Structural Analysis and Optimization A Must in Spacecraft Projects

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***Abstract* -** An efficient weight reduction and improved stiffness requirements of a practical spacecraft Trainsat-1 satellite are presented, utilizing abound high efficient method used in MSC. Nastran. Numerical example was also given to test the validity of the software in spacecraft application.

Key words *- spacecraft; structural analysis; structural optimization; sandwich structure.*

I. INTRODUCTION

The need for effective design of satellite structure with minimum weight since the dawn of space exploration in 1957 has been tremendously pursued and some progress has been achieved via the use of structural weight optimization.

The major requirements that must be satisfied in spacecraft structures are strength and stiffness. Some of the functional requirements of the structural subsystem include providing structural stiffness in accordance with dynamic requirements, accommodating all spacecraft components, and supporting the solar array panels, reflectors and antennas. Analysis of spacecraft structures helps to expose the endurance limit of the structure and workmanship deficiency. So, analysis is very important to be undergone. The type of analysis applied depends on the type of structure, geometry, size and loading environment, so, static analysis in which loads are applied gradually to avoid dynamic amplification, acoustic (for structures of light weight and large surface area) and random vibration analysis(for electronic boxes) can all be used to verify strength.[1]

Significant achievement in the field of structural optimization has been made for the past half century, a number of reviews can be seen in [2-4].

Finite element analysis has provide a robust and practical tool for carrying out analysis to find responses like stresses, displacements and frequencies or modes of structures by performing static and modal analysis. In this study modal analysis is carried out on TRAINSAT-1 satellite which is a student satellite used to train Nigeria's engineers during cause of professional study for satellite at Chinese Academy of Space Technology using MSC. Patran/Nastran to obtained an optimal design subjected to frequency and maximum allowable stress constraints. In addition, numerical example using 72-bar truss was tested to establish the conformity of the method to previously published reports found in [3].

II. 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.5, which includes 35,172 nodes and 35,650 elements, with east panel and east antenna removed. Based on the connecting interface between the satellite and launch vehicle, the boundary condition is to fix the bottom of the joint separating ring.

Modal analysis is used to find the natural frequency of the satellite to ensure that the satellite's first lateral and first longitudinal frequency do not march that of the launch vehicle (dynamic interaction between them) in order to avoid resonance. Other usefulness of normal mode analysis are that decisions regarding subsequent dynamic analysis like transient, frequency dynamic analysis, and so on, can be based on the result of normal mode analysis, to compare the physical test result and to evaluate design changes. Modes are inherent properties of a structure, and are determined by the material properties (mass, damping, and stiffness), and boundary conditions of the structure. Each mode is defined by a natural (modal or resonant) frequency, modal damping, and a mode shape (i.e. the so-called "modal parameters"). If either the material properties or the boundary conditions of a structure change, its modes will change. For instance, if mass is added to a structure, it will vibrate differently.

The use of MSC.Nastran software to optimize satellite structures has been in use for over two decades, while some authors used other in-house developed software in conjunction with MSC. Nastran to achieve robust result, among them are references [5-7]

The theoretical detail of modal analysis can be found in a large number of literatures among of which are [8-10]. The required motion equation can be given in matrix form as:

$$([K] - \lambda_i^2[M])\{\Phi_i\} = 0 \quad (1)$$

Where [K], [M], λ_i , Φ_i are stiffness matrix, mass matrix, i-th eigenvalue and mode shape respectively,

This equation is solved numerically by finite element analysis (FEA) to obtain the frequencies

$$\lambda_i = \omega_i = 2\pi f_i \quad (2)$$

Where f_i and ω_i are natural frequency and circular natural frequency for i[th] modal shape which can also be obtained from Rayleigh's equation

$$\omega_i^2 = \frac{\{\Phi_i\}^T[K]\{\Phi_i\}}{\{\Phi_i\}^T[M]\{\Phi_i\}} \quad (3)$$

where the nominator and denominator are generalized stiffness and generalized mass respectively.

III. DESIGN METHODOLOGY

The satellite which was a parallelepiped is 2300mm*2100mm*3600mm and 5080kg in mass is modularized to allow parallel assembly during AIT (assembly, integration and testing) and to enhance easy access for any required modification during the course of production.

Communication module: consist of five panels, earth panel, North and south panels and North/South shear webs as shown in Fig. 1.

Propulsion module: consist of central cylinder, anti-earth panel, internal panels, and east and west webs, see Fig. 2.

