



Application of Craig Bampton Technique in Flutter Analysis of a Sounding Rocket using MSC NASTRAN

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Abstract: Flutter is a dynamic instability problem. It is a kind of self induced oscillations occurring at the flexible parts like fins of an aerospace vehicle during its atmospheric flight. Flutter analysis is carried out by finite element packages like MSC NASTRAN. Usually the aerospace systems are complicated and due to this their finite element model size is very large. The size of the structure will become a restriction on further analyses, which is handled by using model condensation methods, like substructuring. Craig-Bampton technique is a model reduction technique used in structural dynamic analyses. The present work is a research about the application of Craig Bampton Technique in flutter analysis of a sounding rocket. Flutter analysis of the sounding rocket and its reduced model is carried out. The results obtained are compared and validated.

Keywords: flutter; Craig Bampton technique; substructuring; MSC NASTRAN; sounding rocket

I. Introduction

Any aerospace vehicle during the atmospheric flight subjected to various types of forces such as aerodynamic force, inertia force, elastic force etc. The structural designs of various components consider only static part of loads. But due to flexibility of the vehicle and flight conditions, the loads are dynamic. Hence, during the developmental phase, any design has to be studied by considering the interaction of various forces on the structure. Flutter is one of the fundamental requirements to clear the design. Flutter is defined as the self sustained oscillations without any external input. It is a dynamic instability problem. Flutter can occur in bridges, posts, aero planes, rockets etc. During atmospheric flight the air will act like a virtual mass and it will apply pressure on the rocket fins. The fins continuously release energy to air. This phenomenon continues till a particular velocity. Beyond that velocity the fins will start absorbing energy from air and will start vibrating catastrophically to release out the absorbed energy. Damping energy is getting released. This phenomenon is called flutter and the velocity at which flutter phenomenon occurs is called critical flutter velocity or simply flutter velocity. The aim of flutter analysis is to find out the critical flutter velocity of a system like aero plane, rockets etc. The working velocity of the system should be always less than the first critical flutter velocity. The vibration occurring during flutter is so dangerous that it will result in the failure of the structure. During flutter structural damping is insufficient to damp out the motions which are increasing due to the addition of aero dynamic energy. Flutter analysis requires knowledge in aerodynamics and structural dynamics. Hence, flutter analysis requires dynamic characteristics such as frequency, mode shapes, damping etc and flight dynamic conditions. During flutter the bending mode and torsional mode will be coupled together. Practically, the dynamic characteristics are extracted using the finite element (FE) package MSC NASTRAN. Since the aerospace systems are very complicated, usually, the FE model size becomes very large. The size of the structure may become a restriction on further analyses, which is handled by using model condensation methods, like substructuring. Craig-Bampton technique is a model reduction technique used in structural dynamic analyses. A large degree of freedom structure can be reduced to a manageable size, which will reduce the computational requirements to a large extend. By applying Craig Bampton method the size of the stiffness and mass matrix of the FE model will be reduced.

II. Objective

The objective of this work is to incorporate an efficient memory reduction technique i.e. Craig Bamton technique in flutter analysis of a sounding rocket using MSC NASTRAN and to predict its critical flutter velocity for booster fins. The results obtained with the complete model and reduced model are compared for accuracy, time and memory requirements.

III. Need for Application of Craig Bampton Technique

Aero space systems like sounding rocket are highly complicated systems. Usually the analyses of such systems are carried out by dividing the structure into various substructures and analysis of each substructure is carried out at different analysis sections. For example in the case of a rocket, it is divided into substructures like its fins, motors and its casings, engines and engine casings etc. An advantage of using Craig Bampton technique is that when it is applied to MSC NASTRAN, then it will develop an input file of PCH format which consists of only the reduced mass and stiffness matrices (restitution matrix). Other details like dimensional specifications, materials, type of elements used etc will not be specified in such a file. Then this file will be given to various analysis sections for dynamic analysis. Thus it helps in maintaining security when analyses of structures are done at foreign countries. For flutter analysis the time and memory requirement is very high for complicated structures like rockets since the degree of freedom is very high. The size of the mass and stiffness matrices is of very high order. The size of these matrices can be reduced to a smaller order by the application of Craig Bampton method.

