

Available online at www.sciencedirect.com**ScienceDirect**

Procedia Engineering 99 (2015) 1297 – 1301

**Procedia
Engineering**www.elsevier.com/locate/procedia

“APISAT2014”, 2014 Asia-Pacific International Symposium on Aerospace Technology,
APISAT2014

Optimal Design Aircraft Engine Mount Systems

Jiang Xianghua, Du Ran*

BeiHang University School of energy and power engineering, 37th Xuanyuan Road, Beijing 100191, China

Abstract

The main component of APU (Auxiliary Power Unit) mount systems is a frame structure. A spare beam is a smart structure to ensure the frame structure's reliability. However, light-weighted design and spare beam structure are difficultly considered simultaneously in the traditional design. This paper addresses two techniques to solve this problem, using topology optimization method and the FEM (Finite Element Method). The two methods are put into practice on an example model to prove their validity and compared to attach a report of their characteristic. The two methods this paper addressed also can be references to other frame structures' design optimization.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of Chinese Society of Aeronautics and Astronautics (CSAA)

Keywords: APU mount systems; spare beam; design optimization; topology optimization; FEM

1. Introduction

APU (Auxiliary Power Unit) provide power to start the main engines and run accessories when the engines shut down. At present, APU can be found on most of aircraft. The main component of APU mount systems is a frame structure. Design optimization is an efficient ways which decreases the cost of time, energy and money during product engineering. Meanwhile, using this measure, people can find the best solution by mathematical method without human's experience. Over the past years, numerous works have been done on design optimization. In 1904, Michell [1] first raised the question of frame structure's optimization and found the lightest frame structure in the case of bearing single load through analytic method. Then Dorn, Gomory and Greenberg [2] further demonstrated the Ground structure approach and first used numerical method to solve optimization problem. At

* Corresponding author. Tel.: +86- 13401173807;

E-mail address: 932591385@qq.com

present, the design methods of frame structure have become more and more perfect. However, little attention has been devoted to the spare beam in the frame structure. A spare beam makes frame structure operate normally even when one of its beams is out of action. The spare beam is a redundancy structure, which is against current optimization objectives. Moreover, when the quantity of beams isn't definite, the redundancy structure makes the problem much more complex. Topology optimization is a widely used mathematical approach which helps engineers to find the best concept design that meets the design requirements, and it is the most convenient method to design an initial optimal layout without any structure features. Bendsoe and Kikuchi^[3] first demonstrated topology optimization in 1988. And then, a series of topology methods were worked out, such as Level set method [4], Topological Function Description [5], ESO (Evolutionary structural optimization), Homogenization method [6,7,8]. This paper adopts a widely used interpolation scheme which is called the SIMP (Solid Isotropic Material with Penalization). This interpolation scheme was first advocated by Bendsoe [9].

This paper proposes two techniques to design frame structure with spare beam, using topology optimization method and the FEM (Finite Element Method). One approach is to modify the model's support pattern to simulate the condition that a beam is out of action, while the other one is to modify the loading to simulate it. These two methods improve the general topology optimization, and find new ways to design spare structure.

2. Topology optimization formulation

The formulation for topology optimization in this paper can be stated as follows.

$$\begin{aligned} & \min_{\rho} \int_{\Omega} \phi(\rho) d\Omega & (1) \\ \text{Subject to } & \begin{cases} 0 < \rho_{\min} < \rho \leq 1 \\ g_1(\rho) = \text{Max}\{\sigma_i/\sigma_a\} - 1 \leq 0, i = 1, 2, \dots, M \\ g_2(\rho) = \text{Max}\{u_j/u_a\} - 1 \leq 0, j = 1, 2, \dots, N \\ \text{Governing Differential Equation} \end{cases} & (2) \end{aligned}$$

Here ρ is the Relative element density which is chosen for the design variable. Relative element density is a variable related to elasticity modulus of element material, and it has a minimum value 10^{-3} and a maximum value 1. The material is removed where relative element density is low and retained where relative element density is high. $g_1(\rho)$, $g_2(\rho)$ is the optimization constraints and constructed based on the requirement of strength and stiffness, respectively. σ_i and σ_a are the von-Mises stress of analysis cell i and the allowed von-Mises stress, respectively. u_j and u_a are the global displacement of analysis node j and the allowed global displacement. $\phi(\rho)$ is the objective function which is to be minimized over the selection field. Ω is the designed domain within which the design can exist. The Governing Differential Equation governs the physics of the structure to be built. Topology optimization is applied to determine the best structural layouts meeting the constraints.

3. Design optimization methods

The two methods this paper proposed both are improvements of topology optimization in designing frame structures with spare beam. These methods are completely same as the current topology optimization except their finite element models. The situation that one of structures' beams is out of action should be described in finite element models so that the topology optimization result contains a spare beam. The designed structure is described as elements filling with the designed domain in topology finite element model, and every beam is uncertain before design. Therefore, there are some difficulties in designing the spare beam. There are two methods to solve the above problem in this paper. One is to modify the designed structure's support pattern, and the other is to modify the model's loading pattern.

