiminejad, E Pucci, S Haasl et al.





DISCOVER how sustainability intersects with electrochemistry & solid state science research



This content was downloaded from IP address 3.145.119.199 on 10/05/2024 at 10:46

# Simultaneous size and shape optimization for satellite adapter by using patran command language

#### X R Zhao<sup>\*</sup>, S Hameed, H Huang and O Rehman

School of Astronautics, Beihang University, Haidian District, Beijing, China

\*E-mail: zhaoxurui1126@126.com

Abstract. Adapter is a widely applied structure connecting satellite and launch vehicle with standard interface. In this paper, the described technique simultaneously uses the size and shape optimization on an engineering satellite adapter to achieve more efficient design. The optimization application is achieved by modifying its shape design variables and performing size optimization to obtain optimal design. The process is formulated in Msc.Patran/Nastran with the help of an algorithm generated by patran command language (PCL). Optimization results proved that the modified adapter greatly enhanced the stiffness and strength of the whole satellite while reducing the adapter weight by around 70%.

#### 1. Introduction

The optimization concept was introduced into the field of structure design by L. A. Schimit in 1960 [1]. This work laid up the foundation of structural optimization and progressed massively in the past half century. Nowadays, with the fast development of computational mechanics and the capacity of modern computers, a lot of commercial software for finite element analysis were produced and simulation-based structural optimization has become an indispensable tool in the design of competitive products [2]. One of the most famous commercial software is Msc.Patran, which is an integrated parallel framework system of finite element pre-and-post processing analysis and simulation. It not only provides a complete CAE integrated environment, but also provides user development tool named as patran command language (PCL). PCL is the built-in language of MSC.Patran, which is similar to C language and fortran. Besides basic math functions, PCL also provide many built-in functions for modeling, meshing and post-processing. Through PCL, user-compiled analysis programs can be integrated into software system to solve different kinds of problems [3]. Due to the powerful functions of patran in finite element analysis and secondary development, it has been applied in many researches [4],[5] The described technique in this paper also uses the PCL function to apply simultaneous size and shape optimization on a satellite adapter. Satellite adapter is the primary load-bearing structural part of satellite, connecting the launch vehicle and main satellite body. During launch, the vehicle provides a severe dynamic environment that increases the load of adapter and adapter has to maintain sufficient stiffness to protect the main satellite body.

Optimization has been applied on satellite structure in a lot of studies [6],[7]. However, optimization of adapter is relatively few as different countries use different standard and differences existed between different satellites have a great influence, so that a simultaneous size and shape optimization is performed for current satellite adapter.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under licence by IOP Publishing Ltd 1

The preliminary model of the present study came from Student Small Satellite-1 (SSS-1), which is a co-operated micro-satellite developed by several universities. It was especially derived from the preliminary design review phase (PDR), which is one of development phases of satellite. SSS-1 consists of main satellite body and adapter, which is shown in Figure 1. On current engineering issue, preliminary design of adapter has been designed as Figure 2.

Modal analysis is conducted based on the preliminary design of satellite and the result reveals that the natural frequency of the whole satellite is around 22Hz. According to the user's manuals of Long-March (LM) series launch vehicle, natural frequency of satellite usually should be higher than 15Hz to avoid the dynamic coupling with the launch vehicle. However, as SSS-1 is a micro-satellite with the mass of 35kg, it will not be the main considerations of the launch vehicle design and will face harsher mechanical environment than major satellite. Thus, following the requirement for major satellite design is not enough and analysis result of 22Hz is relatively low for a microsatellite. Therefore, stiffness and strength improvement is strongly recommended to provide a stable connection between satellite and launch vehicle. Nevertheless, the adapter remains metallic and contributes a significant proportion to the spacecraft's mass, so that strengthening this component will definitely increase the cost. On this condition, it is important to determine a compromising design point to satisfy practical considerations and meet launch vehicle's requirements while reducing the weight [7]. Considering the high computational cost of establishing finite element model, PCL is used to perform the simultaneous size and shape optimization for satellite adapter to achieve better design.

The remainder of this paper is organized as follows. Section 2 discusses the core factors of the adapter optimization problem, obtaining corresponding mathematical expression. Section 3 explains the solution of the stated problem, getting the optimization results and determining the final design of adapter. Finally, section 4 concludes the paper.



Figure 1. Configuration of SSS-1.



Figure 2. Preliminary Design of Adapter.

# 2. Problem Formulation

Objective function, constraints and design variables are three important factors of optimization problem. In this chapter, the specific form of adapter optimization will be constructed.