Service module: consist of four panels of North/South service panels which accommodate the battery, power control unit, and other equipments see Fig. 3.

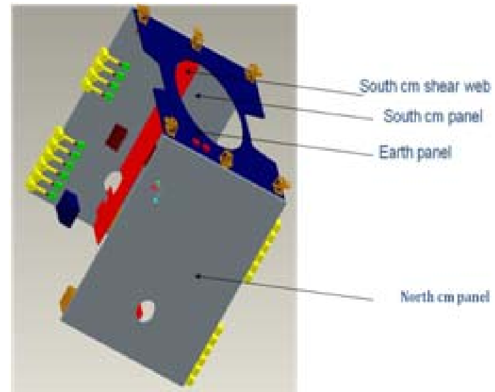

Fig. 1 : Communication Module

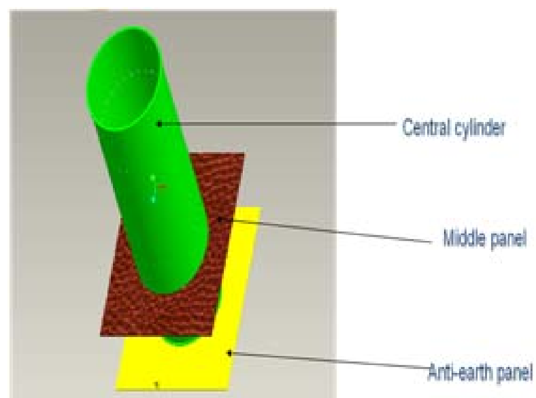

Fig. 2 : Propulsion Module

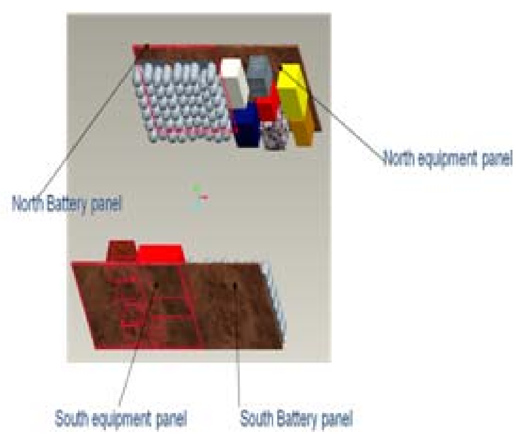

Fig. 3 : Service Module

Access panels: it consist of East/West upper and lower panels which are only assembled after mating of the other modules and can be remove to provide access for modification after complete assembly. All other equipments masses were added as non-structural mass, this is necessary because of the intended optimization with frequency constraint.

Materials: Only the North and south panels including the shear webs were made of Aluminum alloy for both core and the face sheet while the rest panels were of fiber reinforced plastics.

IV. VERIFICATION

Verification goes a long way to bust the engineer's confidence that the design satisfy the requirements and also to expose workmanship, provide better information for modification. Test, analysis, and similarities are some of the verification methods. While test is expensive and time consuming, verification by similarities is cheaper but cannot be used when new processes or methods are used in the manufacturing processes. However, verification by analysis provides a robust opportunity to be confidence on the product designed, can be used to establish test conditions, cheap and pose no danger to the product.

So, from the analysis result shown in table 3 for the initial design one is confident that the TRAINSAT-1 satisfied the stiffness requirements and possible resonance with the launch vehicle will be prevented.

V. OPTIMIZATION OF SPACECRAFT STRUCTURE

In an attempt to reduce the cost of satellite which is directly proportional to its weight , optimization of the structure is eminent since reduction in weight is a direct reduction in cost, subsequently, it cost $21,000 in 2007-08 to lift a kilogram of payload to geostationary orbit according to Frank [11].

In view of these, optimization of the structure was carried out using MSC.Nastran software and the final design obtained after five iterations, however, a numerical example is given to test the validity of the commercial software.

A. *Typical Numerical Example*

The example problem is a 72 member space truss for which results have been previously reported in [12] Figure 3 shows the geometry of the structure and the node as well as member numbering system is illustrated in detail for the uppermost tier. The problem as posed in [12] involves five loading conditions. The symmetry of the structure and the loading conditions are such that the number of load conditions independent design variables can be reduced to 16 using design variables linking. The material properties, stress allowable, and minimum member sizes are given on Fig. 4. The displacements of nodes 1-4 are limited to ± 0.25 in. in the *x* and *y* directions, loading condition are given table 1. Results for this single case are compared with previous work as shown in table 2 and found to be almost the same.