IV. Craig Bampton Method

The technique is developed by R R Craig and M C C Bampton. The technique is able to transform the large matrices to a reduced form that can be put for analysis which gave results having no deviation from the result obtained by using the original form of matrices. The reduction in size of the matrices is done by reducing the unwanted degrees of freedom. Static or Guyan reduction and component mode synthesis (CMS) are two kinds of reduction methods. Craig Bampton technique is a CMS type reduction technique. CMS is performed after conducting Guyan reduction. During Guyan reduction there will be some loss in accuracy of the mass matrix which will make over after CMS. CMS is a dynamic reduction process. The matrix transformation is made by applying the transformation to the Lagrange's equation of motion

$$M\ddot{x} + C\dot{x} + Kx = F \quad (1)$$

In the case of FE method the equation will be transformed to matrix form,

M: Mass matrix, C: Damping matrix, K: Stiffness matrix, $\ddot{u}$: acceleration, $\dot{u}$: velocity, u: displacement

V. Elimination of Unwanted Degrees of Freedom

During FE analysis some degrees of freedom are unwanted or are of secondary importance like in plane displacements in a folded plate structure. The analysis may, therefore be carried out more efficiently if these unwanted degrees of freedom can be eliminated by some procedure before solving the Eigen problem.

VI. Static or Guyan Reduction

In Guyan reduction the degrees of freedom of the FE model is classified or divided into slaves and masters. The reduced matrix will consist only of the master degrees of freedom and the order of the reduced matrix will be equal to the number of master degrees of freedom.

Consider the equation of free vibration

$$M\ddot{u} + Ku = F \quad (2)$$

The degrees of freedom u are partitioned into a set u_m termed master degrees of freedom, which are to be maintained and a set u_s termed slave degrees of freedom, which are to be eliminated.

Partitioning M and K in a compatible manner,

$$\begin{bmatrix} M_{mm} & M_{ms} \\ M_{sm} & M_{ss} \end{bmatrix} \begin{bmatrix} \ddot{u}_m \\ \ddot{u}_s \end{bmatrix} + \begin{bmatrix} K_{mm} & K_{ms} \\ K_{sm} & K_{ss} \end{bmatrix} \begin{bmatrix} u_m \\ u_s \end{bmatrix} = 0 \quad (3)$$

Degree of freedom u got classified into masters and slaves

$$u = \begin{bmatrix} u_m \\ u_s \end{bmatrix} = \begin{bmatrix} I \\ -K_{sm}/K_{ss} \end{bmatrix} u_m = Ru_m \quad (4)$$

New reduced mass (M^R) and stiffness matrix (K^R)

$$M^R = M_{mm} - M_{ms}K_{ss}^{-1}K_{sm} - K_{ms}K_{ss}^{-1}M_{sm} + K_{ms}K_{ss}^{-1}M_{ss}K_{ss}^{-1}K_{sm} \quad (5)$$

$$K^R = K_{mm} - K_{ms}K_{ss}^{-1}K_{sm} \quad (6)$$

Substituting these into Lagrange's equation gives

$$M^R\ddot{u}_m + K^Ru_m = 0 \quad (7)$$

This is Guyan reduction.

VII. Component Mode Synthesis

Craig Bampton technique is one among the variants of CMS. It is also called substructure analysis or building block approach. It is a fixed interface method. This method involves dividing the structure up into a number of separate components or substructures. Each component is then represented by a FE model. The next step is

concerned with reducing the number of degrees of freedom for each component by modal substitution. All the components are then assembled together and the complete structure is analyzed. In this way one large Eigen problem is replaced by several smaller ones.

