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Engineering Notes

Optimum Design of a Space Frame and its Application in Satellite Structure

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Nomenclature

$f(X)$	=	objective function, structural mass, kg
$g_j(X)$	=	jth normalized design constraints
H	=	number of the counted points
m	=	number of design constraints
n	=	number of design variables
X	=	design variable vector
x_i	=	ith design variable, m
x_i^L, x_i^U	=	lower and upper bounds of x_i

Subscripts

i	=	ith design variable
j	=	jth design constraint

I. Introduction

A SPACE frame is often adopted in spacecraft structure for good stiffness and stability with relatively low weight. Because of limitations inherent in the payload capabilities of launch and orbital transfer vehicles, the spacecraft structural weight, which constitutes a significant portion of the total payload weight, is a critical design factor. The need to minimize the structural weight and at the same time satisfy multiple design constraints has significantly increased the cost and time for undertaking conventional engineering design, analysis, and weight-reduction iterations [1]. Designers and engineers therefore need assistance from an optimization methodology that helps them to efficiently design lightweight structures that comply with the structural performance requirements without violating design constraints [2–7].

Significant progress in the field of structural optimization has been made during the past half century. Excellent reviews are given in [8–11]. The theoretical research into the structural optimization of cross-sectional dimensions is reaching a mature state. The emphasis of structural optimization focuses on developing universal optimization software and practical engineering applications [12]. Recently, despite a large number of research projects and paper studies, few optimization results have actually been implemented in any Chinese satellite frame structure. This Note reports a practical approach by using ESSOSII (Engineering System of Structural Optimization for Spacecraft, Version II) [13] for the optimization of a three-dimensional space frame with parameterized element cross sections and its application in the frame structure optimization of a satellite structure design.

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II. Problem Statement

The space frame synthesis problem may be stated as follows: seek a minimum mass design such that all pertinent measures of structural behavior and all structural design variables remain within specified limits. Where the structural topology, configuration, materials, and loading conditions are prescribed, the design problem can be stated mathematically as

$$\begin{cases} \text{Find } \mathbf{x} = \{x_1, x_2, \ldots, x_n\}^T & \\ \text{Min } f(\mathbf{x}) & \\ g_j(\mathbf{x}) \le 0, & j = 1, \ldots, m \\ x_i^L \le x_i \le x_i^U, & i = 1, \ldots, n \end{cases} \tag{1}$$

where the design variables $\mathbf{x}$ are linked cross-sectional dimensions of the frame [e.g., thin-walled circular tube, rectangle section (see Fig. 1)], the objective function $f(\mathbf{x})$ is the weight of the structural system, $g_j(x)$ is the behavioral constraint function, and x_i^U and x_i^L are upper and lower bounds on x_i.

Equation (1) represents a complex, implicit, nonlinear problem in terms of $\mathbf{x}$, and as a result, its direct solution is computationally impractical. The general approach to the optimization problem in Eq. (1) is the approximation concept approach pioneered by Schmit and Farshi [14]. In this approach, the optimization problem is solved by establishing a sequence of explicit approximate problems. Consequently, the overall efficiency of this approach is determined by the accuracy of the approximation. Most of the approximations presented in the literature were the first-order and second-order Taylor series approximations based on the function and gradient information of a single point or two points [15–18]. To improve the quality of approximations, Huang and Xia [19] presented a two-level multipoint approximation method (TMA), which is a powerful structural optimization method based on multipoint and two-level approximation concept. In the present work, TMA and its corresponding optimization system ESSOSII are applied in frame structure design.

III. Structural Optimization with TMA

Within TMA, the constraint functions are approximated on the basis of their values and derivatives at the known points (the points number $H_{\max} \leqq 5$) obtained in the process of optimization, and the nonlinearities of the approximate functions are controlled by the adaptive parameters to approach the real constraint functions in their expansive domains. In such a manner, the original optimization problem (1) is transformed into a sequence of approximate problems called the first-level approximate problems. For each of them, another sequence of approximate problems called the second-level approximate problems is constructed by Taylor expansions, which is solved easily by using dual theory of mathematical programming. The detailed solving procedure is illustrated in [19].