If a beam's supports are removed, the structure will act as if the beam is out of action. The authors make use of this phenomenon to design a method to simulate the loss of beam in topology optimization model. In finite element model, the supports of beams usually are given by boundary conditions or constraint equations with other components. The designed domain's surface on which these boundary conditions and constraint equations exist is averagely divided into some small pieces. The area of these pieces is just a little larger than the beam's sectional area after finishing the topology optimization. Removing a piece's support from the original support formats a new support pattern. Each of these support patterns is connected to a new load step. The topology optimization is applied in all of above load steps, which works out the frame structure with a spare beam.

The force loading on APU is the key factor to simulate the loss of one beam. Thus we can simulate a situation by applying its loading pattern (including the bearing reaction of beams) on APU. A designed loading applied can simulate the loss of one beam. The designed loading has a two to three times greater value than the beam's bearing reaction and has a reverse vector with the beam's bearing reaction. The definite value and vector of additional loading aren't necessary for their approximations also can be accepted in engineering. Consequently, applying additional loadings is an effective way to solve the simulation problem in topology optimization models. For the reason that the beams' bearing reactions are the basis of the additional loadings design, the approximate bearing reactions are informations we need. A general topology optimization is applied to gain a frame structure without spare beam, which can be treated as the first approximation of objective structure. Bearing reactions gained in this approximation are used to design additional loadings to get closer to the best layout. Attaching a new loading means a new load step. The number of beams appearing in the designed structure is equal to the number of load steps. The topology optimization is conducted in the new load steps. And new additional loadings are gained from it, which formats new load steps. This iteration will continue until the optimization result is same as the past. After that, a proper structure meeting all the requirements above has been designed.

After topology optimization, geometry recovery and size optimization is applied in this paper. The topology optimization result is summarized to a frame structure in geometry recovery. And the areas of beams' section are decided in size optimization. In size optimization design, the stability of beams is another requirement taken into account. The stability constraints are attached to the size optimization model.

4. Example

4.1. Example description

To demonstrate the methods above, the topology of APU mount system is optimized. In this topology example, an APU is treated as a rigid regular hexahedron. The hexahedron size is 380mm*200mm*180mm, it is shown in Figure. 1(a). The mount system is a compliant structure connected with APU by hinge joint, and it is fixed on a rigid wall by welding. There are three connections linking the APU to its mounts, one is on the top, the other two lay on the both side. The connections exit in the place where yellow nodes locate in Figure 1(a). The material of the compliant designed mechanism is steel with the Young's modulus (E) of 210GPa, the Poisson's ratio (ν) of 0.3, the allowed stress (σ_s) of 460MPa. To guarantee enough stiffness in the designed structure, the APU's maximum displacement is restricted to 5mm. Loadings imposed on APU are mainly caused by maneuvering flight's apparent force and airflow. The overload factors are given in the Table 1. The n_x , n_y , n_z are the overload factors in X, Y, Z direction, respectively. X is axial direction while Z is gravity direction. Y is a direction perpendicular to the XOZ plane. The ω is the maximum designed cornering rotational speed which cause gyrostatic moments. The ε is the maximum designed angular acceleration which cause inertial moments. The axial moment is given according to the APU's operating rotating speed of 5160r/min and horsepower of 22kw.

Table 1. Overload factors during maneuvering flight.

Overload factors	n_x	n_y	n_z	ω_y (rad/s)	ω_z (rad/s)	ε_y (rad/s ²)	ε_z (rad/s ²)
Situation 1	-2	±4	-6	±2	0	±6	0
Situation 2	-2	±1.5	-10	0	±2	±6	0
Situation 3	2	±1.5	-10	0	±2	±6	0
Situation 4	-4	±4	1	±2	0	±6	0
Situation 5	-10	±2	-4	±1.4	0	±14	±6
Situation 6	2	±2	-10	0	±1.4	±14	±6
Situation 7	2	±2	4	±1.4	0	±14	±6
Situation 8	4	±2	-8	0	±1.4	±14	±6

4.2. Finite element model

The designed frame structure exists in a hexahedron space around the APU with a size of 380mm*400mm*360mm, and its discretization and subdivision are shown in Figure. 1(b). The entire design domain is discretized into 5 mm x 5 mm square design cells. The values of borderline nodes' DOFs (Degree of Freedom) are forced to zero. To connect the designed structure with APU, equations are set up to simulate the hinged connections. The APU is treated as a rigid body in this paper. The overload burden is loading on the APU's barycenter, while the moment caused by the airflow is applied in the same place. All of loading is given in the above section.

4.3. Results

The framed structure designed through modify the designed structure's support pattern is shown in Figure. 2(a). The structure's beam sectional area is optimized to 10.7mm², while the total length of beams is 470mm.

The framed structure designed through modify the designed structure's loading pattern is shown in Figure. 2(b). The structure's beam sectional area is optimized to 12.8mm², while the total length of beams is 437mm.