# 2.1. Initial Structure for Optimization

Launch vehicle has strict standards for mechanical interface of satellite. During launch phase, there is an adapter on the satellite and launch vehicle respectively. Two adapters have the same circular interface, where clampband is used to achieve the attachment [8]. Configuration of separation system is shown in Figure 3.





For SSS-1, The lower surface of adapter is circular to connect with launch vehicle, however, main body of satellite is cuboid so that the load will pass from circular to rectangular shape. On this condition, finding more efficient transformation shape based on preliminary design to perform the optimization, is an important work.

2.1.1. *Preliminary Design.* The preliminary design of adapter has a cylindrical shape with the height of 60mm, as shown in Figure 2. The lower circular surface attaches the launch vehicle by clampband while the upper surface is connected with the lower panel of satellite through eight M5 screws.

2.1.2. Design Modification. Based on the preliminary design, the load path of the satellite is shown in Figure 4. The upper load of main satellite body passes through lower panel of main satellite body, adapter and launch vehicle in turn. Considering the load path inside the lower panel, the load is transferred from the corner to the joint point with adapter, which will cause extremely high stress on the lower panel. Hence, transferring the upper load directly to the adapter without passing through the lower panel maybe a feasible method to improve the design efficiency. The concept can be better understood while visualizing Figure 5.





Figure 4. Load Path of SSS-1 Structure.

Figure 5. Effective Area for Improvement.

According to this idea, several adapters were designed and applied in the structure of SSS-1 to look for a better option as initial design selection. The surface thickness is kept same and modal analysis for SSS-1 is performed to check the influence of different designs. The new designed shapes are shown in Table 1 with the weight and modal analysis result. It can be concluded that the lateral natural frequency value has increased from 22.3 Hz to 73.8 Hz with the reduction of adapter weight from 1.622 to 1.149 kg, thus the proposed methodology is valid. The shape displayed in last column of Table 1 is selected as initial design for optimization.

| Shape of<br>Adapters |        |        |       |        |        |
|----------------------|--------|--------|-------|--------|--------|
| Freq1 / Hz           | 22.325 | 48.214 | 65.2  | 74.257 | 73.801 |
| Mass / kg            | 1.622  | 1.865  | 1.966 | 2.387  | 1.149  |

Table 1. Comparison of structural performance with different adapters.

Details of initial structure of adapter are shown in Figure 6 and Figure 7. The new adapter consists of three parts: base/lower portion is designed as per standard requirements from launch vehicle; upper portion is a combination of four surfaces which are joined in rectangular configuration with lower panel of main satellite body; the middle portion has four surfaces directly attaching from adapter lower to upper portion. Upper and lower portion of adapter are almost fixed, but the middle portion has large space for optimization.





Figure 7. Three Portions of Adapter.

# 2.2. Design Objective

Normally, satellite consists of platform and payload. The payloads are responsible for functional missions of satellite, while the platform provides necessary support including power supply, communication with ground station, etc. Designers should try to increase the weight ratio of payloads because the carrying capacity of launch vehicle is extremely limited. As adapter is part of the structure platform, minimizing the weight of adapter is selected as the design objective.

# 2.3. Constraints

Consideration of stiffness is a prominent feature of spacecraft structure design. Natural frequency of microsatellite generally has to be improved to reduce the coupling vibration with launch vehicle. Drawing on the experience from industrial department, the 1st natural frequency of micro-satellite should be more than 70Hz, avoiding the resonance frequency of launch vehicle Thus, the constraint is set to the first natural frequency of the whole satellite not less than 70Hz.

# 2.4. Design Variables

Three size design variables and two shape design variables are considered in this optimization problem. The panel thickness of three portions are selected as size design variables. Shape design variables include adapter height and middle portion angle, which are explained below:

### Adapter Height

Adapter height is the distance between adapter lower and upper surface and the shape of adapter will change by altering the height. Two different shapes of adapter with different heights are shown in Figure 8.



Figure 8. Comparison of Adapter with Different Heights.

Since the adapter height determines the distance between launch vehicle and main satellite body, it will undoubtedly affect the load path of satellite and has a great influence on the mechanical performance of satellite structure. Therefore, setting adapter height as shape design variable is reasonable.

# Middle Portion Angle

Considering the initial structure design of adapter, an edge is formed between two consecutive surfaces in corner, which makes the structure more stiffened in a certain direction. To balance the stiffness contribution on all the directions, the shape of adapter is further improved by adding a middle surface in each corner, increasing the amount of middle surfaces from 4 to 8. Middle portion angle is proposed to describe the different types of adapter surface layouts. The statement is expressed in Figure 9 for better understating. Obviously, the angle has a constraint from 0 to 45 degrees and it changes back into 4 surfaces adapter when the angle is 0.