TABLE 1 : LOADING CONDITION FOR 72 TRUSS EXAMPLE

Load Condition	Direction			
	Node	X	Y	Z
1	1	5000	5000	-5000
2	1	0	0	-5000
	2	0	0	-5000
	3	0	0	-5000
	4	0	0	-5000

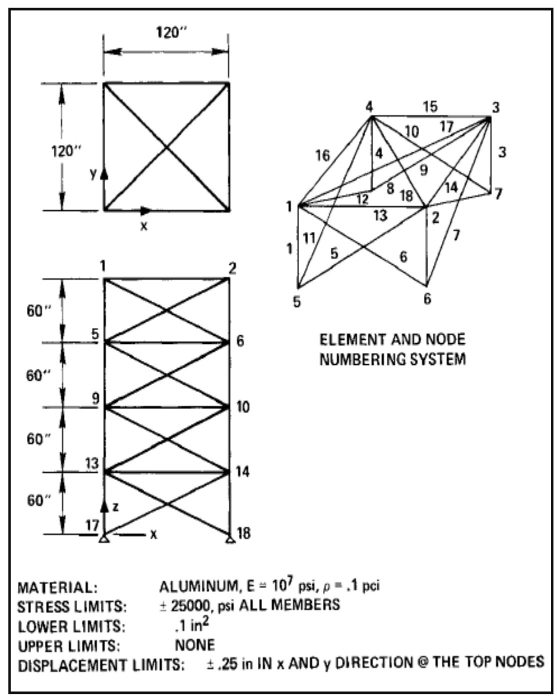

Fig. 4 : Nodal Position and Material Properties of 72 Truss Example

TABLE 2 : FINAL DESIGN FOR 72 TRUSS EXAMPLE

	Final Cross sectional Area (in^2)						
	ACCESS 1[3]					Berke &	
	NEWSUMT	CONMIN	MIT[13]	Venkayya[14]	Gallatly[13]	Knot[13]	Present
1	0.1565	0.1558	0.1585	0.161	0.1492	0.1571	0.157
2	0.5458	0.5484	0.5936	0.557	0.7733	0.5385	0.545
3	0.4105	0.4105	0.3414	0.377	0.4534	0.4156	0.408
4	0.5699	0.5614	0.6076	0.506	0.3417	0.551	0.565
5	0.5233	0.5228	0.2643	0.611	0.5521	0.5082	0.520
6	0.5173	0.5161	0.548	0.532	0.6084	0.5196	0.516
7	0.1	0.1	0.1	0.1	0.1	0.1	0.100
8	0.1	0.1133	0.1509	0.1	0.1	0.1	0.100
9	1.267	1.268	1.1067	1.246	1.0235	1.2793	1.269
10	0.5118	0.5111	0.5792	0.524	0.5421	0.5149	0.511
11	0.1	0.1	0.1	0.1	0.1	0.1	0.100
12	0.1	0.1	0.1	0.1	0.1	0.1	0.100
13	1.885	1.885	2.0784	1.818	1.4636	1.8931	1.877
14	0.5125	0.5118	0.5034	0.524	0.5207	0.5171	0.511
15	0.1	0.1	0.1	0.1	0.1	0.1	0.100
16	0.1	0.1	0.1	0.1	0.1	0	0.100
Final Weight(Ib)	**379.64**	**379.792**	**388.63**	**381.2**	**395.97**	**379.67**	**378.690**
Analysis needed	**9**	**8**	**22**	**12**	**9**	**5**	**6**

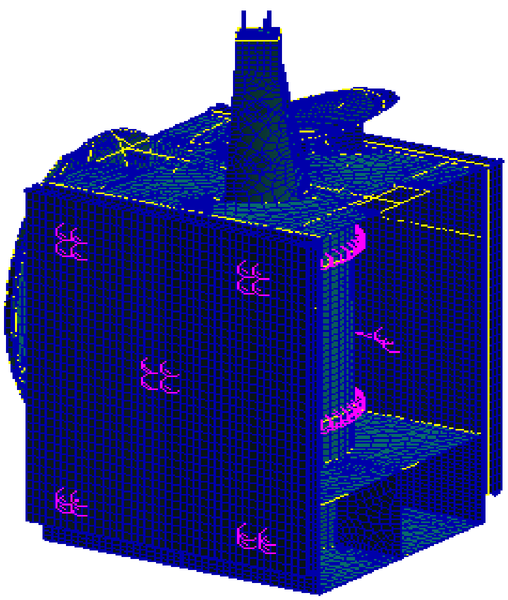

Fig. 5 : TRANSAT-1 Satellite

B. Optimization Procedure

- Establishing the analysis module and perform analysis to obtain the initial design
- Using the above module, enter the optimization parameters like design variables which are the thickness of layers of the sandwich panels, define constraint i.e. the lower band of frequency, ≥12Hz, the minimum lateral bending frequency requirement and 35Hz minimum axial frequency and side constraints on the core height.
- Initiate or run optimization
- Review the resulting design sets data and post process result.

