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Effect of residual modes on dynamically condensed spacecraft structure

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Abstract - *In the present work, an attempt has been made to study the impact of residual modes on fundamental frequencies of condensed spacecraft structure. Finite element model of a spacecraft bus consists of many degrees of freedom, and it is a tedious task to determine the modal frequencies at each and every node. The spacecraft bus is modeled in Msc Patran and it is made up of laminate composites. As a part of dynamic analysis, condensing the spacecraft structure is an essential step where the condensed element behaves like the complete structure in dynamic environment. While condensing the structure, higher frequency modes will be lost which directly affects the dynamic solution. As a necessary step of retaining the lost data, modal augmentation techniques will be employed. In this work, residual modes are retained to trace their impact on data recovery.*

***Key Words*: Craig Bampton method, Dynamic condensation, Modal augmentation techniques, Residual modes, Normal mode analysis, Honeycomb structure**

1. INTRODUCTION

Design and analysis of structures for space missions are too sensitive as space is very much intolerant to minute discrepancies. The structural design is a formidable challenge to design community due to contradictory requirements of low mass and high reliability. These challenges can be met by using sandwich honeycomb structures, stiffened structures etc. Thus these advancements in space missions have lead manufacturing industry to develop advanced composites which are most promising and suitable for industry. The dynamic environment of spacecraft is generally used to describe the level of the excitation on the spacecraft itself and the auxiliary equipment [1]. Therefore, the dynamic environment of spacecraft is a criterion for the structural dynamic design as well as the ground verification test, the reliability assessment of the spacecraft themselves and the auxiliary equipment. However, two major problems are suffered in the prediction process: one is the high time consumption for solving the high-dimensional dynamic equations due to the huge amount of degrees of freedom; the other is the structural dynamic models of different components of spacecraft are usually obtained through different approaches, such as analytical expressions, numerical simulations and modal testing. The dynamic environments of spacecraft are usually classified into the low frequency, the mid-frequency and high frequency, or the deterministic and the random. The present work is concerned to low frequency environment [2]. The FEM is most promising for the low frequency dynamic problem. However, the finite element modeling of complex industrial structures results in the huge amount of DOFs. Moreover, many details of such large models can be neglected when it is just essential to obtain the individual characteristics of the entire model. Thus, it is important to reduce the size of the system for mainly four reasons: the very time consuming for solving the complex dynamic equations, the optimization of the dynamic model, model updating and obtaining the different components of the spacecraft from different approaches. For these reasons, the component mode synthesis (CMS) has been developed for forty years and used extensively in the dynamic analysis of complex structures. The Craig Bampton method is used in this work as a dynamic reduction technique. According to the boundary conditions applied to the substructure interfaces when the normal modes are obtained, the CMS methods can be classified into four groups [3]: fixed interface methods [4, 5], free interface methods [6], hybrid interface methods [7] and loaded interface methods [8]. The differences of four groups are defined by varying the choice of the reduced basis, the generalized coordinates and the coupling procedure. Fixed interface method is preferred in this work. This paper presents determining the normal modes of condensed and uncondensed structure, and residual vector method of data recovery as a modal augmentation technique to recover the data lost during the structural condensation. This paper is organized as follows. Firstly, the dynamic environment of spacecraft and its general prediction process are introduced, as well as the review of the CMS method. Section 2 discusses method for determining the normal modes and residual vectors and constructing a superelement. In Section 3, normal modes of spacecraft bus without data recovery and with residual modes are presented and discussed. Finally, conclusions are drawn in section 5.

2. METHODOLOGY

Geometrical modeling of the structure would be according to the spacecraft standards preferred in the previous spacecraft structural systems. The model of spacecraft structure consists of cylinder, shear webs, top deck, bottom deck, east deck, west deck, north deck, south deck, interface ring and subsystems. Hybrid meshing (fine mesh) is the meshing methodology followed to mesh the structure. A rigid body is linked to the mid node of the outer edge of interface ring from all the bottom edge nodes of interface ring as shown in the fig. Modeling tank 1 and tank 2 simulations would be a necessary step to represent the fuel and oxidizer tank carriers. As a necessary step of testing the accuracy and compatibility of the model, structure will be examined for duplicate elements, duplicate nodes and free edges [9]. The materials used in modeling are carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP), low density aluminum as a core material [10]. Laminate type of composites is used and the core of the composite is honeycomb structure. The first step in structural analysis (dynamic) of spacecraft bus is to find the normal modes of the structure. Determining the normal modes of any structure is an important and first step of performing dynamic analysis as a reason being to assess the dynamic interaction between a component and its supporting structure [11]. In this work, Msc Patran and Msc Nastran are used as the modeling and analysis tools. SOL 101 represents normal mode analysis in Msc Patran. As a part of condensing the structure to a superelement, AUTOSPC =1, EXTSEOUT (ASMBULK EXTID=100 DMIGPCH) cards are inserted in bulk data section of a Nastran input file [12].

