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Flexible Multibody Modeling for Dynamic Analysis Using Craig-Bampton CMS Method

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Abstract: **This thesis presents the flexible multibody model development of the simplified wing-pylon structure using the Craig-Bampton approach. Since the Craig-Bampton method of Component Mode Synthesis is used, the component finite element models are developed separately without inclusion of the local joint details. This approach is used to reduce the substantial amount of modeling effort required to build the detailed finite element model, and the corresponding finite element problem size. The modal analysis of the flexible multibody model has been done and the effects of selection of different sets of fixed interface normal modes and of different cut off frequencies on natural frequencies of the pylon structure are shown. The modal analysis results of the flexible multibody model i.e. natural frequencies and the mode shapes are found to be consistent with those obtained using previously developed detailed FE model and the experimental modal model. The simplified flexible multibody modeling approach suggested in this thesis can be used to model the complex missile systems in order to reduce the modeling as well as the computational effort.**

Keywords: **Component Mode Synthesis, LMS, Nastran, Modal Analysis, Multibody Dynamics.**

1. INTRODUCTION

Computer aided kinematic and dynamic simulation has become an important tool to predict the kinematic and dynamic behavior of all types of multibody systems in their design stages. With the advent of digital computers it is possible to effectively simulate the large, complex systems with more accurate mathematical models which account for the flexibility of the system components. It has been observed in the testing of missile systems that the launching sequence of the missile puts a significant amount of load on the helicopter pylon structures. Since there is enough flexibility present in these pylon structures, it affects the missile trajectory. Multibody systems it is possible to develop the models with various missile and launcher types and configurations, and study their dynamic behavior under different loading conditions. C. B. Birdsong developed a methodology for the development and validation of flexible multibody dynamic models using a simplified pylon structure representing.

A detailed finite element (FE) model was developed and validated using theoretical and experimental modal test data. The flexibility in the model was represented by the modal data obtained from detailed FE model. Generally, it takes a significant modeling effort to create the detailed FE model of an entire pylon structure, especially modeling of the joints. However, for flexible body simulation, these model details are not required. So other possible ways to obtain the modal data without creating the complex FE model are explored. For this purpose, the Craig-Bampton approach of component mode synthesis can be used to obtain the complete structure modal data. With this approach the modal data can be obtained from the simplified FE models of each component separately, which will be of reduced sizes. Moreover, the joint details are not required to be incorporated in the FE model because static constraint modes in the Craig-Bampton mode set will account for dynamic behavior of the structure at the joint locations. The methodology developed for the simplified pylon structure can be extended to more complex models of missile systems in order to increase their computational efficiency.

2. LITERATURE SURVEY

In most of the work described so far the deformation modes, which may include normal vibration modes, constraint modes, attachment modes, or combination of these modes, are obtained from a detailed FE model of the multibody system. These detailed FE models are validated using experimental modal tests. It requires a significant modeling effort to build such complex models, especially during creation of the FE mesh with local joint details. Moreover, the set-up for experimental modal testing becomes a more time consuming process, as it must always be correlated with the detailed FE model. In general, it becomes a long and tedious process to build these complex FE models and validate them using experimental modal test data. Some of the major problems associated with meshing of detailed FE model and its translation from one software to another are addressed in the U.S. Army HMT trailer project report where flexible multibody dynamics is used for fatigue durability analysis of a U.S. Army trailer.

Birdsong has presented a detailed process of validation, correlation and updating detailed FE models used for flexible multibody modeling of a pylon structure. It is seen that at a certain stage of modeling it becomes very difficult to update the detailed FE model based on the results of the experimental modal test. The effort required at various stages of modeling and the uncertainties associated therewith are highlighted. Recently, Tracy Van Zandt has presented the development of efficient reduced models from a detailed FE model of a pylon structure. These reduced models, which can be easily updated from the experimental modal test data, are used for dynamic simulation of a pylon structure.

In this thesis, an effort is made to build a flexible multibody model of a pylon structure without developing a highly detailed FE model. For this purpose, a Craig-Bampton approach (CMS method) is used along with simplified FE models of each component to develop the model. Using this approach, reduction of the modeling effort as well as the computational load will be presented without significant loss in accuracy of the results.

3. NUMERICAL APPROACH

In general, a multibody system can be decomposed into a series of bodies, joints, constraints and force elements. The bodies can be either rigid or flexible. In the rigid multibody model the bodies are assumed to be rigid i.e. the distance between any two points on body remains constant. The flexible bodies are created from a combination of a rigid body model and a collection of deformation modes which are superimposed on the rigid body motion to form the flexible multibody model.