Figure 9. Middle Portion with 8 Surfaces.

Middle portion angle is selected as the second shape variable to be considered in the optimization process.

In the size and shape optimization of the satellite adapter, the structural topology is prescribed in advance and kept fixed in the solution process. Instead, adapter height, middle portion angle and thickness of three portions are referred to as design variables and are assumed to change continuously or discontinuously.

# 2.5. Mathematical Expression of the Adapter Optimization

Based on the idea described above, adapter optimization involving size and shape optimization can be formulated as follows:

$$\begin{cases} find \quad S = \{h, a\}^{T} \\ T = \{t_{1}, t_{2}, t_{3}\}^{T} \\ min \quad W(S, T) \\ s.t. \quad freq_{allow} - freq \le 0 \\ h \in H \\ a \in A \\ t_{i}^{L} \le t_{i} \le t_{i}^{U} \quad i = 1, 2, 3 \end{cases}$$
(1)

where **S** is the shape variable vector, including adapter height *h* and middle portion angle *a*; **T** is the size variable vector including the panel thickness of three portions, and  $t_i$  represents the element in that vector with lower bound  $t_i^L$  and upper bound  $t_i^U$ ; **W**(**S**,**T**) is the objective function which means the weight of adapter; *freq* is the first natural frequency of the satellite and *freq<sub>allow</sub>* is the maximum allowable value; **H** and **A** are two domains of adapter height *h* and middle portion angle *a*.

In this paper,  $freq_{allow}$  is set to 70Hz according to the discussion above. The initial value for  $t_i$  is 2mm, and the lower and upper bounds are 1mm and 5mm. Considering manufacture restriction and the design of whole satellite, the adapter height domain is discrete and set as  $H = \{30,35,40,45,50,55,60,65,70\}$ , while middle portion angle domain is  $A = \{0,5,10,15,20,25,30,35,40,45\}$ .

#### 3. Optimization Scheme

#### 3.1. Optimization Process

According to the foregoing discussion, adapter height and middle portion angle are selected as the shape design variables, while surface thickness of three portions are chosen for size optimization. As values of shape variables are discrete and the number of available value is limited, an algorithm considering the variation of height and angle is established to perform the optimization of adapter, which is shown in Figure 10.



Figure 10. Algorithm for Optimization.

For each adapter height and middle portion angle, a new finite element model will be established and size optimization will be performed. However, it costs a lot to reconstruct each model step by step as only two parameters differ from each other. Since many of the programming structures in PCL, such as conditionals, arrays, and loops, enable programmers to work on a fortran-like environment, it is very suitable for current problems in which the design factors vary. Firstly, record the PCL commands of building FE model, performing size optimization and results output. Then, combine the related commands and a PCL function will be created. By invoking the PCL function, an adapter finite element model with given values of shape variable could be generated automatically. Furthermore, the scripting feature can be used to perform size optimization based on the established model to achieve a minimum weight while satisfying the constraints. Modify the input value of height and middle portion angle, models with different shape could be established and optimized. Under the control of PCL function, the optimization procedure will be performed until all the steps are completed without user intervention.

#### 3.2. Optimization Results

In accordance with the optimization process above, the results of minimum weight in each shape are available, which is shown in Figure 11. The horizontal axes represent adapter height and middle portion angle, and vertical axis represents weight of adapter. The graph clearly reveals that there is a global optimum for adapter design. The minimum weight value is 471.79 grams.



Figure 11. Optimized Weight of Adapter.

For the size and shape optimization, the optimum point is:

$$\begin{cases} S^* = \{45mm, 20^\circ\}^T \\ T^* = \{1.7227mm, 1.4588mm, 2.2847mm\}^T \end{cases}$$
(2)

# Discussion about Influence of Angle

From the graph of optimization results, it could be concluded that the minimum weight for a certain adapter height would be achieved at around 20 degrees. The reason is that the existence of middle portion angle would weakens the particularity of the certain direction and make the stiffness of adapter more balanced in all directions, improving the efficiency of material utilization.