Based on TMA, an engineering optimization system ESSOSII was developed by the authors in which general finite element (FE) program Nastran is adopted to execute structural analysis. In addition to the similar structural optimization functions as Nastran Solution 200 (Sol 200), some special capabilities are further developed to satisfy the requirements presented from practical engineering problems of spacecraft design, such as optimization of nonstandard cross-sectional dimensions [20], optimization with multistructure cases [21]. ESSOSII can also deal with design variables as thicknesses of shell and composite material layers. Before applying ESSOSII in structural optimization of a satellite with frame structure, a typical numerical example is optimized to illustrate the effectiveness of ESSOSII.

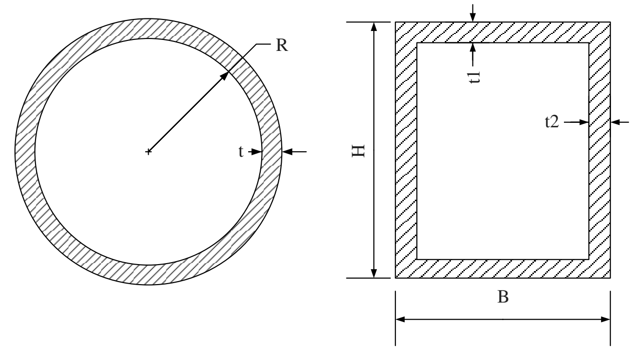

Fig. 1 Element cross-sectional types.

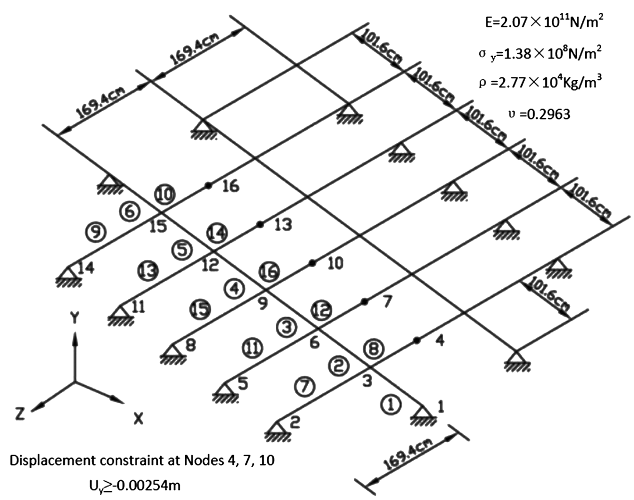

Fig. 2 The 2 × 5 grillage.

IV. Numerical Example

A typical 2×5 grillage [19,22] is selected as a test problem. Figure 2 shows the structure which is in the x-z plane and is subjected to a 175 N/cm (100 lb/in.) distributed load. This problem considers nodal displacement and cross-sectional dimension side constraints. The optimization results and iteration history are given in Tables 1 and 2, respectively. The results of Huang and Xia [19] and Nastran Sol 200 are also shown as comparison. The distribution of material in the present study agrees well with that in [19], and the final mass in the present study is lower with a similar number of iterations; the differences between their results are caused by the different derivative calculation methods. Comparing with the results of Nastran Sol 200, it can be seen that the final mass and analysis numbers are much lower in the present work, which means that the precision and efficiency of TMA are better than the optimization methods adopted in Nastran Sol 200.

V. Application in Satellite Structure Design

A. Problem Description

A satellite structure is composed of two parts: the main structure platform and the payload cabin. It is connected with the launch vehicle through a joint ring in the bottom of the main structure platform. To improve the performance of the main structure platform, a main frame is designed for it, and the cross-sectional dimensions of various kinds of beams in the main frame need to be optimized. The stiffness of the whole satellite should satisfy the requirements that the first-order natural transverse frequency and the first-order longitudinal frequency are not lower than 11 and 30 Hz, respectively. Meanwhile, the design should satisfy the requirements of strength and stability under launch condition loads. The load cases are listed in Table 3.

B. FE Model

Based on the original design of a satellite structure, an FE model was established, which consisted of shell, beam and rod elements. Considering the mass distribution of the payloads and the attachment on the board, nonstructural mass was added to related finite elements, or point mass elements were set to connect with elements at their installation positions with the rigid element RBE2. The FE model of a whole satellite is shown in Fig. 3, which includes 24,669 nodes and 26,844 elements, with a side panel removed. The main frame in the main structure platform is shown in Fig. 4. Based on the connecting interface between the satellite and launch vehicle, the boundary condition is to fix the bottom of the joint ring.