As the structure becomes larger and more complicated, more complex FE models of large size are required to represent their response. The number of DoF needed to represent a complex structure is reduced using CMS in order to reduce the effort and complexity of the model. Among the various CMS techniques, the *Craig-Bampton Method* is the most straightforward and also one of the most widely used techniques. This method of CMS consists of reducing a FE model into a set of generalized mass and stiffness matrices of the components which can be connected to physical interface points. This approach provides reduced problem size and ease of use as it allows multiple configurations of the components. Moreover, for very large and complex structures, the component FE models can be developed by different engineering groups or at different times which can be coupled together using Craig-Bampton method.

The equation of motion ignoring with damping is given by:

$$[M_{AA}]\{\ddot{u}_A\}+[K_{AA}]\{u_A\}=\{F(t)\}$$

m = Bounday mass matrix, k= Interface stiffness matrix

3.1 PARTICULATE PHASE:

3.1.1 The Craig-Bampton Approach:

As the structure becomes larger and more complicated, more complex FE models of large size are required to represent their response. The number of DoF needed to represent a complex structure is reduced using CMS in order to reduce the effort and complexity of the model. Among the various CMS techniques, the *Craig-Bampton Method* is the most straightforward and also one of the most widely used techniques. This method of CMS consists of reducing a FE model into a set of generalized mass and stiffness matrices of the components which can be connected to physical interface points. This approach provides reduced problem size and ease of use as it allows multiple configurations of the components. Moreover, for very large and complex structures, the component FE models can be developed by different engineering groups or at different times which can be coupled together using Craig-Bampton method.

The Dynamic Equation of Motion (Including Damping) Using the C-B Transform is given as:

$$\begin{bmatrix} M_{bb} & M_{bq} \\ M_{qb} & I \end{bmatrix} \begin{Bmatrix} \ddot{u}_b \\ \ddot{q} \end{Bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 2\zeta\omega \end{bmatrix} \begin{Bmatrix} \dot{u}_b \\ \dot{q} \end{Bmatrix} + \begin{bmatrix} K_{bb} & 0 \\ 0 & \omega^2 \end{bmatrix} \begin{Bmatrix} u_b \\ q \end{Bmatrix} = \begin{Bmatrix} F_b \\ 0 \end{Bmatrix}$$

Where $2\zeta\omega$ = Modal damping (ζ=%critical), M = Boundary mass matrix, K= Interface stiffness matrix.

4. PROBLEM DESCRIPTION

4.1 PROBLEM STATEMENT:

The body of this work includes the development of a simplified flexible multibody dynamic model of the pylon structure. This involves development of the CAD model, development of the rigid multibody model, development of FE model of each component and development of Craig-Bampton mode set for each component from its FE model. The process of developing the flexible body model and its simulation will be done using various commercial software packages.

The modal analysis of the flexible multibody model has been done and the effects of selection of different sets of fixed interface normal modes and of different cut off frequencies on natural frequencies of the pylon structure are shown. The scope of this project is limited to obtaining the natural frequencies and corresponding mode shapes of the pylon structure.

4.2 GEOMETRIC MODELING:

The model used in this investigatio n is a simplified structure representing a helicopter wing pylon with two missiles, as shown in Figure 4.1. The structure is made up of four plates bolted together using structural angles at the joints and two round bars to represent the missiles.

The base plate is bolted to the ground as shown in Figure 4.1. The physical wing, represented by the cantilevered horizontal plate, attaches to the fuselage, represented by the vertical plate, with four bolts and two alignment pins. The missile rack attaches to the wing using four bolts and two alignment pins. The two iron rods which represent missile. The angle irons are used to form a bracket joint between adjacent plates.The simplified structure helps in validating the vibration analysis using analytical expressions as well as the experimental modal testing. The development of the flexible multibody model using Craig-Bampton method can be clearly understood with the use of the simplified structure and this approach can be extended to more complicated helicopter pylon and missile structure.

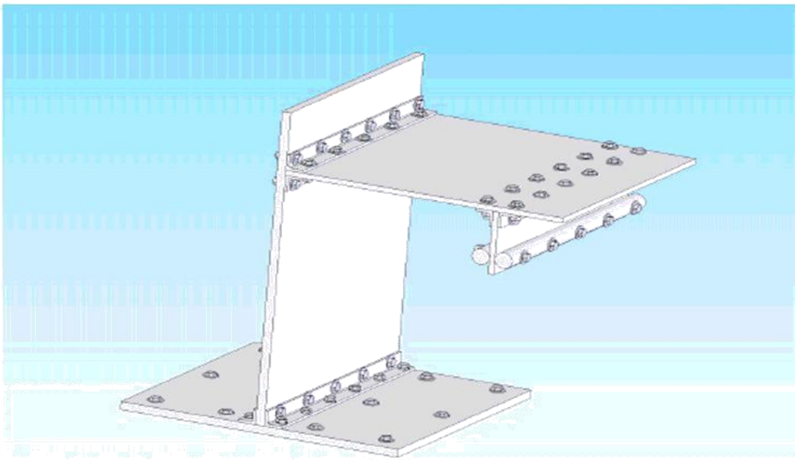

Figure 4.1: Simplified Pylon Fixture

4.2 Modal Analysis using Detailed FE Model:

A detailed finite element model of the simplified pylon structure using Patran/Nastran has already been developed by Brock Birdsong. A screen capture of the FE model is shown in Figure 4.2.