The comparison of the two results is shown in Figure. 2(c). The blue beam is gained through the first method, while the red ones gained through the last method. The maximum displacements of APU and maximum stresses of the mount system are listed in the Table 2. The data in the table include the two result structures working in 8 regimes of flight. The u_m is the largest displacement while the σ_m is the largest von-Mises stress. Analyzing the data of table 2, the structure designed by first method is more flexible and efficient than the other one.

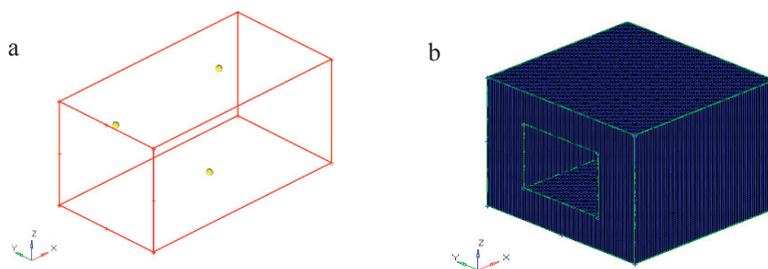


Fig. 1. (a) APU's geometry model; (b) designed domain's finite element model.

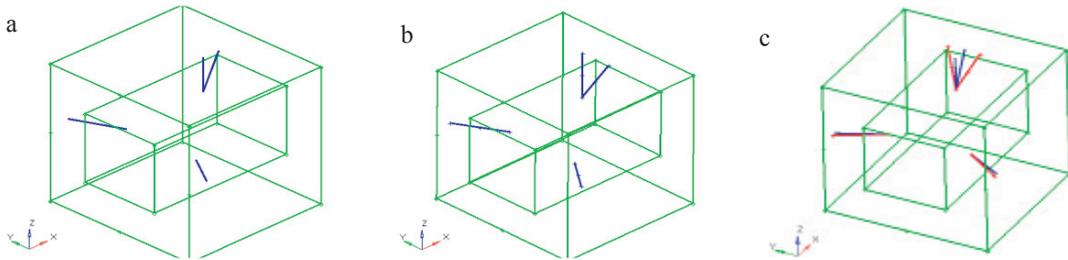


Fig. 2 (a) Result through first method; (b) Result through first method ;(c) Comparison of two method's results.

Table 2. Maximum stresses and displacements in result structures.

Loading situation	1	2	3	4	5	6	7	8
u_{m1}/mm	3.1	2.8	4.2	4.9	4.6	4.8	1.5	4.9
σ_{m1}/MPa	290	413	385	360	450	391	190	428
u_{m2}/mm	3.5	1.7	1.8	3.5	1.9	2.0	1.8	1.9
σ_{m2}/MPa	296	460	355	288	423	355	215	341

5. Conclusion

This paper develops two optimization methods to design frame structures with spare beams, using topology optimization measure. According to the sample's design results, some conclusions can be made. The sample's results prove the two methods proposed by this paper are effective for solving the spare beam problem. Moreover, modifying the support pattern need much more numerical work than the other method but cost less designer's work to build finite element models compared to the other one. Structures designed though prior method have advantages in its strength while the results gained through the last method have more stiffness. Finally, this paper can be a reference to the design optimization of other frame structures with spare beam.

Acknowledge

We greatly appreciate the anonymous reviewers for their insightful suggestions and comments on the early version of this paper. Also, we thank Wang Yanrong of BeiHang University, China for his kind help and great effort to improving the quality of this paper.

References

[1] Michell A.G. M., The limits of economy of materials in frame structures . Philosophical Magazine, 1904, 8(47): 589~597
 [2]Dorn W., Gomory R. , Greenberg H., Automatic design of optimal structures. J. de. Mechanics, 1964,3(1): 25~52
 [3]Bendsoe M P, Kikuchi N. Generating optimal topologies in structural design using a homogenization method. Computer Methods, 1988, 71: 197~224.
 [4]Sethian J.A., Wiegmann A., Structural boundary design via level set and immersed interface methods[J]. Journal of Computational Physics, 1999, 163:489~528
 [5]Ruiter M.J. , Keulen F. , Topology Optimization Approaching The Material Distribution Problem Using a Topological Function Description. In Computational Techniques for Materials Composites and Composite Structures[J]. Edinburgh Civil-Comp Press, 2000: 111~119
 [6] Guedes J. M. and Kikuchi N. Pre-processing and Post processing for Materials Based on the Homogenization Method with Adaptive Finite Element Method. Comp. Methods Appl.Mech.Engrg., 1990, 83: 143-198
 [7]Suzuki K. and Kikuchi N. A homogenization method for shape and topology optimization. Computer Methods in Applied Mechanics and Engineering, 1991, 93: 291-381
 [8]Lazarus H. Teanek and Ichiro Hagiwara. Static and vibrational shape and topology optimization using homogenization and mathematical
 [9] Bendsoe M.P., Optimal shape design as a material distribution Problem. Structural OPTimization.1989,1:193~202