C. Numerical Results

In the optimization calculation, seven design variables were selected for the cross-sectional dimensions of the various kinds of

Table 1 Final design for 2 × 5 frames (in centimeters) by linked groups (member numbers are shown in parentheses)

Size	Initial design	Lower bound	Upper bound	Nastran Sol 200	Huang and Xia (1995) [19]	Present study
				Group 1 (1–6)		
B	30.48	2.54	48.26	30.20	11.58	6.5
H	38.1	2.54	50.8	38.33	50.8	50.8
t_1	2.413	0.1143	2.54	0.4815	0.396	0.114
t_2	2.032	0.127	2.413	0.1456	0. 127	0.127
				Group 2 (7–10)		
B	30.48	2.54	48.26	30.21	5.182	5.06
H	38.1	2.54	50.8	38.13	44.2	50.8
t_1	2.413	0.1143	2.54	0.2776	0.188	0.299
t_2	2.032	0.127	2.413	0.127	0.127	0.127
				Group 3 (15–16)		
B	30.48	2.54	48.26	30.61	47.45	33.0
H	38.1	2.54	50.8	38.99	50.8	50.8
t_1	2.413	0.1143	2.54	2.49	0.925	0.963
t_2	2.032	0.127	2.413	0.851	0.127	0.204
				Group 4 (11–14)		
B	30.48	2.54	48.26	30.45	48.26	48.1
H	38.1	2.54	50.8	39.03	50.8	50.8
t_1	2.413	0.1143	2.54	1.825	1.229	1.04
t_2	2.032	0.127	2.413	0.476	0.127	0.373
				No. of analyses		
——	——	——	——	12	7	8
				Final mass, kg		
——	——	——	——	8750.3	5769.18	5636.3

Table 2 Iteration history for 2 × 5 frames

	Mass, kg [maximum constraint violation, %]		
Analysis no.	Nastran Sol 200	Huang and Xia (1995) case A [19]	Present Note
1	29,406.0 [0]	29,407.54 [0]	29,406.0 [0]
2	18,990.21 [0]	13,496.83 [0]	11,130 [0]
3	13,008.31 [0]	7,463.377 [0]	6,853.8 [0.7]
4	11,006.59 [0]	6,335.101 [0]	6,566.6 [0]
5	9,645.044 [0]	5,834.008 [0.8]	5,930.8 [0.6]
6	9,127.88 [0]	5,764.038 [1.4]	5,759.6 [0.5]
7	9,038.3 [0.2]	5,769.19 [0]	5,686.4 [0.3]
8	8,952.3 [0]	——	5,636.3 [0]
9	8,883.1 [0.2]	——	——
10	8,832.6 [0.2]	——	——
11	8,793.4 [0.2]	——	——
12	8,754.9 [0.2]	——	——
13	8,750.3 [0]	——	——

Table 3 Load cases

	Overloading, g		
	Case 1	Case 2	Case 3
Transverse	2.25	1.5	1.5
Longitudinal	4.5	9.15	−3.9

beams in the main frame. This design problem was solved using the initial design and the lower and upper bounds shown in Table 4. Among the constraints, the first-order transverse frequency and element stresses under three overload conditions are set as constraint functions which will be satisfied automatically during the optimum calculation. The first-order longitudinal frequency and stability requirements act as measurements to verify the optimized structure. The objective is to search the minimum weight.

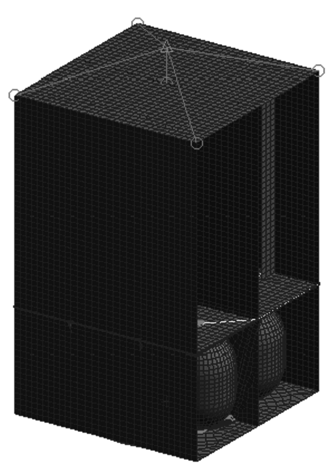

Fig. 3 FE model of a satellite structure.