The finite element model is made up of 0 DoF mass elements, 1 DoF beam elements, 1 DoF bushing elements, and 2 DoFs shell elements. The model contains a total of around 135,000 DoFs. The finite element model is an approximation of the physical structure; however to increase its accuracy, the bracket joints are modeled with great detail. To represent the bolt assembly, Multi-Point Constraint (MPC) elements are used.

The modal analysis of this FE model was done using Nastran. The eigenvalues and the natural frequencies of the first few normal modes obtained with the base plate fixed to the ground are given in Table 4.1.

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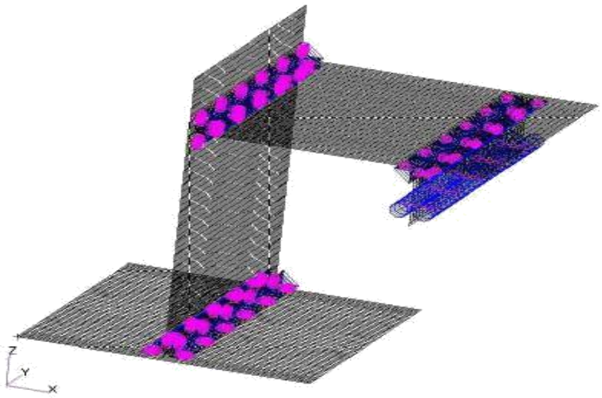
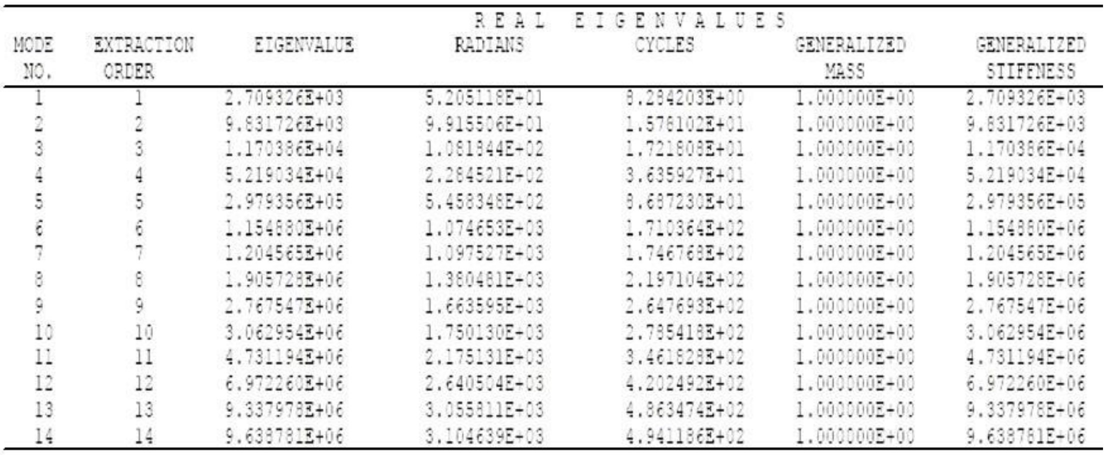


Figure 4.2: A Highly Detailed FE Model of Pylon Assembly

Table 4.1: The eigenvalues and the natural frequencies of the first few normal modes obtained with the base plate fixed



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                                            R E A L   E I G E N V A L U E S
 MODE    EXTRACTION       EIGENVALUE            RADIANS             CYCLES            GENERALIZED         GENERALIZED
  NO.       ORDER                                                                        MASS              STIFFNESS
   1          1        2.709326E+03        5.205118E+01        8.284203E+00        1.000000E+00        2.709326E+03
   2          2        9.831726E+03        9.915506E+01        1.578102E+01        1.000000E+00        9.831726E+03
   3          3        1.170386E+04        1.081844E+02        1.721808E+01        1.000000E+00        1.170386E+04
   4          4        5.219034E+04        2.284521E+02        3.635927E+01        1.000000E+00        5.219034E+04
   5          5        2.979356E+05        5.458348E+02        8.687230E+01        1.000000E+00        2.979356E+05
   6          6        1.154880E+06        1.074653E+03        1.710364E+02        1.000000E+00        1.154880E+06
   7          7        1.204565E+06        1.097527E+03        1.746768E+02        1.000000E+00        1.204565E+06
   8          8        1.905728E+06        1.380481E+03        2.197104E+02        1.000000E+00        1.905728E+06
   9          9        2.767547E+06        1.663595E+03        2.647693E+02        1.000000E+00        2.767547E+06
  10         10        3.062954E+06        1.750130E+03        2.785418E+02        1.000000E+00        3.062954E+06
  11         11        4.731194E+06        2.175131E+03        3.461828E+02        1.000000E+00        4.731194E+06
  12         12        6.972260E+06        2.640504E+03        4.202492E+02        1.000000E+00        6.972260E+06
  13         13        9.337978E+06        3.055811E+03        4.863474E+02        1.000000E+00        9.337978E+06
  14         14        9.638781E+06        3.104639E+03        4.941186E+02        1.000000E+00        9.638781E+06
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4.3 Modal Analysis Using Experimental Modal Test:

Experimental modal analysis provides a means to use measured data to characterize the dynamic response of very complex structures. Generally, experimental modal tests are performed to correlate and update complex finite element models. The physical model is tested under controlled conditions but the test-correlated model can be used to predict dynamic behavior of the model in different operating environments.

LMS Test Lab software was used to analyze the test results. A pretest analysis was done to determine the minimal sensor locations and optimum driving point locations. The details of this method are not included in this work. Figure 4.3 shows the experimental modal model. The results of experimental modal analysis are given in Table 4.2.

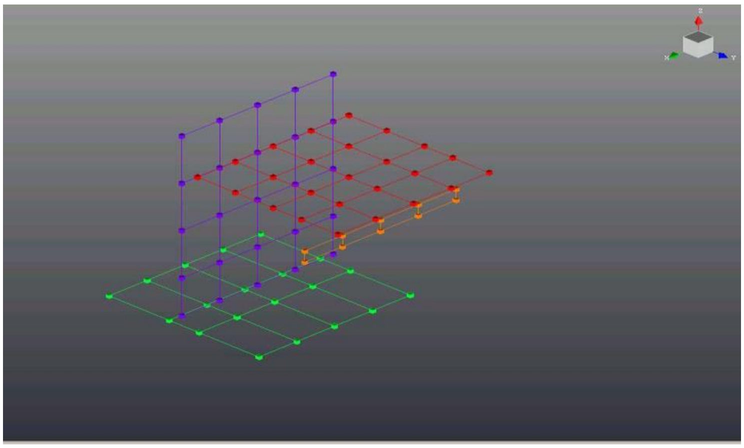

Figure 4.3: Experimental Model

Table 4.2: Experimental vs. detailed FE Model natural frequencies

Mode No.	**Frequencies (Hz)**	
	Experimental Modal Test	**Detailed FE Model**
1	8.66	8.28
2	17.08	15.78
3	17.33	17.22
4	38.69	36.36
5	91.83	86.87
6	135.88	171.03
7	178.22	174.67
8	190.67	219.71

4.4 Modal Analysis of FE model using CMS technique:

The flexible dynamics simulation requires vibration modal data. This consists of both the fixed interface normal modes and the static constrained modes associated with the components. The FE model is developed and vibration analysis is performed to solve for the normal mode. Since CMS technique is used to develop flexible multibody model of pylon structure, the FE model of each component is developed separately. This approach simplifies the procedure of FE modeling, as the local joints are not required to be modeled.

4.4.1 FE Model of the Vertical Plate: The finite element model of the vertical plate is shown in Figure 4.4.1. The elements used are CQUAD4 (quadrangular) shell type elements in the Nastran designation.

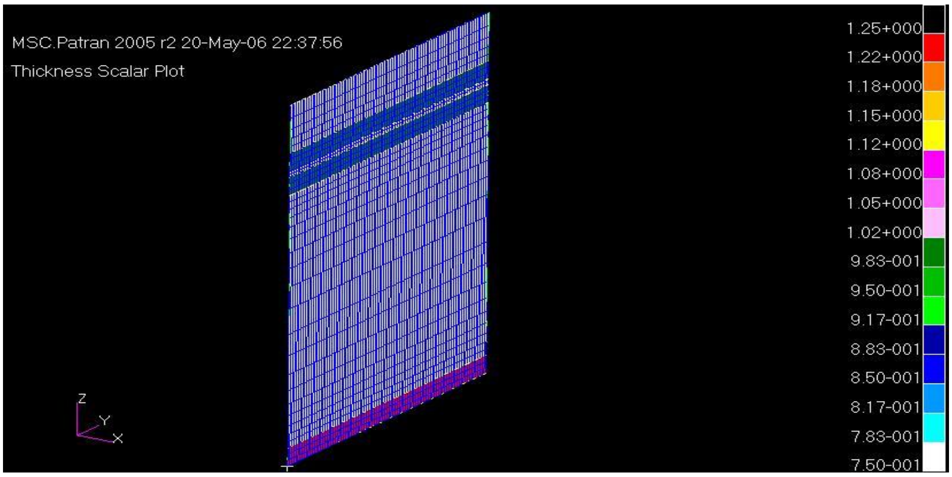

Figure 4.4.1: FE Model of the Vertical Plate

4.4.2 FE model of the wing plate:

The finite element model of the wing plate is shown in Figure 4.4.2. The elements used are CQUAD4 shell type elements.