To reduce the number of degrees of freedom, the following transformation is applied

$$\{u\}_s = \begin{bmatrix} u_I \\ u_B \end{bmatrix} = \begin{bmatrix} \phi_N & \phi_c \\ 0 & I \end{bmatrix}_s \begin{bmatrix} q_N \\ u_B \end{bmatrix}_s = [T_F]_s \{q\}_s \quad (8)$$

The subscript 's' denotes the substructure and suffix I refers to internal node points and suffix B to node points on boundaries common to two or more substructures. The columns of the matrix ϕ_N are the natural mode of the substructure with interface boundaries fixed.

New reduced mass and stiffness matrices are

$$[M] = \begin{bmatrix} \bar{M}_{NN}^I & 0 & M_{NB}^I \\ 0 & \bar{M}_{NN}^{II} & \bar{M}_{NB}^{II} \\ \bar{M}_{BN}^I & \bar{M}_{BN}^{II} & \bar{M}_{BB}^I + M_{BB}^{II} \end{bmatrix} \text{ and } [K] = \begin{bmatrix} \bar{K}_{NN}^I & 0 & 0 \\ 0 & \bar{K}_{NN}^{II} & 0 \\ 0 & 0 & \bar{K}_{BB}^I + K_{BB}^{II} \end{bmatrix} \quad (9)$$

Above matrices are developed when the main structure is divided into two substructures. Superscripts I and II indicates the substructure. Equation of motion of the complete structure is

$$[M]\{\ddot{q}\} + [K]\{q\} = 0 \quad (10)$$

The interior node point degrees of freedom have been eliminated by static condensation. The method has very good convergence properties.

Reference [1] and [19] gives full derivation of Guyan reduction and CMS/ Craig Bampton technique.

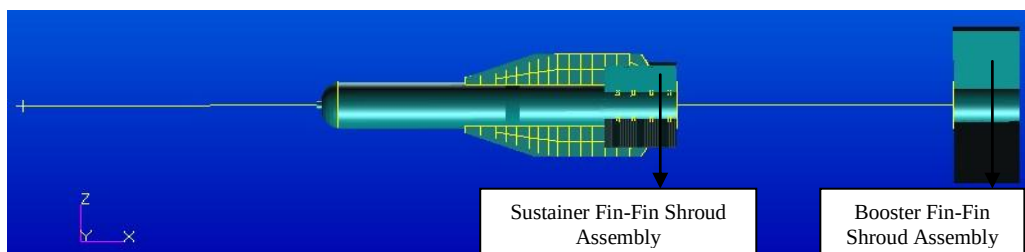
VIII. Analysis Procedure

MSC NASTRAN and PATRAN version 2001 is used. PATRAN is the pre and post processor whereas NASTRAN is the analyzing tool. An input file will be developed by PATRAN in BDF format which can put for analysis by NASTRAN. This input file can be edited for various kinds of analysis. To do flutter analysis, normal mode analysis has to be done first. Then edit the solution sequence 103 to 75 in the input file for flutter analysis. After analysis output files are generated by NASTRAN. These files include XDB files which show graphical demonstration of deformation when imported in PATRAN, F06 files which gives the details about frequencies in normal mode analysis or flutter velocity in flutter analysis. The mode for which damping changes from negative to positive is the flutter occurring mode and corresponding velocity is flutter velocity. Flutter velocity is obtained in meter per second. F04 files gives the amount of time and memory used for analysis. All the files except XDB can be opened using word pad or note pad and values can be noted or checked. Reduced frequency has to be calculated for flutter analysis. For developing Craig Bampton model node points have to classified into internal and boundary nodes. This is done by giving internal nodes to SESET and boundary node (nodes common to both substructures) to SEBSET1 in the input file and all other nodes in SECSET1. Include the Solution sequence for CMS from NASTRAN library 'ssalter' for creating boundary matrices for solution 103. Give MPC for nodes coming under SEBSET1. Standard procedures are being followed for doing normal mode analysis and flutter analysis using MSC NASTRAN.