The design optimization problem was to minimize the structural weight subject to constraints on frequency, for panel buckling margins of safety to be positive, and the stress in the trusses not to lead to violation of the Euler buckling allowable. The design models included a total of 28 design variables representing honeycomb core height and face sheet thickness, truss cross sectional dimension and cylinder thickness. The initial design has a structural weight of about 5080Kg with the frequency requirement satisfied.

C. Result and Discussion

TABLE 3 FINAL DESIGN OF TRANSAT-1 SATELLITE

Design Variables	Initial	Result	Design Variables	Initial	Result	Design Variables	Initial	Result
1	1.00E-04	9.99E-05	11	1.00E-04	1.00E-04	21	2.50E-02	1.48E-02
2	1.00E-04	1.00E-04	12	2.02E-02	1.49E-02	22	7.50E-05	7.50E-05
3	2.02E-02	1.00E-02	13	1.00E-04	7.11E-05	23	7.50E-05	7.50E-05
4	2.25E-04	2.25E-04	14	1.00E-04	9.96E-05	24	2.02E-02	2.02E-02
5	2.25E-04	2.25E-04	15	2.50E-02	1.88E-02	25	1.00E-02	5.43E-03
6	1.00E-02	1.00E-02	16	1.25E-04	1.22E-04	26	1.00E-02	9.89E-03
7	1.00E-04	1.00E-04	17	1.25E-04	1.22E-04	27	2.00E-03	1.99E-03
8	1.00E-04	7.10E-05	18	2.02E-02	1.89E-02	28	2.00E-03	1.72E-03
9	2.02E-02	1.86E-02	19	7.50E-05	7.50E-05			
10	1.00E-04	1.00E-04	20	7.50E-05	7.50E-05			

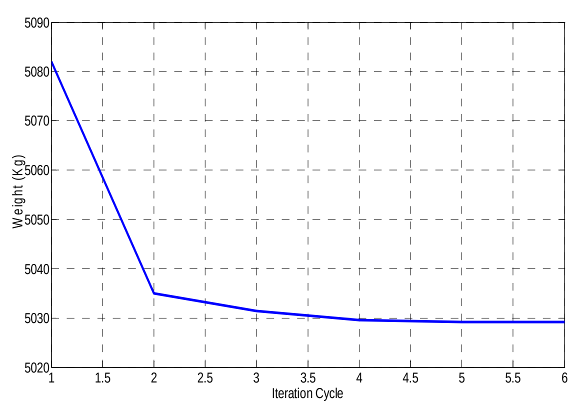

Fig. 6 : Iteration History of TRANSAT-1 Satellite

TABLE 4 : SUMMARY OF TRAINSAT-1 OPTIMUM DESIGN

Objective/constraints	Initial Result	Optimization Result
Mass change, kg	5082.02	5029.10
The first-order frequency, Hz X-direction	**14.94**	16.41
The first-order frequency, Hz Y-direction	**14.83**	17.85
The first-order longitudinal frequency, Hz	**70.87**	67.73
The first-order torsion frequency, Hz	28.93	34.73

From table 3, 4 and fig. 6 above reduction of about 53kg was evident which can be used to carry more valid payload or increase the fuel so as to increase the lifespan of the satellite while the stiffness requirements are adequately satisfied even after optimization. The lateral frequencies both on X and Y direction increases to 16.41 and 17.85 Hz respectively while central cylinder and shear webs remain unchanged.

VI. CONCLUSION

The application of MSC.Nastran software in spacecraft analysis and optimization was established. The comparison given in table 2 shows the present study's agreement with previous published work. So the stiffness requirements were met and industrial application is advised.

We can see from these analysis and optimization procedure that a mass of 53Kg was saved, making the satellite lighter and saves money as more fuel can be accommodated to increase the lifespan of the system thereby increasing the income from the mission, so, this procedure is inevitable in spacecraft design.

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