2.1 Craig-Bampton Method

Rubin S. et.al [13] represented the improved methods of component mode synthesis which is most commonly used in every domain of dynamic analysis. As a first step of condensing, the matrices are partitioned as per the general convention. K and M are the stiffness and mass matrices of the structure. The Craig-Bampton transformation matrix of the structure helps to transform the structure into mathematical form and is computing using eq.1. The reduced stiffness and mass matrices are determined using eq.2 and eq.3.

$$K = \begin{bmatrix} K_{AA} & K_{AD} \\ K_{DA} & K_{DD} \end{bmatrix} \qquad M = \begin{bmatrix} M_{AA} & M_{AD} \\ M_{DA} & M_{DD} \end{bmatrix}$$

Where,

K_{AA} – Retained degrees of freedom M_{AA} - Retained degrees of freedom

K_{DD} – Omitted degrees of freedom M_{DD} - Omitted degrees of freedom

The Craig – Bampton transformation matrix is,

$$T_s = \begin{bmatrix} I & 0 \\ \Phi_{CN} & \Phi_{NN} \end{bmatrix} \longrightarrow 1)$$

Where $\Phi_{CN} = -1*(K_{AA})^{-1}*(K_{AD}) \longrightarrow 2)$

Φ_{NN} – Mass normalized matrix

I – Identity matrix

$K_r = [T_s]' [K] [T_s] \longrightarrow 3)$

$M_r = [T_s]' [M] [T_s] \longrightarrow 4)$

2.2 Residual modes

The residual flexibility vector of ψ_i are static solutions to unit loading at the force input point and improve the accuracy of static contribution in the mode displacement method (MDM). R.R Craig [14] et.al considered residual attachment modes in substructure coupling as a part of dynamic analysis and highlighted the enhancement of accuracy. It is an efficient method since the data recovery procedure is equivalent to the MDM once a few static problems are solved. Rose et.al [15] proposed a method to find the static part of the dynamic loads as given below. Residual vectors are computed in Msc Nastran by inserting RESVEC=YES command in case control section [16].

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$[F] = [\{F_1\},\{F_2\},\ldots\ldots]$ is written as

$$[K][x_{res}] = [F] \longrightarrow 5)$$

The vector $[x_{res}]$ will be made orthogonal with respect to the modal base $[\phi]$ .The new modal base $[\psi]$ consists of

$$[\psi] = ([\phi],[x_{res}]) \longrightarrow 6)$$

$$[\hat{K}]\{\gamma\} = \langle\lambda\rangle[\hat{M}]\{\gamma\} \longrightarrow 7)$$

With

$$[\hat{K}] = [\psi]^T [K][\psi] \longrightarrow 8)$$

$$[\hat{M}] = [\psi]^T [M][\psi] \longrightarrow 9)$$

The solution of the Eigen value problem of Eq will result in the original modes, plus new (high-frequency) pseudo modes. The new modal base becomes,

$$[x] = [\psi]\{\gamma\} \longrightarrow 10)$$

The physical displacement vector {x (t)} is expressed as follows

$$\{x(t)\} = [x]\{\eta(t)\} \longrightarrow 11)$$

Where

$\hat{K}$, $\hat{M}$ - structural matrices in modal coordinates.
x_{res} – Displacement vector based on residual load vector.
$[\psi]$ - New modal base

3. RESULTS AND DISCUSSION

The modeled structure of a spacecraft bus is as shown in the figure 1. The finite element data of the model is given in the table 1. The cylinder layup was bounded by east deck, north deck, south deck, west deck, top deck and bottom deck and linked through shear panels. The bottom deck of the structure was linked to the interface ring, through which the satellite gets separated from its lower stage. The subsystems are attached to the east and west decks of the spacecraft. The model consists of RBE, BAR2, QUAD4 and TRIA3 elements. The properties of the composites used in modeling are given in table 2.

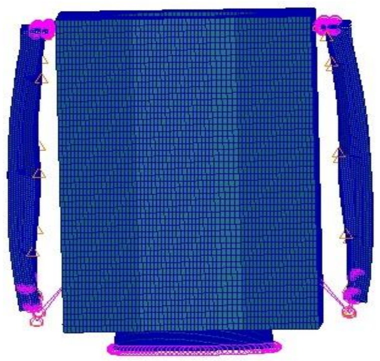

Fig -1: Spacecraft structural system

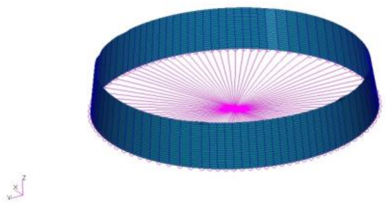

Fig -2: Interface ring with rigid link.