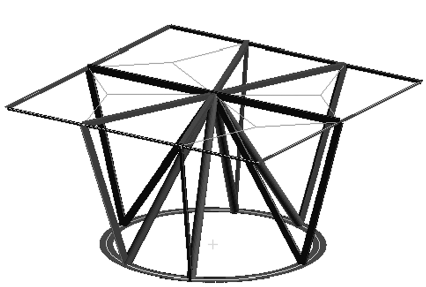

Fig. 4 Main frame.

Table 4 Optimization result (in millimeters)

Variable	Initial value	Lower bound	Upper bound	Result
1	2	1.5	3	1.98
2	2	1.5	3	2.52
3	2	1.5	3	2.52
4	2	1.5	3	2.64
5	4	1	4	4
6	0. 16	0.02	0. 4	0.094
7	2.7	0.5	5	1.15

Table 5 Objective and constraints comparison

Objective/constraints	Initial	Result
Mass change, kg	372.8	369.6
The first-order frequency, Hz	10.79	10.99
The first-order longitudinal frequency, Hz	34.67	34.27
Max stress, MPa	106	118
Critical bulking factor	2.02	2.21

Table 4 shows that variables 1–4 increased, variable 5 was still at the upper bound, and variables 6 and 7 decreased to half the original values. The objective and constraints comparison in Table 5 shows that the first-order frequency was the critical constraint, which increased from 10.79 to 11 Hz, and the mass decreased by 3.2 kg. The maximum stress (149 MPa) took place in load case 2, which is far lower than the strength limit. Comparing the final solution with the initial design, Table 5 shows that the longitudinal frequency changed very little and that the critical bulking factor increased from 2.02 to 2.21, indicating higher stability. Therefore, the stiffness, strength, and stability of the final solution satisfied all the design constraints and the mass decreased, which provided guidelines to the detail design of the satellite structure.

The iteration history is shown in Fig. 5, in which W is the mass that can be optimized and its initial value is 372.8 kg. It can be seen that only eight structural analyses were implemented during the whole process, which means that the ESSOSII can achieve an optimum solution efficiently.

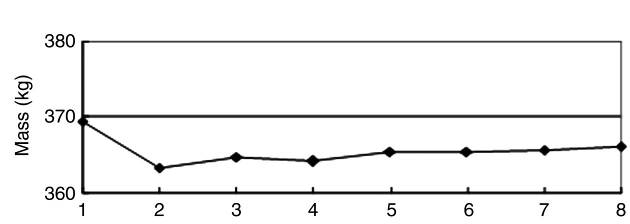

Fig. 5 Iteration history of objective.

VI. Conclusions

This Note has described an application in space frame design of a structural optimization method that combines multipoint approximation and dual methods. Initially, the optimization problem and application technique of the optimization method were illustrated. Next, an example of a typical 2×5 grillage was shown. By comparing the results with other published work and Nastran, the applicability, calculation cost, and quantitative and qualitative characteristics were discussed. Through the presentation of the example and discussion, we conclude that the method is suitable for use in the structural optimization of a space frame. As an example of structural optimization, a frame structure in a satellite platform was optimized. For this problem, a reasonable solution was also obtained. In addition, as the computational cost in terms of the iteration history was evaluated, it was shown that the computational cost for the optimization was less, in which the structural analysis number is lower than 10 even for a complex structure. From these numerical results, it is considered that the method and developed system are suitable for industrial applications.

References

[1] Woo, T. H., "Structural Optimization of Large Spacecraft," AIAA Paper 92-1227, 1992.

[2] Woo, T. H., "Space Frame Optimization Subject to Frequency Constraints," *AIAA Journal*, Vol. 25, No. 10, 1987, pp. 1396–1404. doi:10.2514/3.9795

[3] Vanderplaats, G. N., and Thomas, H. L., "An Improved Approximation for Stress Constraints in Plate Structures," *Structural Optimization*, Vol. 6, No. 1, 1993, pp. 1–6. doi:10.1007/BF01743168

[4] Zhou, M., "An Efficient DCOC Algorithm Based on High-Quality Approximations for Problems Including Eigenvalue Constraints," *Computer Methods in Applied Mechanics and Engineering*, Vol. 128, 1995, pp. 383–394. doi:10.1016/0045-7825(95)00851-9