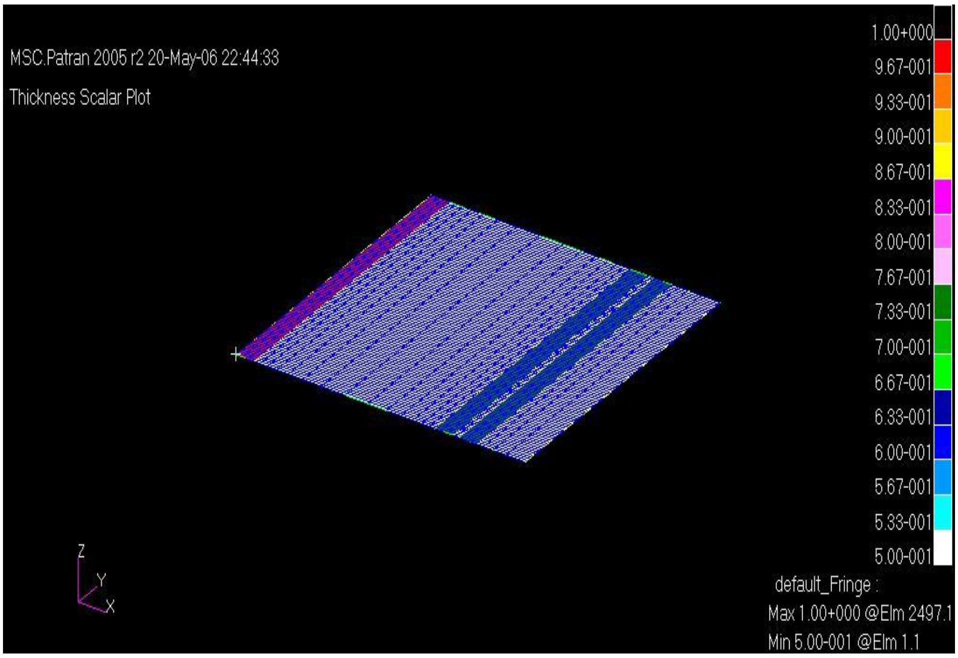

Figure 4.4.2: FE Model of the Wing Plate

4.4.3 FE Model of the missile rack:

The finite element model of the missile rack is shown in Figure 4.4.3. The plate is modeled using CQUAD4 shell type elements. The missile rods (steel rods) are modeled using CBAR2 beam type elements. The steel rods are bolted to the Aluminum plate. The mass of the bolt assembly is represented using point mass elements (CONM2).