IX. Sounding Rocket

Sounding rocket is a two stage, unguided, spinning and fin stabilized vehicle under development. The primary objective of the rocket is to reach the environment for demonstrating the scram jet propulsion technology. Launch vehicle system consists of booster motor with fin-fin shroud assembly, sustainer motor with shroud assembly, fuel feed system structure, scramjet engines and nosecone payload. The fin assembly in rocket is given in Fig. 1. FE model of the rocket is shown. The rocket has two sets of fins (each set has 4 fins) attached to it. The fins at middle portion are called 'sustainer fins'. They are arranged in a particular included angle of 71 degree and 109 degree. The fins at the bottom portion are called 'booster fins'. They are arranged at 90 degree to each other. Except the fins all the other rocket structure is considered as rigid. Fins are the only flexible structure and flutter analysis is carried for these fins. In this project flutter analysis of the booster fins are done.

Figure 1 Fin Assembly of Sounding Rocket



For generating Craig Bampton model the structure is divided into two substructures as shown in Fig. 2 and Fig. 3

Figure 2 Substructure 1

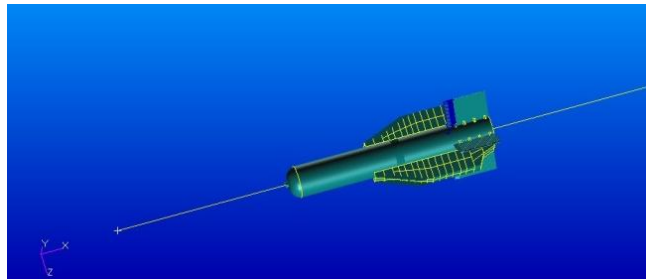
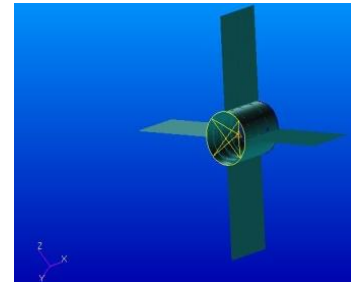


Figure 3 Substructure 2



X. Results and Discussion

Normal mode analysis and flutter analysis of complete model and reduced models are done. For both the cases frequencies and flutter velocity obtained were same, which shows application of Craig Bampton technique in flutter analysis is a success.

Table I Shows Comparison of Frequencies of Complete Model and Reduced Model

Complete Model			Reduced Model		
Cycles	Generalised Mass	Generalised Stiffness	Cycles	Generalised Mass	Generalised Stiffness
3.410214E+00	1.000000E+00	4.591166E+02	3.410341E+00	1.000000E+00	4.591509E+02
3.439001E+00	1.000000E+00	4.669006E+02	3.439160E+00	1.000000E+00	4.669438E+02
3.440952E+00	1.000000E+00	4.674304E+02	3.441060E+00	1.000000E+00	4.674597E+02
3.592396E+00	1.000000E+00	5.094814E+02	3.592593E+00	1.000000E+00	5.095372E+02
1.272229E+01	1.000000E+00	6.389841E+03	1.272201E+01	1.000000E+00	6.389568E+03
1.272488E+01	1.000000E+00	6.392452E+03	1.272459E+01	1.000000E+00	6.392160E+03
1.272828E+01	1.000000E+00	6.395867E+03	1.272811E+01	1.000000E+00	6.395691E+03
1.273112E+01	1.000000E+00	6.398720E+03	1.273088E+01	1.000000E+00	6.398480E+03

Frequencies obtained can be checked by equation

$$f = 1/2\pi\sqrt{k/m} \quad (11)$$

Taking the first case, here

$$K = 459.11\text{N/m}$$

$$M = 1.00\text{N}$$

Putting these values in equation (11)

$$f = 3.41 \text{ Hz}$$

Figure 4 Booster Fin Bending Mode at 3.4 Hz

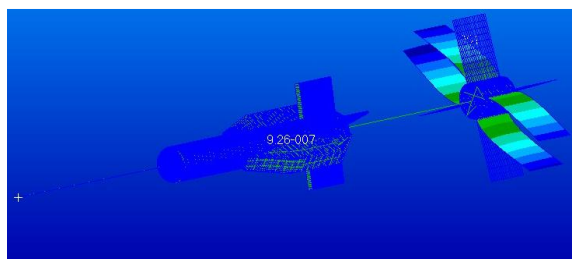
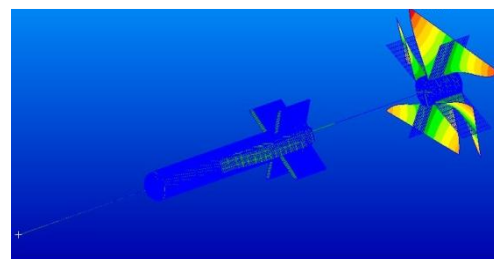