### Discussion about Influence of Adapter Height

Similarly, for a constant middle portion angle, the minimum weight is achieved at around 35~45mm. This result appears because that there is a tilt angle between the lower portion and middle portion of adapter, which is shown in Figure 12. Increase of the tilt angle tend to improve the stiffness of the satellite. While improving the height of adapter, on the one hand, increase of tilt angle leads to the improvement of stiffness so that 70Hz could be achieved with smaller value of surface thickness. However, on the other hand, more material will be necessary, resulting in more weight of the adapter. The increase of tilt angle is more significant when adapter height below 40mm, and it becomes insignificant after a certain increase of the adapter height. So further increase in height will only add extra weight. Due to the influence of these two factors, the minimum weight is achieved at a certain height.



Figure 12. Tilt Angle for Middle Surface.

#### 3.3. Final Design of Adapter

According to the optimization results, the improved design of adapter could be determined. Considering the fact of manufacturing constraints, we need to round off these values. Final optimized values and manufacture values are mentioned in Table 2.

| Specifications     | Optimized Values | Manufacture Values |
|--------------------|------------------|--------------------|
| h/mm               | 45               | 45                 |
| a/°                | 20°              | 20°                |
| t <sub>1</sub> /mm | 1.7227           | 1.74               |
| t <sub>2</sub> /mm | 1.4588           | 1.47               |
| t <sub>3</sub> /mm | 2.2847           | 2.30               |
| freq1/Hz           | 69.803           | 70.020             |
| W/ g               | 471.79           | 474.12             |

Comparison between the preliminary and improved design of adapter is shown in Table 3. It could be concluded that the weight of the adapter reduces from 1.622kg to 474.12g, while the 1st natural frequency rise from 22Hz to 70Hz. Also, the results of mechanical analysis indicate that the new design is reliable.

Table 3. Comparison of preliminary and optimized adapter.

| Specifications        | Preliminary Adapter | Optimized Adapter        |  |
|-----------------------|---------------------|--------------------------|--|
| Picture               |                     |                          |  |
| Weight                | 1.622 Kg            | 474.12 Grams             |  |
| 1st Natural Frequency | 22.325 Hz           | 70.020 Hz                |  |
| Surface Thickness     | 5 mm                | Mentioned in above table |  |
| Adapter Height        | 60 mm               | 45 mm                    |  |
| Maximum Stress        | 60.2 MPa            | 70.9 MPa                 |  |
| Maximum Displacement  | 1.12 mm             | 0.65 mm                  |  |

#### 4. Conclusion

In this paper, simultaneous size and shape optimization is applied on a satellite adapter by using PCL. Originated from practical engineering problems, initial exploration is made based on the preliminary design of the SSS-1 satellite adapter. After more efficient shape was fixed, corresponding optimization problem is formulated. Then size and shape optimization are applied simultaneously following the proposed optimization process. By recording patran commands for establishing finite element model and performing size optimization, a PCL function is formed and the optimization results are obtained rapidly. The final structure of adapter is determined based on the optimization results and the improved adapter greatly enhanced the stiffness of the whole satellite while reducing the weight of adapter by around 70\%.

The work presented in this paper proved that the PCL function is an effective method for optimization, and the application on the micro-satellite adapter could provide some inspiration to transformation shape design between a rectangular and circular portion.

#### Acknowledgements

This research work is supported by the National Natural Science Foundation of China (Grant No.11672016), which the authors gratefully acknowledge.

### References

- [1] SCHMIT L A 1960 Structural Design by Systematic Synthesis. *Proc of Second Conference on Electronic Computation Asce.*
- [2] Guo X and Cheng G D 2010 Recent development in structural design and optimization. Acta Mechanica Sinica 26 pp 807–823
- [3] Li Z Y, Ren H L and Qi Y W 2015 Structural Parametric Modeling and Analysis of a Ship Stiffened Deck Plate Based on the Patran Command Language Applied Mechanics and Materials 733 pp 842-845.
- [4] Huang H, An H C, Ma H B and Chen S Y 2019 An engineering method for complex structural optimization involving both size and topology design variables *International Journal for Numerical Methods in Engineering* 117 pp 291-315
- [5] Sui Y, Du J and Guo Y 2006 Independent continuous mapping for topological optimization of frame structures *Acta Mechanica Sinica (English Series)* **22** pp 611-619
- [6] Sairajan K K and Nair P S 2011 Design of low mass dimensionally stable composite base structure for a spacecraft *Composites Part B: Engineering* **42** pp 280-288
- [7] Yoon Y H, Kim S J 2012 Asynchronous Swarm Structural Optimization of Satellite Adapter Ring *Journal of Spacecraft & Rockets* **49** pp 101-114.
- [8] Qin Z Y, Yan S Z and Chu F L 2011 Dynamic characteristics of launch vehicle and spacecraft connected by clamp band *Journal of Sound and Vibration* **330** pp 2161–2173