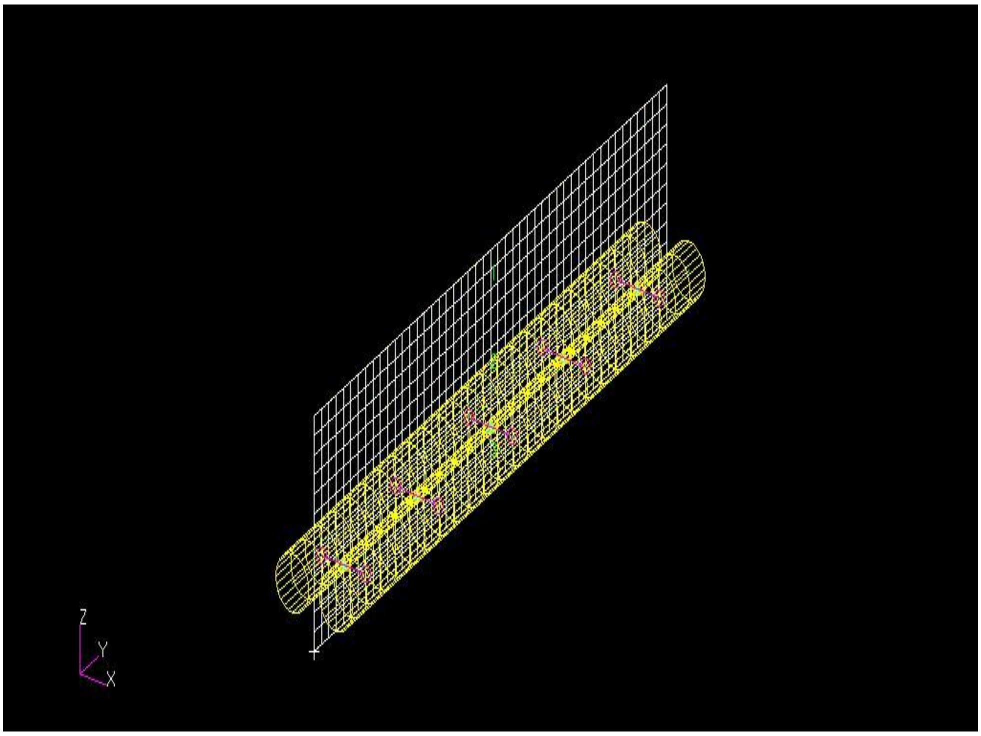

Figure 4.4.3: FE Model of the Missile Rack

Table 4.3: Normal Modes of each component

Mode No.	Frequencies (Hz)		
	Vertical Plate	Wing Plate	Missile Rack
1	21.9	23.3	153.1
2	105.5	85.9	253.2
3	156.0	174.2	576.3
4	295.1	272.4	1050.7
5	365.1	301.1	1065.4
6	454.5	492.0	1227.3
7	579.7	534.6	1406.5
8	594.5	574.5	1412.6
9	880.9	668.9	1509.2
10	884.1	780.2	1799.2
11	935.1	875.6	1998.1
12	967.0	896.8	2094.3
13	1089.8	941.3	2277.8
14	1103.1	1139.4	2490.2
15	1209.4	1140.7	2566.0
16	1309.1	1233.4	2760.2
17	1395.1	1243.7	2801.2
18	1522.7	1297.8	3015.0
19	1622.4	1301.1	3051.7
20	1622.5	1380.0	3057.3

4.5 Development of the Flexible Multibody Model:

The flexible body model is developed by combining the rigid model and the FE model. The CAE interface of VL allows the direct translation of FE model from Patran into VL environment. The translation should be done in a way such that the FE mesh matches with the rigid body geometry and the interface points at the joint location should be coincident with the node points of the FE mesh.

The next step of flexible body modeling is the inclusion of the modal data associated with the FE models. The Craig-Bampton mode set for each component which includes a truncated set of fixed interface normal modes and static constraint modes can be obtained directly in VL, using ‘Nastran Analysis Driver’.

The Flexible Multibody Model in Figure 4.5

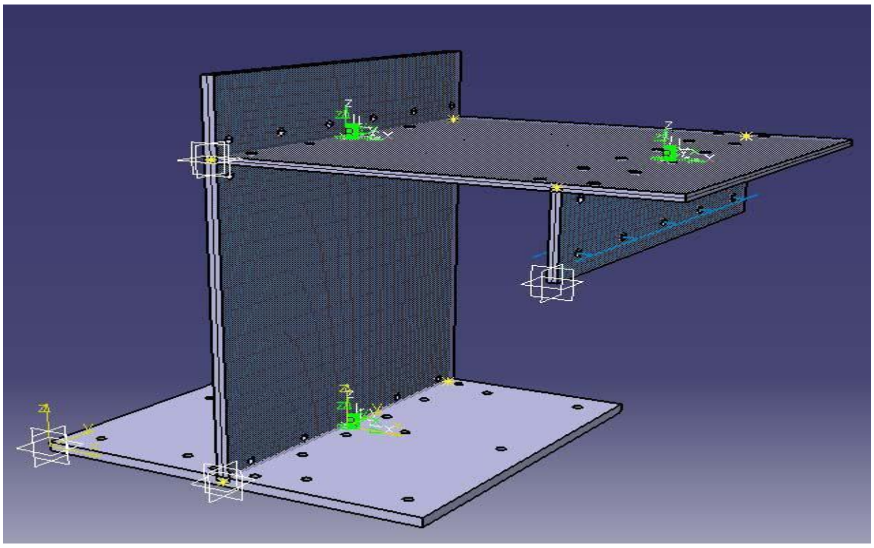

Figure 4.5: Flexible Multibody Model

5. RESULTS AND DISCUSSION

The results of modal analysis of the pylon structure using these various modeling. The natural frequencies of different models of the pylon structure are shown in Table 5.1, and the graphical representation of these frequencies is shown in Figure 5.1

Table 5.1: The natural frequencies of the pylon structure using different approaches

Mode No.	Natural frequencies of the pylon structure (Hz)		
	Detailed FE Model [1]	Flexible body model (VL model)	Experimental Modal Test (Exp. Model) [1]
1	8.28	8.77	8.66
2	15.78	15.54	17.08
3	17.22	17.44	17.33
4	36.36	32.83	38.69
5	86.87	94.66	91.83
6	171.03	125.2	135.88
7	174.67	166.0	178.22
8	219.71	170.2	190.67