Figure 5 Booster Fin Torsional Mode at 12.7 Hz



Flutter analysis of complete model and reduced model gave flutter velocity as 171m/s. For doing the flutter analysis the flight parameters like Mach number, atmospheric density etc are provided the by flight mechanics division. Here Mach number used is 0.27 and atmospheric density is 1.17 kg/m^3

Table II Shows Comparison of Flutter Velocity of Complete Model and Reduced Model

Complete Model		Reduced Model	
Damping	Velocity	Damping	Velocity
-9.4520143E-04	1.6989990E+02	-8.7993802E-04	1.6989990E+02
-6.9068733E-04	1.7039040E+02	-6.3014170E-04	1.7039040E+02
-4.4266120E-04	1.7088087E+02	-3.8675641E-04	1.7088087E+02
-2.0108608E-04	1.7137137E+02	-1.4975626E-04	1.7137137E+02
3.4064298E-05	1.7186186E+02	8.0870399E-05	1.7186186E+02

Figure 5 and Figure 6 gives damping v/s velocity graphs for complete and reduced model

Figure 6 Flutter Analysis of Complete Model

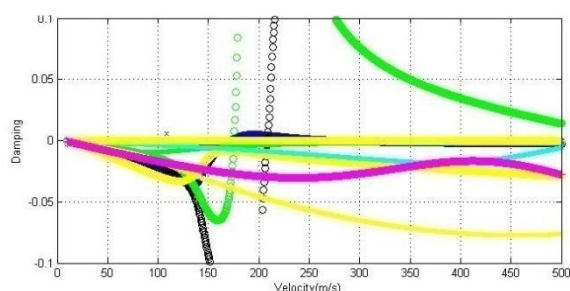
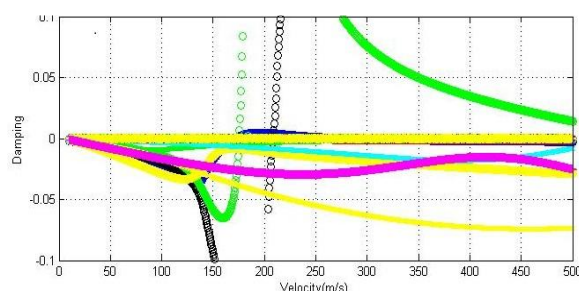


Figure 7 Flutter Analysis Reduced Model



Memory/Disc usage used and time consumed by complete model and reduced model can be obtained by referring the F04 file created after analysis by NASTRAN.

Table III Shows Comparison between Complete Model and Reduced Model in terms of Time and Disc Usage

MODEL TYPE	TIME (IN SECONDS)	DISC USAGE (IN MB)
COMPLETE MODEL	181.2 seconds	2197 MB
REDUCED MODEL	36 seconds	68 MB

By referring the time and disc usage comparison it is clear that the model reduced using Craig Bampton technique consumes only very small amount of time and disc usage as compared to the complete model.

XI. Conclusion

This paper is a research work conducted on the application of Craig Bampton technique in flutter analysis of a typical sounding rocket using MSC NASTRAN. Here solution sequence of CMS for normal mode analysis (Solution 103) is used in flutter analysis and the result obtained was success. The model reduced using Craig Bampton technique gave the same result as that of the complete model for both normal mode analysis and flutter analysis. The time required and disc usage got reduced from 181.2 seconds to 36 seconds and 2197 MB to 68 MB respectively for the reduced model when compared to the complete model.

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