[5] Kodiyalam, S., Graichen, C. M., Connell, I. J., and Finnigan, P. M."Object-Oriented, Optimization-Based Design of Satellite Structures," *Journal of Spacecraft and Rockets*, Vol. 31, No. 2, 1994, pp. 312–318. doi:10.2514/3.26439

[6] Vidal, C. A., Filho, M. K., Takahashi, W. K., and Desouza, P. N., "Application of Sensitivity Analysis for Optimization of a Satellite Structure," *Journal of Spacecraft and Rockets*, Vol. 37, No. 3, 2000, pp. 416–418. doi:10.2514/2.3576

[7] Silvano, T., "Procedure for Optimization of Truss Space Structures with Fixed Minimum Vibration Frequency," *Journal of Spacecraft and Rockets*, Vol. 46, No. 4, 2009, pp. 892–899. doi:10.2514/1.39353

[8] Schmit, L. A., "Structural Synthesis—Its Genesis and Development," *AIAA Journal*, Vol. 19, No. 10, 1981, pp. 1249–1263. doi:10.2514/3.7859

[9] Vanderplaats, G. N., "Structural Optimization—Past, Present, and Future," *AIAA Journal*, Vol. 20, No. 7, 1982, pp. 992–1000. doi:10.2514/3.51158

[10] Haftka, R. T., and Adelman, H. M., "Recent Developments in Structural Sensitivity Analysis," *Structural Optimization*, Vol. 1, No. 3, 1989, pp. 137–151. doi:10.1007/BF01637334

[11] Rozvany, G. I. N., "A Critical Review of Established Methods of Structural Topology Optimization," *Structural and Multidisciplinary Optimization*, Vol. 37, No. 3, 2009, pp. 217–237. doi:10.1007/s00158-007-0217-0

[12] Thomas, H., Zhou, M., and Schramm, U., "Issues of Commercial Optimization Software Development," *Structural and Multidisciplinary Optimization*, Vol. 23, No. 2, 2002, pp. 97–110. doi:10.1007/s00158-002-0170-x

[13] Chen, S. Y., Huang, H., "Engineering System for Structural Optimization—ESSOSII," *Proceeding of CJK-OSM5*, Jeju Island, ROK, June 2008.

[14] Schmit, L. A., and Farshi, B., "Some Approximation Concepts for Structural Synthesis," *AIAA Journal*, Vol. 12, No. 5, 1974, pp. 692–699. doi:10.2514/3.49321

[15] Vanderplaates, G. N., and Salajegheh, E., "New Approximation Method for Stress Constraints in Structural Synthesis," *AIAA Journal*, Vol. 27, No. 3, 1989, pp. 352–358. doi:10.2514/3.10119

[16] Zhou, M., and Xia, R. W., "Two-Level Approximation Concept in Structural Synthesis," *International Journal for Numerical Methods in Engineering*, Vol. 29, 1990, pp. 1681–1699. doi:10.1002/nme.1620290805

[17] Wang, L., and Grandhi, R. V., "Improved Two-Point Function Approximation for Design Optimization," *AIAA Journal*, Vol. 33, No. 9, 1995, pp. 1720–1727. doi:10.2514/3.12715

[18] Xu, S., and Grandhi, R. V., "Effective Two-Point Function Approximation for Design Optimization," *AIAA Journal*, Vol. 36, No. 12, 1998, pp. 2269–2275. doi:10.2514/2.337

[19] Huang, H., and Xia, R. W., "Two-level Multipoint Constraint Approximation Concept for Structural Optimization," *Structural Optimization*, Vol. 9, No. 1, 1995, pp. 38–45. doi:10.1007/BF01742643

[20] Zhou, Z., Huang, H., and Qu, G., "Multi Structure Cases Optimization of Satellite Composite Material Parts," *Journal of Beijing University of Aeronautics and Astronautics*, Vol. 35, No. 7, 2009, pp. 821–823.

[21] Ren, W., Huang, H., and Chen, S. Y., "Arbitrary Section Beam Optimization in Complex Structure," *Proceeding of Conference on Structural and Multidisciplinary Optimization—Theory and Applications*, Dalian, PRC, Sept. 2009.

[22] Lust, R. V., and Schmit, L. A., "Alternative Approximation Concepts for Space Frame Synthesis," NASA CR-172526, 1995.

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