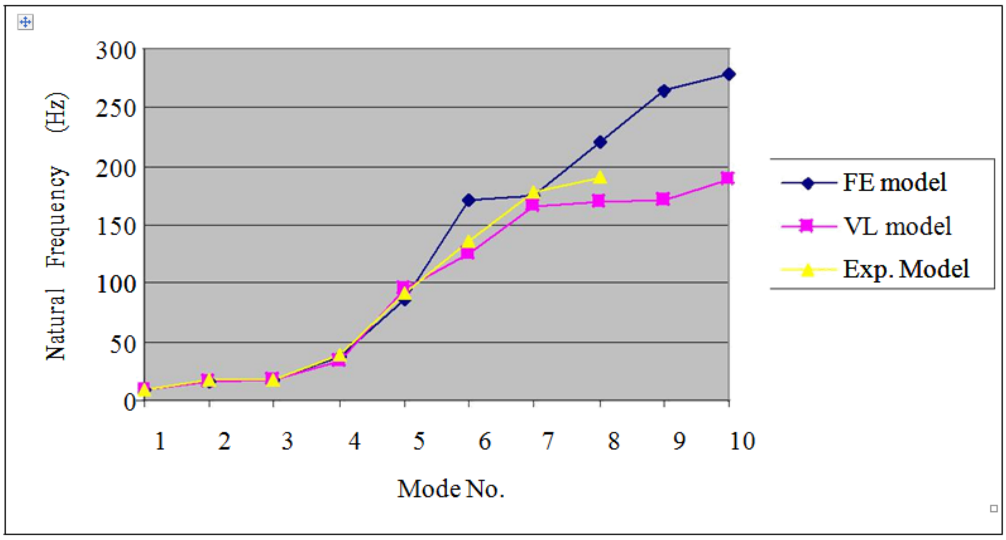

Figure 5.1: Natural Frequencies Using Different Modeling Approaches

5.1 Evaluation of the Results:

5.1.1 Comparison of the natural frequencies of the pylon structure:

The various approaches of modeling of the pylon structure and the results obtained by each method have been discussed so far. It is more intuitive to compare the results of only two modeling approaches at a time. The difference in the natural frequencies among each pair of modeling methods is shown in Table 5.1 and also, in the bar chart shown in Figure 5.1

Again it can be seen from Figure 5.1.1 that the difference in the natural frequencies is greater in the higher frequency range than in the lower frequency range. In the higher frequency range, the flexible body model gives closer results to the experimental results than detailed FE model. However, no particular trend is observed in deviation of the natural frequencies of different models.

Table 5.1.1: Difference in the natural frequencies among individual pairs of the models

Mode No.	Difference in the natural frequencies of the pylon structure					
	Experimental model - FE model		Experimental model - Flexible body model (VL model)		FE model – Flexible body model (VL model)	
	Δ (Hz)	Δ%	Δ (Hz)	Δ%	Δ (Hz)	Δ%
1	-0.38	4.39	0.11	1.27	-0.49	5.59
2	-1.3	7.61	-1.54	9.02	0.24	1.54
3	-0.11	0.63	0.11	0.63	-0.22	1.26
4	-2.33	6.02	-5.86	15.15	3.53	10.75
5	-4.96	5.40	2.83	3.08	-7.79	8.23
6	35.15	25.87	-10.68	7.86	45.83	36.61
7	-3.55	1.99	-12.22	6.86	8.67	5.22
8	29.04	15.23	-20.47	10.74	49.51	29.09