2.1 Finite element data

Table -1: Shows the finite element data of the model

Types of elements	Number of elements
Bar elements (Bar2)	180
Shell elements (QUAD4)	70038
Bush elements (CBUSH)	8
Triangular elements (TRIA3)	458
Rigid body elements (RBE2)	33
Total number of elements in the finite element model	70717

Table -2: Shows the properties of aluminium honeycomb core of the model

Property	Value	Unit
Young's Modulus	1.00E+4	N/m^2
In plane Shear Modulus	1.00E+4	N/m^2
Poisson's ratio	0.3	---
Mass Density	72	kg/m^3
Shear modulus G_{13}	3.7E+8	N/m^2
Shear modulus G_{23}	3.7E+8	N/m^2

Table -3: Shows the mass of individual components of the spacecraft structural system

Components	Mass	Unit
Top and bottom decks	55 each	Kg
Cylinder	30.39	Kg
Tank1	940	Kg
Tank2	890	Kg
Interface ring	6	Kg
Face sheet	Al density	kg/m^3
Total mass	1993.8635	Kg

3.1 Normal modes of the structure

The normal mode analysis in Msc Nastran will be done without inserting residual vector card. Residual vector card is inserted in case control section to compute the residual modes in f06 file (Output file of Msc Nastran). The structure is further condensed as per the preliminary objective of the work. Craig-Bampton method (CMS method) is used as the dynamic condensation technique. Residual vectors of condensed model are computed. This work is restricted to 10 modes. The table below shows the modal frequencies of the complete model and the condensed model.

Table -3: Shows the fundamental frequencies of the complete model and super element including residual frequencies

Sl No	Frequency of the complete model in Hz	Frequency of the condensed model in Hz
1	21.53488	21.53488
2	21.60565	21.60565
3	22.88971	22.88971
4	23.79123	23.79123
5	32.76614	32.76614
6	33.08495	33.08495
7	33.66083	33.66083
8	34.06837	34.06837
9	65.82056	65.82056
10	66.49674	66.49674
11	77.06128	77.06128
12	82.22667	82.22690
13	93.47472	93.47480
14	102.058	102.0580
15	160.1069	160.1070
16	177.5703	177.5780

The modal frequencies given in the table 3 are obtained from the f06 file of the Nastran output. During the truncation of modes, higher frequency modes will be lost and thus it affects the dynamic solution directly. In order to retain the impact of lost modes, the residual modes are computed which enhances the solution. The structural system is condensed to a superelement. Further, residual modes are involved in the dynamic analysis. The residual frequencies obtained for a complete structure and a superelement are almost same. This means, Craig-Bampton method is an efficient method for dynamic condensation of spacecraft structural system and involving the residual frequencies in the analysis spectrum improves the solution. The figures shown below are the structural deformations for mode 1 (without residual vectors) and mode 16 (with residual vectors). The structural deformation shown in fig 4 is obtained at 177.57 Hz which is a residual modal frequency computed in Msc Nastran.

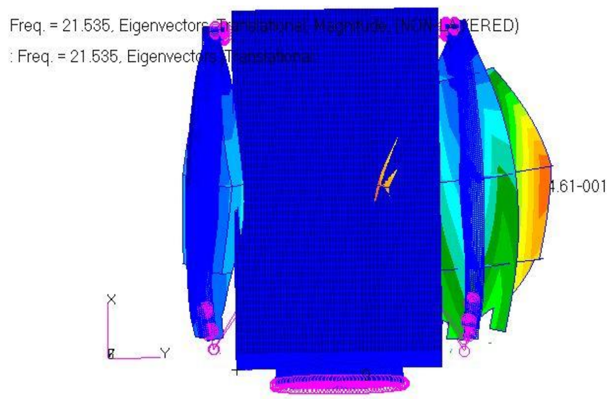

Fig -3: Deformed structure at 21.535 Hz

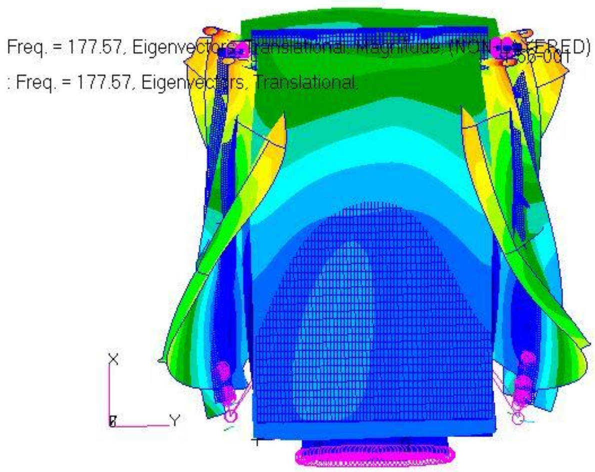

Fig -4: Deformed structure at 177.57 Hz

4. CONCLUSIONS

Dynamic condensation is the most effective method of condensing a spacecraft structure into a superelement. Component mode synthesis (Craig-Bampton method) is adapted in the present case as a dynamic condensation technique. As a step of enhancing the accuracy of dynamic solution, modal augmentation methods are preferred in which residual modes are adapted in this case. The residual vectors play an important role in improving the data lost during the structural condensation. The residual vectors computed for a superelement are almost same as that of the complete model, which means, the mathematical behavior of a superelement is much similar to that of the complete model.

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