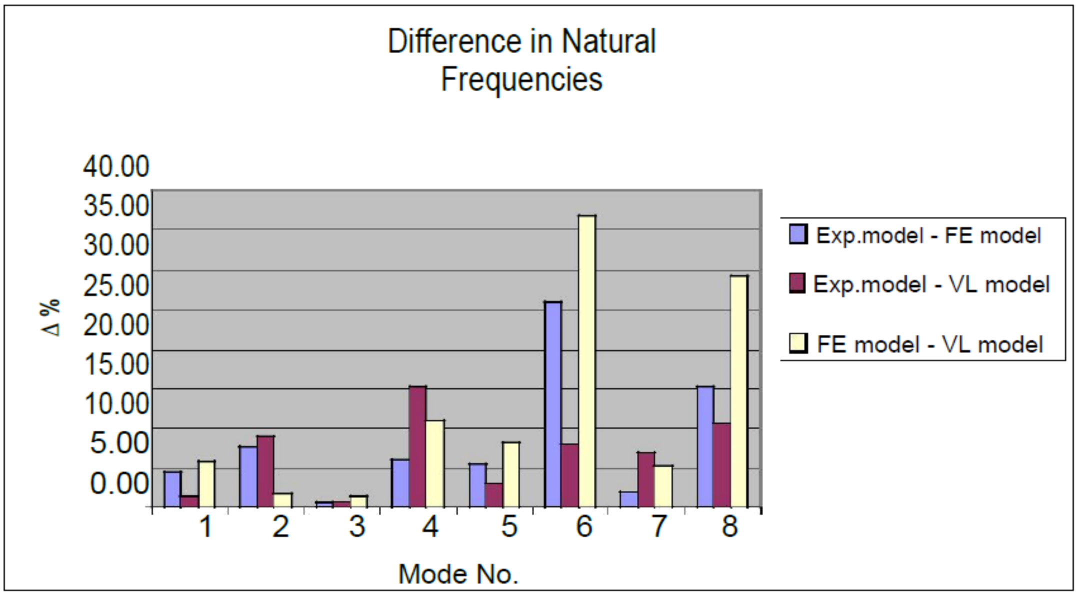

Figure 5.2: Difference in the Natural Frequencies among Individual Pairs of the Models

5.2 Comparison of the FE problem size

The flexibility in the VL model (i.e. flexible multibody model) is incorporated using modal data of each component represented by its Craig-Bampton mode set. Since the modal coordinates are used along with rigid body coordinates in the formulation of the flexible body dynamics problem, the computational efforts are saved significantly as less number of DoFs is used to represent the system. However, it should be noted that the Craig-Bampton mode set is obtained by solving the FE problem individually for each component. It is important to see how much computational effort is required to solve these problems. The FE model size of each component is summarized in Table 5.2.

The FE problem size i.e. number nodes and number of DoFs used in each modeling approach is compared in Table 5.2.1

It can be seen from Table 5.2.1 that the FE problem size is significantly reduced in the VL modeling approach as compared to detailed FE modeling approach. It should be noted that even if the total FE size of VL model is compared to that of the detailed FE model,

Table 5.2: FE model size used to get Craig-Bampton mode set in VL model

Description	Component			Total
	Vertical Plate	Wing Plate	Missile Rack	
No. of nodes	3,492	2,910	687	7,089
No. of DoF	20,952	17,460	4,122	42,534

Table 5.2.1: FE problem size used in different modeling approaches

Description	Modeling Method		
	Detailed FE model	VL model (Total)	Experimental Modal Model
No. of nodes	22,644	7,089	80
No. of DoF	135,864	42,534	240

The FE problem size, the modeling efforts and the computational efforts required to obtain the natural frequencies of the pylon structure involved in the various modeling approaches were compared. It is seen that these efforts were reduced significantly with the use of flexible body modeling approach developed in this study.

6. CONCLUSIONS

The following conclusions can be drawn from the observations and results of this study.

1. The Pro/E CAD model of the pylon structure was developed and validated by comparing its geometry and mass properties with measurements of the physical model.

2. The use of composite section approach to develop FE models of the components was proposed in this thesis to reduce FE modeling efforts. This approach simplified the modeling procedure to a great extent. The bracket joint details such as angle irons and bolt assemblies are not required to be modeled separately in this approach. As, the results of modal analysis using this approach are fairly close to those obtained using the detailed FE model. So this approach can be adopted in practice.

3. The FE problem size is reduced significantly with the use of simplified FE models of components in which the local joint details are eliminated. Moreover, the computational time can be saved as the component FE models can be simultaneously solved for eigenvalue analysis.

4. A significant amount of modeling effort can be reduced using the Craig-Bampton approach as components are modeled separately. The complete model of the pylon structure can be easily built in VL from the component models, using kinematic constraints imposed by a bracket joint. This approach allows use of multiple configurations of components in the multibody system using separate component models. One of the major advantages of this approach is that the selected group of the bodies can be modeled as flexible and other bodies can be treated as rigid. For example, in the flexible multibody model of the pylon structure the base plate was treated as rigid body as it was bolted to the ground. This facility is not available in other modeling approaches reviewed in this thesis.

5. The natural frequencies of the pylon structure obtained using the flexible multibody modeling approach are highly dependent on the selection of deformation modes in the Craig-Bampton mode set of the each component. The natural frequencies of the pylon structure obtained using different Craig-Bampton mode. The fixed interface normal modes should be selected along with the constraint modes such that they span entire subspace of the deformation.

6. The Craig-Bampton approach employed in this thesis can be effectively used to develop the flexible multibody model of the pylon structure. The results of the modal analysis of the simplified flexible multibody model are in close agreement to those obtained from detailed FE model and experimental modal model in lower frequency range (i.e. 0-100 Hz) as shown in Figure 7.9. This approach can be successfully implemented in practice as most of the energy is associated with the low frequency modes.

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